EXPEDITING TRANSITIONS IN UNMET ELECTRICITY MARKETS: THE CASE OF LEAPFROGGING RENEWABLE ENERGY IN AFRICA

By

BENJAMIN BATINGE

Dissertation presented for the degree of **Doctor of Philosophy** in the Faculty of Economic and Management Sciences, at Stellenbosch University

Supervisor: Prof. Josephine Kaviti Musango (Stellenbosch University)

Co-Supervisor: Prof Alan C. Brent (Victoria University of Wellington)

December 2018

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes one original paper published in peer-reviewed journal and three unpublished papers currently in review with peer-reviewed journals. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

Benjamin Batinge

December 2018

ABSTRACT

The importance of access to modern energy, especially electricity, is evident in the quality of service it offers in sectors such as education, health, business, manufacturing, construction, and many other facets of human living. Despite the enormous benefits derived from access to electricity, over one billion people in the world, 588 million of whom are in Africa, still did not have access to electricity as at 2016. The abundant renewable energy resources available in Africa can quickly supply the needed electricity through new technologies. It is therefore essential to consider potentially leapfrogging Africa's unmet electricity markets from traditional energy to renewable energy, in order to achieve the Sustainable Energy for All goal of universal energy access by 2030. Thus, the overall research question for this study was: how can an energy transition, particularly leapfrogging to renewable energy, accelerate universal access to electricity in Africa? This question was addressed through systematic literature review, which resulted in the development of a modified transition framework that captures the unique characteristics of unmet electricity markets. These characteristics included unmet power market; small-scale; renewable energy; fast transition time; niche opportunities, and multi-dimensional pressures. The study highlights the need for contextual awareness, and socio-cultural and political lock-ins in adopting the energy transition framework for unmet electricity markets. The study also identified key drivers of energy leapfrogging in an African context. They included large unmet electricity market, the urgency for universal energy access, and the availability of renewable energy resources. Three potential leapfrogging paradigms were eventually conceptualised, namely: *Revolutionary, Scattered, and Coned* leapfrogging. They were defined by the pace and magnitude of transition, and depended on the intensity of the leapfrogging drivers. The study concluded that Africa has the opportunity to leapfrog the fossil-intensive energy regime, to a renewable energy regime. Further, two system dynamics models were developed, namely: the African Electricity Access (AFELA) model, and the Ghana Electricity Access (GELA) model. The AFELA model results showed access to funding for energy infrastructure as a key challenge in Africa, and the reason for its large unmet electricity market. After examining four different scenarios, the Electricity Access Investment Scenario, which entailed an increase in the annual power investment by two per cent of GDP, was found to be most ideal path to close the funding gap and ensure attainment of universal access to electricity in Africa by 2030. Further, the GELA model results indicated that under

the existing electricity investment trajectory, Ghana would not achieve its dual energy goal of universal electricity access and 10% renewable energy in the electricity sector energy mix by 2020. In order to accelerate universal access to electricity in Africa, the study recommended regulatory reform to attract investment from private sector, and investment diversification to promote renewable energy leapfrogging.

OPSOMMING

Die belang van toegang tot moderne energie, veral elektrisiteit, is duidelik in die gehalte diens wat dit vir onder meer die onderwys-, gesondheid-, sake-, vervaardiging- en konstruksiesektor, asook vir vele ander fasette van die menslike bestaan bied. Ten spyte van die enorme voordele wat uit toegang tot elektrisiteit verkry word, het meer as een miljard mense wêreldwyd, waarvan 588 miljoen in Afrika, teen 2016 steeds nie toegang tot elektrisiteit gehad nie. Die oorvloedige hernubare energiebronne in Afrika kan egter vinnig die nodige elektrisiteit deur middel van nuwe tegnologie voorsien. Dit is dus noodsaaklik dat daar oorweeg word dat Afrika se onbevredigde elektrisiteitsmarkte spronggewys van tradisionele energie na hernubare energie geneem word, om sodoende die Volhoubare Energie vir Almal-doelwit van universele energietoegang teen 2030 te verwesenlik. Die oorkoepelende navorsingsvraag vir hierdie studie was dus: hoe kan ’n energie-oorgang, veral deur ’n groot sprong na hernubare energie, universele toegang tot elektrisiteit in Afrika versnel? Hierdie vraag is aangepak met behulp van ’n sistematiese literatuuroorsig, wat gelei het tot die ontwikkeling van ’n aangepaste oorgangsraamwerk wat die unieke eienskappe van onbevredigde elektrisiteitsmarkte omvat. Hierdie eienskappe is onder meer die onbevredigde kragmark; klein skale; hernubare energie; vinnige oorgangstyd; nisgeleenthede; en meerdimensionele druk. Die studie beklemtoon die behoefte aan kontekstuele bewustheid, asook sosiokulturele en politieke insluitings ten opsigte van die aanvaarding van die energie-oorgangsraamwerk vir onbevredigde elektrisiteitsmarkte. Die studie identifiseer ook sleuteldrywers vir energiespronge in ’n Afrikakonteks. Dit sluit in ’n groot onbevredigde elektrisiteitsmark, die dringendheid van universele energietoegang, en die beskikbaarheid van hernubare energiebronne. Drie potensiële sprongparadigmas is uiteindelik gekonseptualiseer, naamlik: *Revolusionêre, Verspreide, en Gefokusde spronge*. Hierdie paradigmas word omskryf aan die hand van die tempo en omvang van die oorgang, en hang af van die intensiteit van die sprongdrywers. Die studie kom tot die gevolgtrekking dat Afrika die geleentheid het om die fossielintensiewe energie-regime heeltemal oor te slaan en na ’n hernubare energie-regime te versnel. Verder is daar twee stelseldinamika-modelle ontwikkel, naamlik: die AFELA-model (Afrika-elektrisiteitstoegangmodel) en die GELA-model (Ghana-elektrisiteitstoegangmodel). Die AFELA-modelresultate dui aan dat toegang tot befondsing vir energie-infrastruktuur ’n belangrike uitdaging in Afrika is, en die rede vir die groot onbevredigde elektrisiteitsmark is. Nadat vier verskillende scenario’s ondersoek is, is

daar bevind dat die Elektrisiteitstoegang-beleggingscenario, wat 'n toename in die jaarlikse kraginvestering van twee persent van die BBP behels, die mees ideale pad is om die finansieringsgaping te oorbrug en te verseker dat universele toegang tot elektrisiteit in Afrika teen 2030 verkry word. Verder dui die GELA-modelresultate aan dat Ghana volgens die huidige elektrisiteitsbeleggingtrajek nie sy tweeledige energiedoelwit van universele elektrisiteitstoegang en 10% hernubare energie in die elektrisiteitsektor se energiemengsel teen 2020 sal bereik nie. Ten einde die universele toegang tot elektrisiteit in Afrika te versnel, beveel die studie regulatoriese hervorming aan om investering vanuit die privaat sektor te lok, asook beleggingsdiversifikasie ter bevordering van die sprong na hernubare energie.

ACKNOWLEDGEMENTS

"Every history has one quality in common with eternity. Begin where you will, there is always a beginning back of the beginning. And for that matter, there is always a shadowy ending beyond the ending." Edward Eggleston (1837 - 1902) - *The Circuit Rider*.

My most profound gratitude goes to my supervisor, Prof. Josephine Kaviti Musango for shepherding me through this journey. When our paths first crossed in Boston in 2015, and you advised me to undertake my doctoral studies at Stellenbosch University, I knew it would be an electrifying research journey, and indeed, at every stage, I have been leapfrogging towards the zenith of fulfillment continuum. Thank you for guiding me through all the steps and stages of doctoral research, and steering me on course whenever I go adrift.

I equally express my heartfelt gratitude to my co-supervisor, Prof. Alan C. Brent, for his unsurpassed guidance, advice, mediation and direction throughout this process. Your attention to detail and comments on my drafts really made me rethink every word I write and every sentence I construct, consequently I have grown tremendously in research and understanding. I could not have done it without you, and I am very grateful.

I wish to extend appreciation to the Graduate School of Economics and Management Sciences for providing funding for this study. The financial and administrative support you provide cushioned me against the sharp pinches of stress and worry associated with this kind of research. Thank you.

To Dr. Jaco Franken, coordinator for the GEM programme at the Graduate School, thank you for your advice and tit-bits on navigating the nooks and crannies of doctoral research. Your guidance and GEM meetings have helped a lot. I also thank the Urban Modelling and Metabolism Assessment (UMAMA) research team for your insightful inputs during our monthly meetings. To my colleagues from the 2016 cohort, your company and shared experiences ensured there was never a lonely moment.

I also thank the institutions that provided insights for this study including the Ghana Energy Commission and the Volta River Authority. I appreciate the International Energy Agency and the United Nations for their open access online data retrieval system through which I obtained key data for validating my models.

To the editor of this dissertation, Anita van der Spuy, thank you for the time invested in making sure that my thoughts and ideas were conveyed with brevity and clarity.

My parents, Mr. Suwiere Batinge and Mrs. Janet A.L. Batinge, thank you for initiating the journey at childhood that took me to this point. To my brothers and sisters Kwame (always in my memory), Maxwell, Emmanuel, Julius, Mavis, and Victoria, you have all made this journey way easier for me than it has been for many who have embarked upon it. You have given me a stream of support and motivation, so, may the portion of your reward be divine.

I owe gratitude to my uncle and aunt, Mr. Wilson M. Batinge and Bibiana K. Batinge for pulling me back on course when I hit a snag. To Dorah, my cousins, my playful nieces and nephews, you have all provided me with the support that could not be obtained in school, thank you.

To my potential children who would probably never be born for your own good because the world is a difficult place, just know your absence helped me do this research with much ease, and in the event that you are born, know that you helped in absentia, so thank you. I appreciate laws of nature and ‘conspiracies’ of the cosmos for the good things that helped me live, the bad things that helped me learn, and all that is in-between that helped me love.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AfDB	African Development Bank
AFELA	Africa Electricity Access
AREA	African Renewable Energy Alliance
CAPP	Central Africa Power Pool
CIF	Climate Investment Fund
COP	Conference of Parties
EAPP	Eastern Africa Power Pool
EERA	Eco development and Resilience in Africa
GELA	Ghana Electricity Access
GW	Gigawatt
GWh	Gigawatt-hour
ICA	Infrastructure Consortium for Africa
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IRENA	International Renewable Energy Agency
ITF	Infrastructure Trust Fund
KWh	Kilowatt-hour
LF	Leapfrogging

MW	Megawatt
MWh	Megawatt-hour
SAPP	Southern Africa Power Pool
SDG	Sustainable Development Goals
SE4All	Sustainable Energy for All
SNEP	Strategic National Energy Plan
UN	United Nation
UNDP	United Nation Development Programme
UNEP	United Nation Environment Programme
UNFCCC	United Nation Framework Convention on Climate Change
UNSD	United Nation Statistics Division
WAPP	Western Africa Power Pool
WHO	World Health Organisation

1 CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Energy is an integral part of the global economic foundation in the twenty-first century (see: IEA, UNDP and UNIDO, 2010). Most daily activities, including economic sectors such as education, health, manufacturing, and construction, are becoming more energy-driven (Ackah, Adu and Takyi, 2014), underscoring that the role energy assumes today is more relevant than ever. Studies have established a positive correlation between electricity consumption and economic growth rates and development (Apergis and Payne, 2011; Ferguson, Wilkinson and Hill, 2000). Access to energy, especially in the form of electricity, is thus, a principal objective of governments for economic and social development (Winkler, Simões, La Rovere, Alam, Rahman and Mwakasonda, 2011).

Notwithstanding the immense importance of electricity access, many global citizens are yet to benefit from it. According to the IEA (2015), nearly 1.2 billion people, equivalent to 17% of the total world population, still lack access to electricity as of 2013. Africa ranks as the most energy-impoverished region globally. Approximately 622 million people on the continent lacked access to electricity as at 2012, which is equivalent to 57% of the population (IEA, 2014b). Besides North Africa and island nations such as Cape Verde and Mauritius, only seven countries, namely; Cameroon, Côte d'Ivoire, Gabon, Ghana, Namibia, Senegal and South Africa, have electricity access covering above 50% of the total population (Castellano, Kendall, Nikomarov and Swemmer, 2015). Given the vastly unmet electricity market demonstrated by IEA (2015), the severity of its implications in sub-Saharan Africa (Scott, 2015), and the efforts towards a sustainable future and Sustainable Energy for All (SE4ALL), (UNFCCC, 1992; UN, 2015; EC, SE4All and UN., 2012; IPCC, 2014; UNDP, 2015), the transition to achieve universal access to modern energy is inevitable. This transition would entail a transformation in large-scale socio-technical systems such as energy (Dijkema and Basson, 2009), and expansion of the energy infrastructure.

Globally, the existing electricity generation systems are dominated by fossil fuel (REN21, 2014). These fossil fuel based electricity generation systems are contributing to greenhouse gas emissions, and exacerbating the consequential impact on climate change (IPCC, 2014; REN21, 2014). The United Nations, through various treaties such as Framework Convention on Climate Change (UNFCCC, 1992), the Kyoto Protocol (Goldemberg, 1998), the Copenhagen Accord (2009), the Cancun Agreement (Andreas, Ulf and Dirk, 2010) and, more recently, the Paris Agreement (UN, 2015), is championing initiatives geared towards adopting environmental-friendly, clean, and sustainable technologies for the provision of energy.

The United Nations, having recognised the immense importance of energy, introduced the Sustainable Energy for All (SE4All) initiative, as part of the Sustainable Development Goals (SDGs). This research is therefore in accordance with the SE4ALL objective of ensuring universal access to modern energy services and increase in the share of renewable energy in the total energy mix (UN, 2012). The obligation of addressing energy-related issues has prompted assessment of energy technologies, particularly renewable energy, as a sustainable alternative.

Different transition frameworks have emerged to guide the introduction of sustainable energy resources to ensure (i) universal access to electricity amid concerns of a scarcity of energy resources; and (ii) protect the environment in the face of growing energy needs and demand. These transition frameworks include: the multi-level perspective (Elzen, Geels and Green, 2004; Geels, 2004; Geels, 2005; Kemp, Arie and Johan, 2001), transition management (Loorbach, 2010; Kemp and Rip, 1998; Rotmans, Kemp and van Asselt, 2001), innovation systems (Bergek, Jacobsson, Carlsson, Lindmark and Rickne, 2008; Edquist, 2011; Hekkert, Suurs, Negro, Kuhlmann and Smits, 2007) and strategic niche management (Kemp and Rip, 1998; Raven and Geels, 2010; Smith, 2007). The transitions frameworks have attempted to prescribe an appropriate transition blueprint in the energy sector. In addition, they are centred on transition paradigms that are focused on sustainability of resources.

Another concept that is promulgated in the sustainable energy spectrum is ‘leapfrogging’, which is generally defined as a development strategy whereby industrialising nations skip conventional economic growth stages by immediately adopting contemporary resource–efficient technologies, in order to reduce post-consumption repercussions such as pollution (Perkins, 2003). The concept of leapfrogging is not novel in academic literature, (Gallagher, 2006; Goldemberg, 1998; Lee and Lim, 2001; Murphy, 2001; Perkins, 2003; Szabó, Bódis, Huld and Moner-Girona, 2013). Goldemberg (1998) argued that developing countries, by nature of their small-size infrastructure, could easily adopt new and/or emerging technologies that are more advanced from the start, hence leapfrogging over the resource-intensive path of conventional energy development that developed countries have experienced. One challenge to leapfrogging in developing countries is that, they are often reliant on their developed counterparts to provide such technologies (Tukker, 2005). Due to the limited technological capabilities for implementation of complex innovations in the field of large-scale socio-technical systems, energy technology leapfrogging in such developing countries is challenged by policy inconsistency, the unwillingness of developed countries to transition, and limited domestic capabilities (Gallagher, 2006). Notwithstanding other technological challenges such as the slow pace of the development, adoption and acceptance of technology, the success of energy technology leapfrogging could come about because of the global interest in reducing emissions and the growing pressure from the international bodies such as the United Nations. Another potentially prominent success factor for leapfrogging in energy technology is the pursuit of renewable energy quotas in the total energy mix as part of the Sustainable Development Goals (ICSU and ISSC, 2015).

Transition in energy systems can be challenging. A common characteristic associated with the transition from one energy regime to another is the long time it takes: decades, to emerge in full scale (Grubler, 2012). Indeed, change, especially of socio-technical systems, can be slow and uncomfortable, and when it finally occurs, remnants of the past may still linger. Energy transitions in the past have been partial, involving a transformation in some energy fuels (Sgouridis and Csala, 2014). Biomass, one form of which, wood, is a traditional energy, for example is still a significant energy source, especially in developing countries, and exceeds nuclear energy as a fuel source, notwithstanding the general belief that, the fossil fuel dominance has replaced the use of biomass (IEA, 2015). Other transitions like the case of the transition from coal to petroleum and natural gas took over a century of innovation and diffusion to reach efficiency of scale (Fouquet, 2010; Fouquet and Pearson, 2012; Grubb, Hourcade and Neuhoff, 2015; Grubler, 2012; Smil, 2010).

While some scholars (Grubler, 2012; Smil, 2010) are reserved about energy transition and its implications, others (Sovacool, 2016; UN, 2015) are optimistic and advocate for a radical transition approach. Grubler (2012) characterises quick introduction and instantaneous policies in simulated innovation as detrimental and a predestined transition failure when dealing with new technology deployment, and cautions that it takes decades for innovation success to occur. Grubler's position, however, does not address the different niche features that might propel the adoption of innovation in a shorter time. On the contrary, Sovacool (2016) affirms that energy transition has occurred, and can occur, in a short period but may remain inconspicuous unless assessed based on a given significance, society, and energy resources and services.

1.2 ENERGY SECURITY

The challenges associated with an energy transition can create energy insecurity. Energy security is varied in definition for contextual reasons. The difference in energy consumption and intensity, especially between developed and developing countries, demonstrates the essence for contextual variations in definition. According to IEA (2011) energy security is 'the uninterrupted availability of energy sources at an affordable price'. This brief definition adequately captures the core of energy security across contexts. Sovacool, Mukherjee, Drupady and D'Agostino (2011) point out that energy security consists of interconnected criteria or dimensions, which include availability, affordability efficiency, and environmental stewardship. The availability dimension refers to the security of supply and production of energy to deliver energy services. It also implies sustainable energy systems that can recover quickly from attack or disruption, and minimise dependence on foreign suppliers (Sovacool and Mukherjee, 2011). Affordability means provision of energy services that are affordable for consumers and that minimize price volatility (Sovacool and Mukherjee, 2011). Efficiency involves improving the performance of energy equipment and altering consumer attitudes (Sovacool and Mukherjee, 2011). Stewardship consists of protecting the natural environment, communities, and future generations (Sovacool and Mukherjee, 2011). Consistent with the definition by IEA (2011) is that security needs to include sustainability for future needs as well as affordability to the people.

Though these energy security definitions are not necessarily set in the context of developing countries, they capture the general understanding of energy poverty. Contextualising the definition for developing countries Martchamadol and Kumar (2012), defines energy security as supplying enough energy, in both quantity and quality, to meet all requirements at all times of all citizens at an affordable and stable price, as well as sustaining economic performance and poverty alleviation, and a better quality of life without harming the environment. This definition highlights the need for energy security to have an impact on quality of life through improved performance. It also captures the core aspects of the definitions by IEA (2011) and Sovacool and Marilyn (2009), namely: availability, sustainability, affordability and environmental protection.

According to IEA (2011), an estimated USD38 trillion is needed if the world is to meet its energy demand by 2035. The magnitude of energy insecurity globally is of concern, particularly in sub-Saharan Africa, where a vast majority of the population does not have access to it (IEA, 2015). Efforts to remedy the problem are quite diversified: from promoting energy efficiency and sustainable consumption particularly in developed countries, to increasing scale of production, and diversifying the portfolios of energy investment in developing countries. Consensus on an advancement trajectory has always been problematic. Assessing the cost of one policy over another and short-term return over long-term gain are some contentions that policy makers encounter. The economic, political, and environmental costs of a given policy, the timeliness of an intervention or implementing of a proposed solution are among the factors that need to be considered.

Present indicators and global trends suggest that measures undertaken to tackle the problem of energy insecurity are inadequate (IEA, 2011; Pachauri, Rao, Nagai and Riahi, 2012). Amid growing population in the most energy insecure regions, efforts towards energy access must be intensified, because of the positive correlation between population growth and energy use (Araújo, 2014; IEA, 2009; IEA, 2015). The growing global population is widening the energy access gap. Urbanisation is also increasing the energy demand. Cities are becoming congested thereby increasing the energy use. More than half of the world population now live in urban areas (IEA, 2014a; UNDP, 2015). Through research and development, emerging innovations for alternative energy production present a promising future. The need for the development of new energy alternatives is compelling because of issues relating to sustainability, environmental protection, and insufficiency of the existing energy production.

1.3 ENERGY TRANSITION AND ELECTRICITY ACCESS

The developing world, especially sub-Sahara Africa, still suffers from an energy deficit in many parts and in diverse ways, including access to electricity, which provides a range of essential modern services such as electronic communication, lighting, heating, and transport (IEA, 2011). Diversification in and transition of energy supply is necessary to meet the growing diversity in end-use energy needs. Grubler (2012) supports this stance, cautioning that present energy systems may not be sustainable in economic, social, and technical spheres. Miller, Richter and O'Leary (2015), reiterate that future energy systems should feature as a major policy decision especially in industrial economies. Giddens (2009) posits that humanity is approaching the threshold where, unless acted upon, the global economy will have exceeded the point of no return. He used the maximum emission target as a basis for what he terms as the climate paradox. The need for inclusion of alternative energy sources in current infrastructure to meet future energy needs is inevitable.

There is often resistance to change and, as such, it does not usually happen in the timely and orderly fashion intended. Large-scale transitions such as that of energy sources are often beyond the control of a single sector or entity, whether private market or public agency (Davison, Vogel, Harris and Jones, 2000). The conditions required for significant transition go beyond a change in technology; they include changes in political regulations, pricing schemes, and end-user behaviour towards such change. This has been the case in large transitions like that to renewable electricity (Painuly, 2001; Sovacool, 2009) and electric vehicles (Nielsen, Hovmøller, Blyth and Sovacool, 2015; Sovacool and Hirsh, 2009).

There is growing research on transition, especially as novel technologies emerge and out-dated ones fade into oblivion (Fouquet, 2010; Geels, 2002; Grubler, 2012; Kemp, Rotmans and Loorbach, 2007; Sovacool, 2016). New technologies generally build on existing ones with a unique value proposition that the competing technology lacks. Developed countries that have renewable energy resources, for instance, often take advantage of the long-term benefits of generating electricity using renewable energy resources. About 95% of Norway's electricity is generated through hydropower (García-Gusano, Iribarren, Martín-Gamboa, Dufour, Espegren and Lind, 2016). Denmark is one of the leading countries with wind-generated power (REN21, 2014). Germany has significantly increased its solar power within a relatively short time

(REN21, 2014), notwithstanding the country's limited solar resources compared to those of most African countries. Following the decommissioning of nuclear plants, Germany increased its solar PV from less than one gigawatt (1 GW) to twenty-four gigawatts (24 GW) between 2004-2011 (Morris and Pehnt, 2012). This is, however, not the case with developing countries, especially in Africa, where renewable energy such as solar is relatively abundant and yet, more than half the population do not have access to electricity (Scott, 2015; IEA, 2014b). A limited number of African countries have made significant progress in the renewable energy development arena. For instance, according to the 2018 REN21 (2018) report, Kenya is one of the leading countries in geothermal power, behind only the United States, the Philippines, Indonesia, Turkey, New Zealand, Mexico, Italy, and Iceland. Since African countries are not laden with large-scale infrastructure that could act as inertia and be a major impediment to transition or adoption of new technology, leapfrogging to renewable energy should be more viable.

Energy transition in the context of developed countries may not necessarily be the same in Africa, which is characterised by unmet energy markets. The level of receptivity and challenge in a fully satisfied market such as in developed countries also differs from that in unmet market, such as Africa. Despite the unmet electricity market, end-user needs are still essential considerations in the leapfrogging of renewable energy technologies. Limited investigation exists on the potential for developing countries to leapfrog to renewable energy as a conduit for bridging their unmet electricity demand gap. This study therefore addressed this empirical gap by investigating how unmet power markets can transition. The study explored the energy transition in unmet electricity markets in Africa and how leapfrogging to renewable energy can accelerate universal electricity access. The study also recognised the financial challenge that exists in unmet electricity markets in Africa, and examined how the funding problem might be addressed. At the national level, there are challenges to attaining national energy transition and electricity access goals. This study used Ghana as a case study to examine how its universal electricity access and renewable energy goals can be achieved.

1.4 PROBLEM STATEMENT AND RESEARCH QUESTION

The existing transition frameworks do not account for unmet electricity markets, which are dominant in Africa. To achieve the Sustainable Energy for All goal of universal energy access by 2030, there is the need to consider potentially leapfrogging to renewable energy in an unmet electricity market. Thus, the overall research question for this study was; how can an energy transition, particularly by leapfrogging to renewable energy, accelerate universal electricity access in Africa?

1.5 RESEARCH OBJECTIVES

The overall objective of the study was to explore how an energy transition, particularly leapfrogging to renewable energy, can accelerate universal electricity access in Africa. This was achieved through the following sub-objectives:

i. To develop a framework for energy transitions in unmet electricity markets;
ii. To investigate leapfrogging to renewable energy as an opportunity for accelerating electricity access in unmet markets;
iii. To explore the potential of private sector finance to bridge the funding gap and expedite universal electricity access; and
iv. To examine the progress Ghana made with its universal electricity access and renewable energy goals.

This study is presented in chapters, and the four middle chapters (2 to 5) are the study objectives, which were written as journal articles and submitted to different journals for publication. As a result, some overlaps may occur in the discussions in the different chapters.

1.6 RATIONALE AND JUSTIFICATION OF THE RESEARCH

Electricity access provides a range of services that improves individuals' quality of life, well-being, and stimulates economic growth. A largely unmet electricity market is therefore deprived of a range of services, including the use of various technological innovations that are reliant on electricity to function. Basic household activities such as washing, cooking, heating, cooling, among others, that can be carried out easily with modern electricity are still performed with traditional energy resources, which are less effective. It is necessary, therefore, to examine ways and means of increasing access to modern electricity. The continuous consumption of fossil energy pollutes the environment, and has adverse climatic effect. Transition to a renewable energy source is thus deemed ideal.

The energy transition frameworks contextualised in developed countries are not suitably and readily applicable to developing countries, due to differences including the existing energy infrastructure, and the availability of alternative energy sources. This study provides a conceptual framework that is suitable for assessing transitions in an unmet electricity market. It therefore supports policy-makers' efforts to improve electricity access in Africa. By nature of its geographic location, Africa is endowed with renewable energy resources such as sun, wind, biofuel, and water bodies for hydropower. The cost of renewable energy is expected to decline due to research and development, the learning curve effect. There is also growing external pressure to curtail fossil fuel consumption. Renewable energy, therefore, presents a brighter prospect for developing countries in Africa. It offers these countries the potential to leapfrog the stage of currently conventional energy, directly to renewable energy sources for electricity generation. Transition can therefore occur at a faster pace and to a greater magnitude in Africa's unmet electricity markets.

In addition, new research by the IBRD, Bank and IEA (2015), finds that 7 million premature deaths each year are attributable to outdoor air pollution, and 3.5 million from household indoor pollution alone, due to solid fuels usage (Lim, Vos, Flaxman, Danaei, Shibuya, Adair-Rohani, AlMazroa, Amann, Anderson and Andrews, 2013). This figure is much higher than previous estimates, primarily due to the inclusion of new diseases, such as cardiovascular disease and lung cancer. The need for a transition to cleaner energy is thus apparent.

Conventional electrification systems have lately appeared inefficient, most especially in sub-Saharan Africa. Besides the fact that the grid system is sub-standard, and requires costly refurbishment, there are sparsely populated settlements where grid extension may not be cost-efficient compared to off-grid or distributed renewable energy technology (Szabó et al., 2013). The study offers insights into the system of electrification (grid, off-grid, distributed, and stand-alone) that is suitable for any unmet power market given its specific and unique features.

Ghana's Strategic National Energy Plan, designed by the Energy Commission in 2006, contained a 10% renewable energy target in the total energy mix by 2020. A decade after the policy came into effect, and two years before its deadline, the renewable energy in the total energy mix is still less than 2%. Attaining the policy goal is becoming a mirage with the current slow growth of renewable energy. This trend also hampers the United Nation's Sustainable Energy for All goal of achieving a universal access to modern energy by 2030. The presence of a critical monitoring and evaluation tool, such as a practical model of analysis as developed in this study, is therefore needed to provide deeper insights and understanding of the complexities in the country's electricity system and pre-empt some policy implementation challenges. The outcome of the study benefits different stakeholders at different levels inter alia:

International/Global level: International organisations, such as the United Nations, have undertaken measures for the past decade to avert the repercussions of fossil fuel use such as the amount of CO_2 in the atmosphere. Given that most of global electricity is supplied through fossil fuel, the study's focus on transition to renewable energy for electricity provision is an impetus towards the global efforts to reduce CO_2 emission.

National policy-makers: The challenge of electricity access has been a focus of national policy institutions charged with the responsibility of providing electricity. The findings of this study offer more insights that can enable policy makers at national level to take proactive steps towards addressing the present and pre-empting future, electricity access challenges. The findings also inform stakeholders of the dynamics of the electricity sector, as well as of the alternative solutions to the sector's challenges. It offers insights into the private funding opportunities to accelerate electricity access, which is an implied goal in the United Nations' Sustainable Energy for All.

Managers and Financial stakeholders: The market condition for major fossil fuels, such as oil, has been relatively volatile. Managers and financial stakeholders considering renewable energy as an alternative portfolio to diversify their investment would find the outcome of this study useful. This is because the study explores the avenues and invites the inclusion of private finance as a mechanism for increasing electricity access for a vastly unmet market.

End-users: From end-users' economic and social standpoints, electricity access relates to pertinent issues such as poverty reduction, economic growth, as well as employment and other social services, including healthcare and education, that promote sustainable human development (Kanagawa and Nakata, 2008). Hence, this study on improvement in access would transform societies and improve lives and economic conditions.

1.7 SCOPE AND LIMITATIONS OF THE STUDY

Though the study discusses energy transition frameworks, the focus is on transitions in electricity systems. The findings are therefore limited to generalisation in other energy services, such as transport energy from fossil fuel sources. The adoption and application of energy transition frameworks and references remain relevant, because electricity is generated from an energy source. Transitions in electricity systems therefore require a change in the energy source from which such electricity is generated.

1.8 RESEARCH STRATEGY AND DESIGN

Transition frameworks for electricity systems, in the context of a power deficit market, are largely limited. The strategy for this study therefore started with an introduction, which presented an overview of electricity access globally, with focus on Africa. The study reviewed literature on transition and focused on energy transitions and frameworks found in the context of academic literature, and case studies. Based on the existing frameworks found for energy transition, the objectives of the study were then outlined, which included the development of a conceptual framework for transitions in an unmet electricity market. The study assessed the concept of leapfrogging, and how unmet electricity markets could leapfrog to renewable energy, and examined the electricity access trend in Africa.

The study took a case study approach to investigating the electricity system in Ghana. An overview of Ghana's electricity system was presented, followed by a detailed analysis of the various electricity sources that are presently available. Studies on electricity access in Ghana have so far relied on economic models and econometric analysis in their prognosis. This study uses system dynamics modelling; a simulation based modelling approach that captures the complexities in the underlying system. This approach addresses some limitations often associated with economic models. The models developed in this study were tested and validated to ensure their suitability as decision-making tools in analysing the electricity systems of Africa, specifically Ghana. The research strategy is depicted in Figure 1.1.

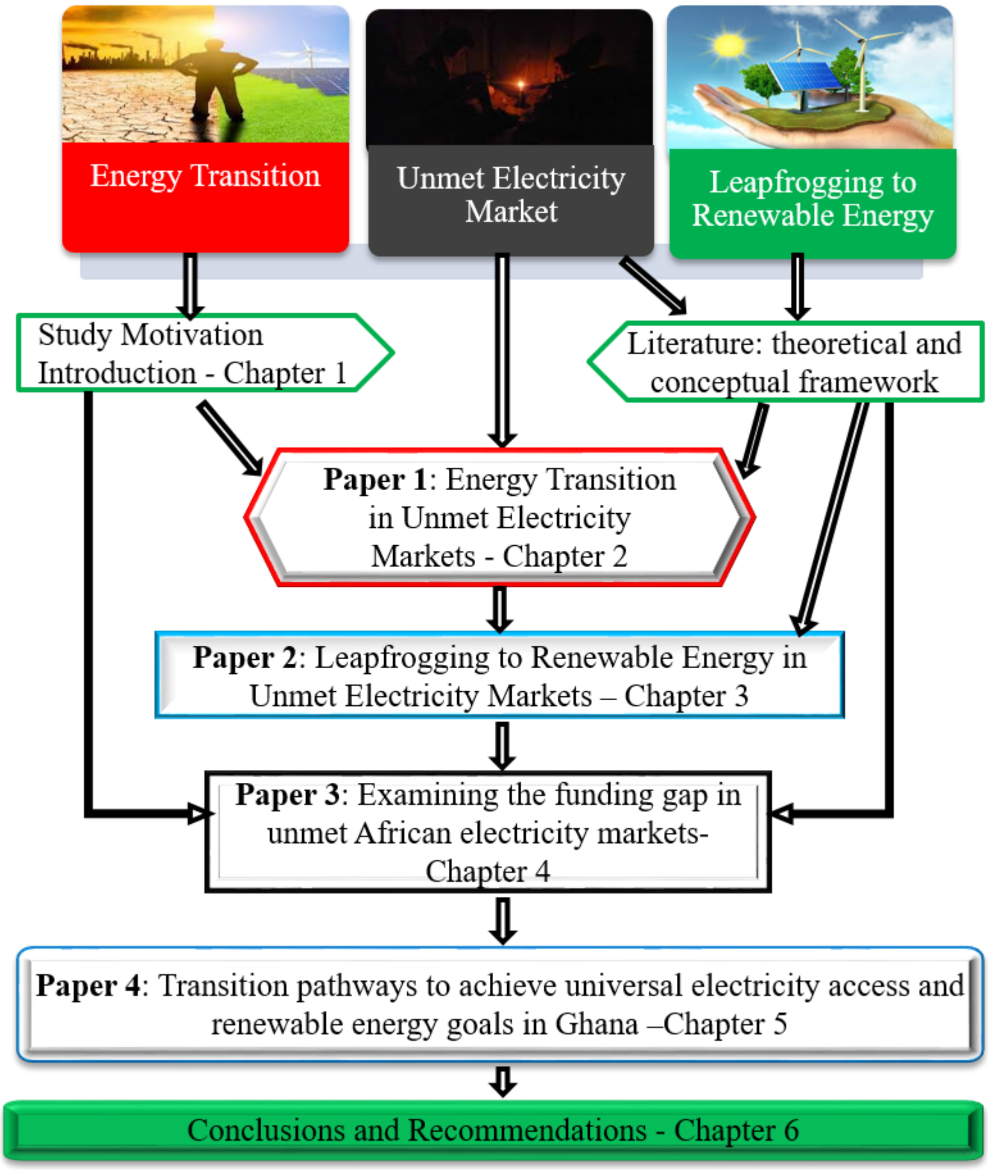


Figure 1.1: Research Strategy

The study adopted a mixed method, which involved the use of qualitative, quantitative, and simulation methods to address the research objective. A mixed research method is defined as a combination of both qualitative and quantitative methods in a single study, with the objective of securing a broader and deeper understanding of an investigated issue (Chen, 1997; Greene, Caracelli and Graham, 1989; Morse, 2003). It is a methodological design that involves the use of both quantitative and qualitative data (Creswell, 2013; Johnson and Onwuegbuzie, 2004; Tashakkori and Teddlie, 1998). In the study, a mixed method is referred to as the combination of qualitative and quantitative research techniques to model and simulate the historical and potential future trends of a phenomenon of a dynamic and complex nature. A mixed research method rejects dogmatism, offering the researcher the opportunity to draw lessons from different methodological approaches in addressing a research problem (Johnson and Onwuegbuzie, 2004). It adopts pragmatic methods to boost the validity and robustness of the study outcome. This study method also hinges on the rationales of a mixed method, such as participant enrichment, treatment integrity, instrument fidelity and enhancement of the significance of study (Collins, Onwuegbuzie and Sutton, 2006).

A mixed method can take the form of convergent, explanatory sequential, or exploratory sequential design, depending on the problem statement (Creswell and Clark, 2007). Convergent design involves addressing a research issue by converging both qualitative and quantitative data and making a comparison. Explanatory sequential design employs qualitative data as a follow-up to explain a quantitative database (O'Cathain, Murphy and Nicholl, 2007). The third mixed method of research design involves quantitative measurement, by first using information obtained through qualitative exploration such as interviews, to design an instrument of analysis (Creswell, 2013).

This research used an exploratory sequential design where qualitative information, through unstructured interviews, informed the structure and design of the quantitative system dynamics modelling to provide insights on the research objective. Although the focus of the study was Africa in general, a case study of Ghana was used to demonstrate the application at a country level. A case study is a type of qualitative research design that encompasses an in-depth analysis of a given process, activity, event, or programme (Yin, 2009). A case changes over time; hence, a case study research format entails an extensive information gathering process involving different data collection tools over a period (Yin, 2009; Yin, 2012).

The appropriateness of this approach extends from the need for system dynamics models representing the existing fundamental electricity system in Africa and Ghana to be informed by both qualitative and quantitative data. An unstructured stakeholder interview enhanced understanding of the electricity system layout and informed both the model structure and the data requirements for the model. Quantitative secondary data was then collected to populate the model. The design of this study is illustrated in Figure 1.2.

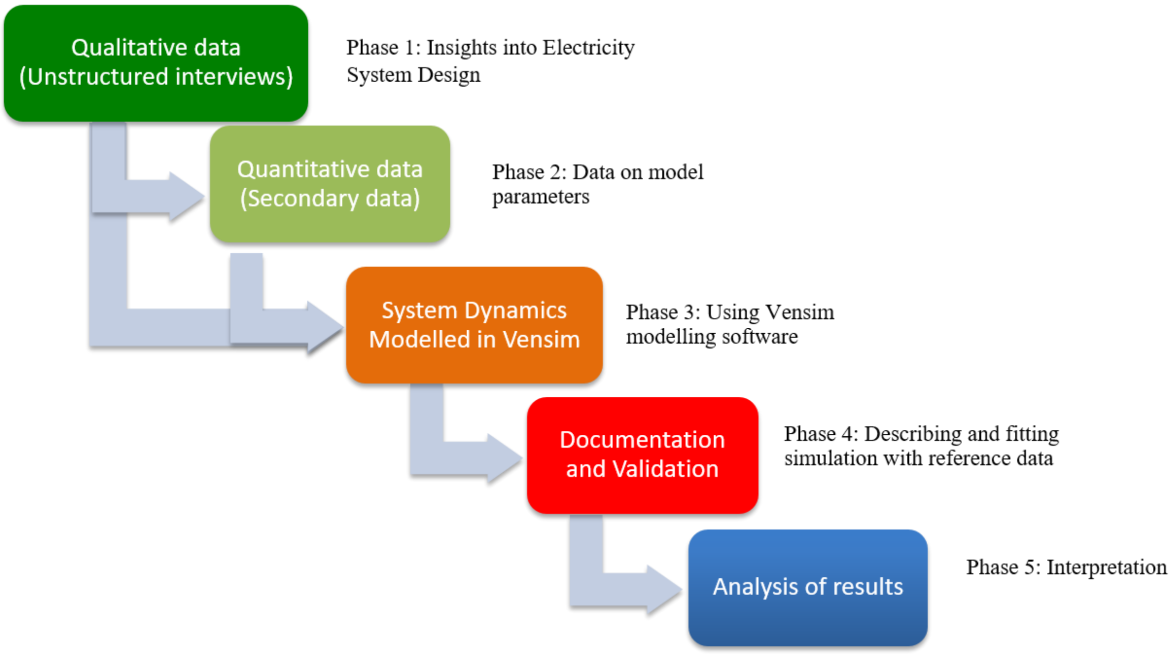


Figure 1.2: Research Design

1.9 DISSERTATION LAYOUT

This dissertation was written in paper format, and four papers were produced based on the research objectives. One paper has been published, and the remaining three are under review. The layout of the dissertation is subsequently described as follows:

Chapter One is an introduction to the research thesis. It gives the background and defines the problem statement, rationale, objectives, and the methodological approach adopted toward attaining the stated objectives.

Chapter Two answers the first research objective. It is also the first paper, titled: *A sustainable energy transition framework for unmet electricity markets*. The process towards achieving this objective included undertaking a systematic literature review pertaining to energy, electricity, sustainability, and unmet electricity markets.

Chapter Three answers the second thesis objective by discussing the concept of leapfrogging and the potential for leapfrogging unmet electricity markets directly to renewable energy as a means to provide universal energy access more quickly and easily. The second paper, titled: *Leapfrogging to renewable energy: the opportunity for unmet electricity markets* which was published in the South African Journal of Industrial Engineering, was based on this chapter,

Chapter Four assesses the African electricity access and investment trend through simulation with a system dynamics model to ascertain the funding gap in relation to the attaining of universal electricity access. It answers the third objective, and the third paper, titled: *Assessing the funding gap of Africa's Unmet Electricity Markets* is a product of this chapter.

Chapter Five is where an overview of Ghana's electricity system is presented and the unmet market is assessed in the context of the country's dual energy goal: universal electricity access and renewable energy in the total electricity sector energy mix by 2020. The achievement of the fourth research objective is described in this chapter and the fourth paper: *Pathways for attaining universal electricity access and renewable energy goals in Ghana* was also written as a result of this chapter.

Chapter Six is the concluding chapter, which provides a summary of the findings and key insights, as well as recommendations for future research. The limitations, as well as the implications for policy-makers, are also highlighted.

CHAPTER ONE REFERENCES

ACKAH, I., ADU, F. & TAKYI, R. O. 2014. On The Demand Dynamics of Electricity in Ghana: Do Exogenous Non-Economic Variables Count? *International Journal of Energy Economics and Policy,* 4**,** 149-153.

ANDREAS, L., ULF, M. & DIRK, T. G. R. 2010. Indicators of energy security in industrialised countries. *Energy Policy,* 38**,** 1665-1671.

APERGIS, N. & PAYNE, J. E. 2011. A dynamic panel study of economic development and the electricity consumption-growth nexus. *Energy Economics,* 33**,** 770-781.

ARAÚJO, K. 2014. The emerging field of energy transitions: Progress, challenges, and opportunities. *Energy Research & Social Science*, 1**,** 112-121.

BERGEK, A., JACOBSSON, S., CARLSSON, B., LINDMARK, S. & RICKNE, A. 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37**,** 407-429.

CASTELLANO, A., KENDALL, A., NIKOMAROV, M. & SWEMMER, T. 2015. Brighter Africa: The growth potential of the sub-Saharan electricity sector. Mckinsey.

CHEN, H. T. 1997. Applying mixed methods under the framework of theory-driven evaluations. *New directions for evaluation*, 1997**,** 61-72.

COLLINS, K. M., ONWUEGBUZIE, A. J. & SUTTON, I. L. 2006. A model incorporating the rationale and purpose for conducting mixed methods research in special education and beyond. *Learning Disabilities: A Contemporary Journal*, 4**,** 67-100.

CRESWELL, J. W. 2013. *Research design: Qualitative, quantitative, and mixed methods approaches*, Sage.

CRESWELL, J. W. & CLARK, V. L. P. 2007. Designing and conducting mixed methods research.

DAVISON, R., VOGEL, D., HARRIS, R. & JONES, N. 2000. Technology leapfrogging in developing countries-an inevitable luxury? *The Electronic Journal of Information Systems in Developing Countries*, 1**,** 1-10.

DIJKEMA, G. P. J. & BASSON, L. 2009. Complexity and Industrial Ecology. *Journal of Industrial Ecology*, 13**,** 157-164.

EC, SE4ALL & UN. 2012. Sustainable Energy For All Action Plan.

EDQUIST, C. 2011. Systems of innovation: perspectives and challenges. *African Journal of Science, Technology, Innovation and Development (AJSTID)*, 2**,** 14-43.

ELZEN, B., GEELS, F. W. & GREEN, K. 2004. *System innovation and the transition to sustainability: theory, evidence and policy,* Edward Elgar Publishing.

FERGUSON, R., WILKINSON, W. & HILL, R. 2000. Electricity use and economic development. *Energy policy,* 28**,** 923-934.

FOUQUET, R. 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy,* 38**,** 6586-6596.

FOUQUET, R. & PEARSON, P. J. 2012. Past and prospective energy transitions: insights from history. *Energy Policy,* 50**,** 1-7.

GALLAGHER, K. S. 2006. Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry. *Energy Policy,* 34**,** 383-394.

GARCÍA-GUSANO, D., IRIBARREN, D., MARTÍN-GAMBOA, M., DUFOUR, J., ESPEGREN, K. & LIND, A. 2016. Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. *Journal of Cleaner Production,* 112**,** 2693-2696.

GEELS, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy,* 31**,** 1257-1274.

GEELS, F. W. 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research policy,* 33**,** 897-920.

GEELS, F. W. 2005. *Technological transitions and system innovations: a co-evolutionary and socio-technical analysis,* Edward Elgar.

GIDDENS, A. 2009. *The politics of climate change,* Cambridge, Polity.

GOLDEMBERG, J. 1998. Leapfrog energy technologies. *Energy Policy,* 26**,** 729-741.

GREENE, J. C., CARACELLI, V. J. & GRAHAM, W. F. 1989. Toward a conceptual framework for mixed-method evaluation designs. *Educational evaluation and policy analysis,* 11**,** 255-274.

GRUBB, M., HOURCADE, J.-C. & NEUHOFF, K. 2015. The Three Domains structure of energy-climate transitions. *Technological Forecasting and Social Change,* 98**,** 290-302.

GRUBLER, A. 2012. Energy transitions research: Insights and cautionary tales. *Energy Policy,* 50**,** 8-16.

HEKKERT, M. P., SUURS, R. A. A., NEGRO, S. O., KUHLMANN, S. & SMITS, R. E. H. M. 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change,* 74**,** 413-432.

IBRD, BANK, W. & IEA 2015. Progress Towards Sustainable Energy 2015 - Global Tracking Framework Report.

ICSU & ISSC 2015. Review of Targets for The Sustainable Development Goals: The Science Perspective. Paris: International Council for Science (ICSU).

IEA 2009. Cities, towns & Renewable Energy: Yes In My Front Yard. *International Energy Agency*. Paris: OECD/IEA.

IEA 2011. World Energy Outlook 2011. Paris: OECD/IEA.

IEA 2014a. The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems. Paris: OECD/IEA.

IEA 2015. World Energy Outlook 2015 Paris: OECD/IEA.

IEA, UNDP & UNIDO 2010. Energy Poverty: How to Make Modern Energy Access Universal. Paris: OECD/IEA.

IEA, A. E. O. 2014b. A focus on the energy prospects in sub-Saharan Africa, World Energy Outlook Special Report. *International Energy Agency Publication.* Paris: OECD/IEA.

IPCC 2014. Climate Change 2014 Synthesis Report.

JOHNSON, R. B. & ONWUEGBUZIE, A. J. 2004. Mixed methods research: A research paradigm whose time has come. *Educational researcher,* 33**,** 14-26.

KANAGAWA, M. & NAKATA, T. 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. *Energy Policy,* 36**,** 2016-2029.

KEMP, R., ARIE, R. & JOHAN, S. 2001. Constructing transition paths through the management of niches. *In Path dependence and creation.* . Lawrence Erlbaum.

KEMP, R. & RIP, A. 1998. *Technological change. IN RAYNOR, S. & MALONE, EL (Eds.) Human choice and climate change.* , Columbus, Battelle Press.

KEMP, R., ROTMANS, J. & LOORBACH, D. 2007. Assessing the Dutch Energy Transition Policy: How Does it Deal with Dilemmas of Managing Transitions? *Journal of Environmental Policy & Planning,* 9**,** 315-331.

LEE, K. & LIM, C. 2001. Technological regimes, catching-up and leapfrogging: findings from the Korean industries. *Research policy,* 30**,** 459-483.

LIM, S. S., VOS, T., FLAXMAN, A. D., DANAEI, G., SHIBUYA, K., ADAIR-ROHANI, H., ALMAZROA, M. A., AMANN, M., ANDERSON, H. R. & ANDREWS, K. G. 2013. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The lancet,* 380**,** 2224-2260.

LOORBACH, D. 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance,* 23**,** 161-183.

MARTCHAMADOL, J. & KUMAR, S. 2012. Thailand's energy security indicators. *Renewable and Sustainable Energy Reviews,* 16**,** 6103-6122.

MILLER, C. A., RICHTER, J. & O'LEARY, J. 2015. Socio-energy systems design: A policy framework for energy transitions. *Energy Research & Social Science,* 6**,** 29-40.

MORRIS, C. & PEHNT, M. 2012. Energy Transition: The German Energiewende. *Heinrich Böll Stiftung*. Berlin.

MORSE, J. M. 2003. *Principles of mixed methods and multimethod research design,* housand Oaks, Sage Publication.

MURPHY, J. T. 2001. Making the energy transition in rural East Africa: Is leapfrogging an alternative? *Technological Forecasting and Social Change, ,* 68**,** 173-193.

NIELSEN, J. R., HOVMØLLER, H., BLYTH, P.-L. & SOVACOOL, B. K. 2015. Of "white crows" and "cash savers:" A qualitative study of travel behavior and perceptions of ridesharing in Denmark. *Transportation Research Part A: Policy and Practice,* 78**,** 113-123.

O'CATHAIN, A., MURPHY, E. & NICHOLL, J. 2007. Why, and how, mixed methods research is undertaken in health services research in England: a mixed methods study. *BMC health services research,* 7**,** 1.

PACHAURI, S., RAO, N., NAGAI, Y. & RIAHI, K. 2012. Access to modern energy: Assessment and outlook for developing and emerging regions. *Laxenburg: IIASA*.

PAINULY, J. P. 2001. Barriers to renewable energy penetration; a framework for analysis. *Renewable energy,* 24**,** 73-89.

PERKINS, R. 2003. Environmental leapfrogging in developing countries: A critical assessment and reconstruction. *Natural Resource Forum,* 27**,** 177-188.

RAVEN, R. & GEELS, F. 2010. Socio-cognitive evolution in niche development: comparative analysis of biogas development in Denmark and the Netherlands (1973–2004). *Technovation,* 30**,** 87-99.

REN21 2014. Renewables 2014 Global Status Report. *Tech. Rep.* Paris: REN21.

REN21 2018. Renewables 2018 Global Status Report. Paris: REN21 Secretariat.

ROTMANS, J., KEMP, R. & VAN ASSELT, M. 2001. More evolution than revolution: transition management in public policy. *Foresight*, 3**,** 15-31.

SCOTT, A. 2015. Building Electricity Supplies in Africa for Growth and Universal Access. *Working Paper, The New Climate Economy*.

SGOURIDIS, S. & CSALA, D. 2014. A Framework for Defining Sustainable Energy Transitions: Principles, Dynamics, and Implications. *Sustainability,* 6**,** 2601-2622.

SMIL, V. 2010. *Energy transitions: history, requirements, prospects,* Santa Barbara, ABC-CLIO.

SMITH, A. 2007. Translating sustainabilities between green niches and socio-technical regimes. *Technology Analysis & Strategic Management,* 19**,** 427-450.

SOVACOOL, B. K. 2009. Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. *Energy Policy,* 37**,** 4500-4513.

SOVACOOL, B. K. 2016. How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science,* 13**,** 202-215.

SOVACOOL, B. K. & HIRSH, R. F. 2009. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy,* 37**,** 1095-1103.

SOVACOOL, B. K. & MARILYN, A. B. 2009. Competing Dimensions of Energy Security: An International Perspective. *Annual Review of Environment and Resources,* 35**,** 77-108.

SOVACOOL, B. K. & MUKHERJEE, I. 2011. Conceptualizing and measuring energy security: A synthesized approach. *Energy,* 36**,** 5343-5355.

SOVACOOL, B. K., MUKHERJEE, I., DRUPADY, I. M. & D'AGOSTINO, A. L. 2011. Evaluating energy security performance from 1990 to 2010 for eighteen countries. *Energy,* 36**,** 5846-5853.

SZABÓ, S., BÓDIS, K., HULD, T. & MONER-GIRONA, M. 2013. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. *Renewable and Sustainable Energy Reviews,* 28**,** 500-509.

TASHAKKORI, A. & TEDDLIE, C. 1998. *Mixed methodology: Combining qualitative and quantitative approaches,* Sage.

TUKKER, A. 2005. Leapfrogging into the future: developing for sustainability. *International Journal of Innovation and Sustainable Development,* 1**,** 65-84.

UN 2012. Sustainable Energy for All. *In:* ALL, T. S.-G. S. H.-L. G. O. S. E. F. (ed.) *A Framework for Action.*

UNDP 2015. Sustainable Development Goals.

UNFCCC, C. 1992. United Nations Framework Convention On Climate Change. *Kyoto Protocol.* Kyoto: UN.

UN. 2015. Conference of the Parties. Framework Convention on Climate Change, 2015 Paris. UN.

WINKLER, H., SIMÕES, A. F., LA ROVERE, E. L., ALAM, M., RAHMAN, A. & MWAKASONDA, S. 2011. Access and affordability of electricity in developing countries. *World Development,* 39**,** 1037-1050.

YIN, R. K. 2009. Case study research: Design and methods, 4th. Sage.

YIN, R. K. 2012. *Applications of case study research,* Thousand Oaks, Sage.

2 CHAPTER TWO: SUSTAINABLE ENERGY TRANSITION FRAMEWORK FOR UNMET ELECTRICITY MARKETS[1]

2.1 CHAPTER OVERVIEW

This chapter assesses various transition frameworks suggested in the literature and focused on those pertaining to energy, infrastructure, and other socio-technical transitions. The chapter addresses the research objective: to develop a framework for energy transitions in unmet electricity markets. This entailed a systematic literature review that resulted in the development of a unique transition framework for unmet electricity market. A paper titled: *Sustainable Energy Transition Framework for Unmet Electricity Markets*, submitted to the Energy Policy Journal and currently in review, was based on this chapter.

Abstract

In today's global economy, an efficient supply of energy ensures access to a wide range of services and benefits yet, in developing countries, an inadequate energy supply means that these benefits are not realised. There are over a billion people globally still living without any electricity, mainly in Africa and Asia. This phenomenon has prompted research on energy transition, specifically a transition to renewable and sustainable energy, as a way of ensuring the rapid diffusion of access to energy in these regions. Existing energy transition frameworks, however, are predominantly contextualised in and for developed economies, and a paucity of studies exists on their applicability in the context of developing countries. This chapter, therefore, reports on the development of a contextual energy transition framework for unmet electricity markets, which characterises developing countries. This was achieved through a systematic review of the literature on transition framework, with an emphasis on transitions in the energy sector, and specifically relating to sustainable transitions of electricity systems. Contextual limitations were observed in the energy transition literature pertaining to: market demand, scale of energy infrastructure, type of energy resource, time-span, and novelty of opportunities and level of external influence. Based on these limitations, an energy transition

[1] BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Sustainable Energy Transition Framework for Unmet Electricity Markets. *Energy Policy*

framework for unmet electricity markets was conceptualised. The key characteristics of this modified transition framework are: (i) traditional technology; (ii) defunct deceleration; (iii) a niche technology curve; (iv) landscape support for niches; and (v) new regime condensation (emergence). The author contends that contextual awareness in designing policy frameworks for energy transition is essential to achieve sustainable energy for all, particularly in unmet electricity markets.

Keywords: E*nergy transition*; *Electricity transition*; *Renewable energy*; S*ustainability transition; Unmet electricity market.*

2.2 INTRODUCTION

The developing world, especially Africa and Asia, remains the most energy-deficient region in many and diverse ways (IEA, 2011). This ranges from the lack of access to electricity, which undermines the quality of health and education services (Kanagawa and Nakata, 2008), as well as failing to meet essential services such as electronic communication, lighting, heating, and transport (IEA, 2011). Transition in energy supply is increasingly becoming a prerequisite for addressing the growing diversity in end-use energy needs, not just in the developing world, but also in industrialised countries. Grubler (2012) emphasises this need by questioning the sustainability of current energy systems. He points out that these systems are simply unsustainable and calls for the 'next' energy transition. Miller, Richter and O'Leary (2015) reiterate that future energy systems require major policy changes, especially in industrial economies. Further elaborating on the urgent need for transition in energy, Giddens (2009) posits that humanity is approaching the carbon emission threshold, where the global economy would exceed the point of no return if no action were taken. He based this postulation, which he termed as the climate paradox, on the maximum emission target stipulated by the UNFCCC (1992). The need for the inclusion of alternative energy sources to supplement current infrastructure to meet future energy needs is thus inevitable.

Transition has broad connotations across disciplines, and literature on transition spans different domains including: demographic studies (Caldwell, 1976; Chesnais, 1992; Kirk, 1996; Meir, 1986), health (Frenk, Bobadilla, Stern, Frejka and Lozano, 1991; Mackenbach, 1994; Omran, 1971), politics, power and democracy (Adler and Webster, 1995; De Soysa, Oneal and Park, 1997; Lemke and Reed, 1996; Linz and Stepan, 1996; Offe and Adler, 1991), economic and market forces (Nee, 1989; Roland, 2002; Weitzman, 1993), environment (van den Bergh, 2007), and energy (Kern and Smith, 2008; Meadowcroft, 2009; Meadows, Meadows, Randers and Behrens, 1972). This chapter examines transitions in the energy sector, with specific focus on electricity generation. Transitions, particularly in infrastructural systems, do not occur easily (Verbong and Geels, 2010). Transition in fundamental systems is often met with inertia, and seldom come about in as timely and orderly fashion as intended. According to Davison, Vogel, Harris and Jones, (2000), large-scale transitions, such as energy systems infrastructure, are often beyond the control of a single sector or entity, whether private markets or public agencies. The condition for significant transition is not just a change in technology, but also includes changes in political regulations, pricing schemes, and end-user behaviour (Sovacool, 2016). This was found to be the case in large transitions such as a move to renewable electricity (Painuly, 2001; Sovacool, 2009) and the introduction of electric vehicles (Nielsen, Hovmøller, Blyth and Sovacool, 2015; Sovacool and Hirsh, 2009). In the wake of this growing need for transition, a number of transition scholars have attempted to prescribe an appropriate transition framework for the energy sector. The frameworks also extend to transition paradigms that focus on the sustainability of resources.

One of the present transition frameworks pertaining to energy is the multi-level perspective. It is, however, predominantly contextualised in developed economies where energy, in the form of electric power for electricity services, has reached the entire population (Fouquet, 2010; Geels, 2002; Geels, 2005a; Kemp, Rotmans and Loorbach, 2007b; Sarrica, Brondi, Cottone and Mazzara, 2016; Shackley and Green, 2007). The implication is that this framework might not be suitably applicable to unmet electricity markets, such as in Africa. This is because of the vast differences between developed and developing countries in areas such as economic, social, technical, and geographical status, among other factors. Infrastructural development in developing countries is at an infantile stage (Tukker, 2005). As a result, infrastructural lock-in and path dependence that favours particular socio-technical alignments are either weak or non-existent. It must be mentioned, however, that political, socio-cultural, and financial factors might inhibit transition and account for a lock-in or path dependence. Some transition literature also defines transitions as including the overhaul of large physical infrastructure, such as power plants (Dijkema and Basson, 2009), in an attempt to migrate to novel technologies such as photovoltaic solar power. This definition does not take into consideration the fact that Africa is not characterised by such large-scale infrastructure and the merits of the previous energy transitions that improved lives and businesses elsewhere, have yet to reach over one billion people on the planet (IEA, 2011). Because of the largely unmet electricity demand in Africa, adoption of renewable energy as a means of providing electricity, may become obligatory, rather than a choice. In addition, transitioning to renewable energy technologies may not necessarily require centralised large physical infrastructure, especially in the context of achieving sustainable energy for all, but could involve a more decentralised system.

The purpose of this study, unlike others that advocate a transition to renewable energy, is neither to provide reactionary commentary to the 'peak oil' hypothesis as discussed by scholars (Hallock, Tharakan, Hall, Jefferson and Wu, 2004; Jefferson, 2014; Meadows et al., 1972), nor to highlight the economic consequences (such as recession) that oil-importing industrialising nations have suffered over the past four decades, following periods of sudden oil price hikes (Hamilton, 2008). The study is based on the notion of a transition to sustainable energy resources to ensure: (i) universal access to electricity amid concerns regarding the scarcity of energy resources; and (ii) to protect the environment in the face of growing energy need and demand. This study therefore, based on significant contextual differences between industrialised countries and those of Africa, questions the applicability of industrialised nations' energy transition frameworks in the African context. It addresses this theoretical and empirical gap by investigating and developing a contextual energy transition framework for unmet electricity markets.

2.3 METHOD

The objective of the study was achieved by conducting a systematic review of literature from peer reviewed journal articles and grey research, including material outside traditional peer reviewed academic literature. The choice of this method was to ensure that all significant key energy and transition literature was considered. This method was useful for revealing similar studies because of its ability to uncover publications that shared key search queries. The grey literature in this chapter includes policy statements, dissertations, conference proceedings, government reports, and organisational research publications related to transitioning, with an emphasis on transitions in the energy sector, specifically those relating to sustainable transitions in electricity systems. The literature reviewed to identify the gaps and subsequent conceptualisation of a framework, spanned the period from 1970 to 2016. The choice of timespan was to enable as exhaustive a study of the literature on energy and electricity sector transitions as possible, as most of the research on this topic has occurred over the past forty years. Prior to the 1980s, energy transition, especially to renewable energy, was not a prominent topic of academic discourse, hence the limited available literature (Araújo, 2014). Very few scholars, most notably Meadows et al. (1972) demonstrated concern for the subject. Climate change was thus not considered a collective global responsibility until the 1990s, when the first climate treaty – the United Nations Framework Convention on Climate Change (UNFCCC) – acknowledged the existence of global warming and surmised its link to greenhouse gas emissions (UNFCCC, 1992). Similarly, alternative renewable technologies such as solar photovoltaic (PV) received little attention, as fossil fuel production boomed.

A qualitative approach to gathering data was adopted, and the search focused on text documents. Information was gleaned from published books, grey literature, and peer reviewed articles from the following internet databases: Google Scholar, SCOPUS, Science Direct, and direct Google searches. Specific key phrases namely: e*nergy transition*, *electricity transition*, *renewable energy*, *sustainability transition*, and *unmet electricity market* were used, not as one query but as separate and combination queries. The use of these individual phrases, or in combinations of two or more in the searches, ensured sufficient content analysis of past studies on the subject matter, and thus offered insights on theoretical and contextual uniqueness to inform the framework design. The search was conducted in April 2016, without any geographic demarcation. A total of 141 articles was found and classified according to the year of publication. These articles can be found in the internet databases mentioned. After examining these articles, four transition frameworks namely: *transition management*, *socio-technical transition*, *innovation systems* and *strategic niche management* were found and discussed. Two transition theories: *complex systems* and *evolutionary systems* were also identified in the literature. Analysis of the textual data was carried out by way of critical examination of the literature. The frameworks were then juxtaposed in the context of an unmet energy market, to assess their empirical suitability. A robust energy transition framework for unmet electricity markets was developed with considerations of the unique features of unmet energy markets as identified in Africa. A key challenge in this process was how to filter the extensive literature to focus on those publications that addressed transition approaches and framework issues. Figure 2.1 represents the year and number of articles used in this study after scaling and refining the literature according to the criteria described.

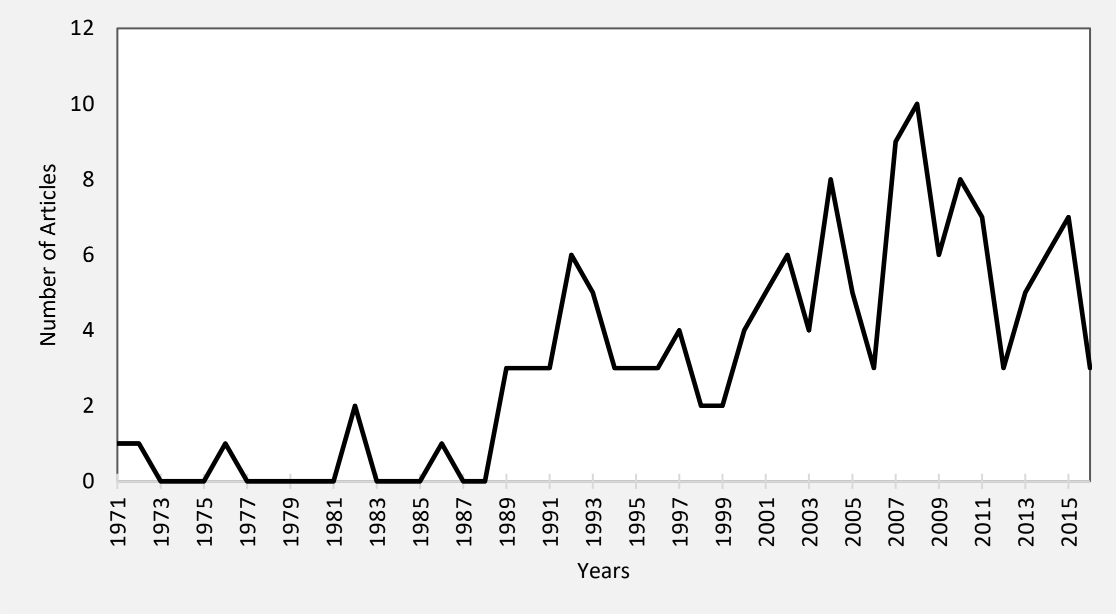


Figure 2.1: Number of citations per year shortlisted in the systematic review

Source: Author

The results from the systematic review were discussed within four broad themes: (i) energy transition frameworks; (ii) observations from historical energy transitions literature; (iii) limitations of present transition frameworks in the context of Africa; and (iv) a modified transition framework for unmet electricity markets.

2.4 ENERGY TRANSITION FRAMEWORKS

Like other disciplines, the energy sector has attracted varied academic discourse over the past few decades. This led to the formulation of hypotheses and the eventual development of frameworks and approaches to assessing energy system transitions. The energy transition frameworks and approaches that emerged through empirical and theoretical studies include: transition management (Kemp and Rip, 1998; Loorbach and Rotmans, 2010; Rotmans, Kemp and van Asselt, 2001), the multi-level perspective (Geels, 2002; Geels, 2011; Kemp, Arie and Johan, 2001), innovation systems (Bergek, Jacobsson, Carlsson, Lindmark and Rickne, 2008; Carlsson, Jacobsson, Holmén and Rickne, 2002; Edquist, 2011; Hekkert, Suurs, Negro, Kuhlmann and Smits, 2007; Jacobsson and Bergek, 2011), and strategic niche management (Kemp, Schot and Hoogma, 1998; Raven and Geels, 2010; Smith, 2007). The frameworks, though diverse in focus and emphasis, recognise the energy sector as a dynamic field of multiple stakeholders that can be categorised into upstream suppliers, downstream consumers, and independent stakeholders influencing both supply and demand dynamics. This study is focused on an energy transition framework for the empirical context of unmet electricity markets in Africa.

2.4.1 Transition management

A fundamental goal in managing a transition is ensuring that changes in systems are sustainable, future-oriented, and adaptive. This ensures that the relationship or linkage between technical services and social functions is not destroyed (Kemp, 2010). In most transitions, challenges are bound to arise, and sometimes things get worse before eventually getting better. This is the critical stage where knowledge of transition management is of enormous significance. The concept of transition management is traced back to Ackerman (1982) who defined it as a '*systematic study and design of an organisation's strategy and supporting structures, followed by the formal planning, implementation and monitoring of the changes required*'. This emphasises that changes in socio-technical systems are not a result of a natural evolutionary process but, instead, engineered by human activity (Kemp et al., 2001). Transition in technical systems emanates from management decisions pioneered by improved end-use service needs. The goal of transition management, therefore, is to institute optimal policies that systematically result in change in the socio-technical system (Kern and Smith, 2008).

Management is a crucial aspect of organisations, especially within large-scale socio-technical systems in transition. Management within complex socio-technical systems, such as energy systems, is different and more compelling compared to, for example, the management of human resources in an organisation. Nonetheless, application of the basic management principles namely planning, organising, staffing, motivating, and monitoring, remain essential. Expertise in these managerial principles, as well as fundamental knowledge of the socio-technical structure and its accompanying complexities, are prerequisites in order for transition managers to oversee socio-technical systems during a transition (Chappin and Dijkema, 2010). Research on transition management is based on case studies (Geels, 2002; Geels, 2005a), and management processes (Rotmans and Loorbach, 2009; Rotmans et al., 2001).

Transition management offers a remedy to recurring problems that are not easily solved by conventional means, in areas such as energy, agriculture, construction, and transport

(Loorbach, 2010). Transition management is most required in the transition from one energy source such as fossil fuel, to another, such as renewable energy sources. The interaction between society (energy end-users) and technology (provision of energy services e.g. lighting, heating, cooking, cooling), requires transition management to maintain a balance and ensure proper adjustment and adaptation.

2.4.2 Socio-technical transition and the multi-level perspective

Transitions occur within both small and large scale infrastrucutre. Mitchell (2008) contends that transition involving large-scale infrastructure, such as energy, often requires a change in ideological stance, as well as the political environment. The responsibility falls to policy-makers to access and manage the changes anticipated from potential transitions (van den Bergh, 2007). The interaction between society and technology varies, depending on a range of factors, including the stage of development, and the unique benefits the technology offers society. Kemp and Rip (1998) proposed the concept of socio-technical transition based on the co-evolutionary nature of technology, and its interaction with society in different spheres. Socio-technical change involves a reconfiguration and rearrangement of core elements to establish new links of interconnectedness within a system (Geels, 2002). This study expanded the interplay between society's electricity needs e.g. lighting, cooking, heating, and cooling, and the technical means e.g. oil, gas, coal, nuclear, hydroelectricity, wind, and solar, through which electricity services are provided, given that downstream end-use largely drives the transition in energy systems (Grubler, 2012).

Research on transition in the energy sector, unlike other disciplines, is concentrated in specific geographic locations. Over half of the energy transition literature is traceable to three countries: The Netherlands, the United Kingdom, and the United States of America. The present literature addressing large-scale social and technical infrastructural change or transition, such as energy or electricity (Elzen, Geels and Green, 2004; Geels, 2002; Geels, 2004a; Geels, 2005b; Geels and Schot, 2007) fully or partially adopts the socio-technical multi-level perspective framework developed by Geels (2002).

The multi-level perspective remains the most common socio-technical transition framework used in sustainable transition research literature (Geels, 2002; Geels, 2004a; Kemp et al., 2007b). It highlights the different levels of society's interaction with technology. The connection between technology and society is acknowledged and substantiated in fields such as actor-network theory (Callon, 1999; Law, 1992). From an evolutionary standpoint, van den Bergh (2007) demonstrates the linkage between innovation and behavioural routines, as well as organisational structures. The multi-level perspective Geels (2002) proposed, (see: Figure 2.2) depicts the relationship of the three different levels of system innovation and the potential outcome of their interaction.

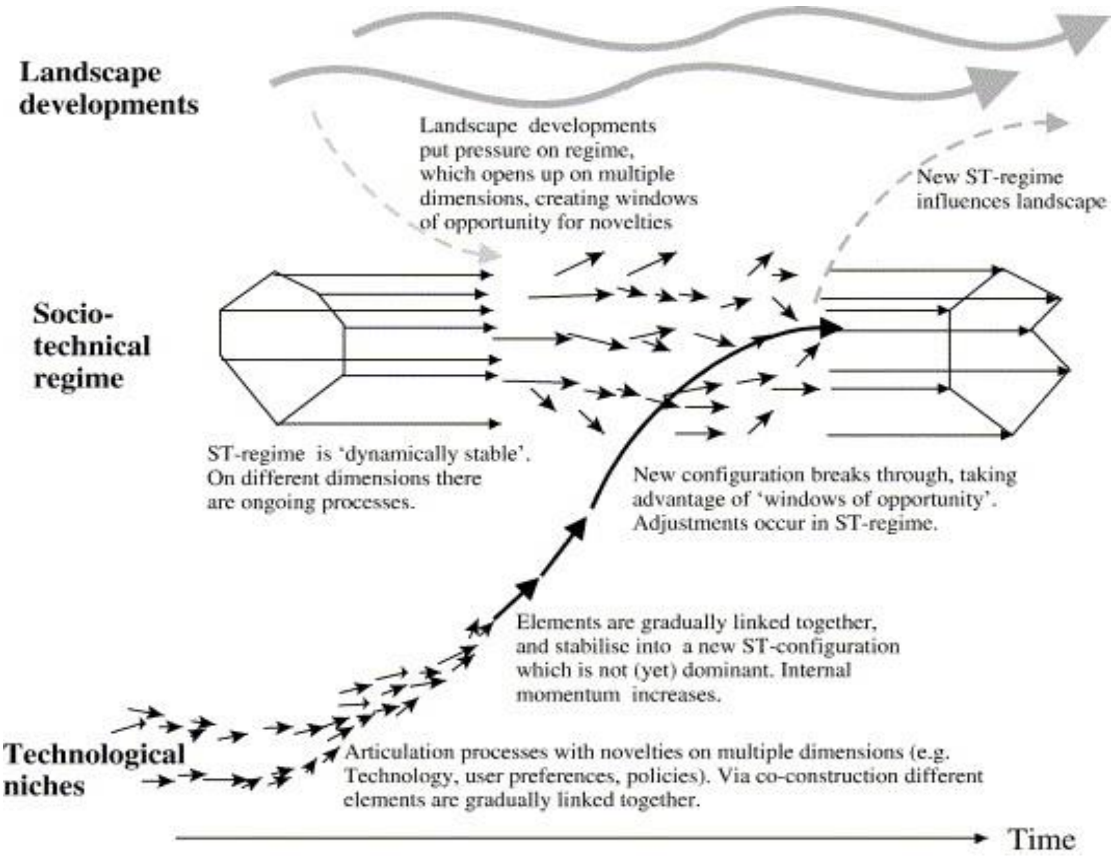


Figure 2.2: A dynamic Multi-Level Perspective of System Innovations

Source: Geels (2005a)

The multi-level perspective of innovation systems suggests that niche technologies encounter extensive competition from regime technologies that already possess a greater market share and benefit from scale of production. Niche technologies that survive the stiff competition of the regime create instability in the market, facilitated by pressure from landscape development on regime technologies (Geels, 2005a). A new technological regime consequently emerges from the interaction between the landscape, regimes and niches in the technology diffusion path.

2.4.2.1 Landscape

Concerns over the exploitation and depletion of fossil energy resources emerged in the latter half of the twentieth century. Early scholarly works relating to energy resources include the limits to growth (Meadows et al., 1972) and advocacy for a green economy transition (Pearce, Markandya and Barbier, 1989). It would take decades before the global community initiated efforts to collaborate on the potential problems of continued fossil dependency. The energy landscape, the dynamic space where the discourse of influencing regime and niche development trajectories takes place, was thus established. Geels (2004b) considers this landscape as a collection of cultural values, political coalitions, environmental programmes, growth, and economic developments that do not easily change. Landscape refers to an independent exogenous space that is not affected by the activities of the regime or niche.

The socio-technical landscape plays a crucial role in the length of a regime's reign and the speed at which a niche technology advances to overthrow a regime. The International Framework Convention on Climate Change and the most recent Conference of Parties (COP21, 2015) by the UN (2015) for example, tasks member countries to cut emissions by reducing their fossil fuel consumption and promoting the use of sustainable fuel from renewable sources. The effect of a global landscape policy stance such as COP21, trickles down to influence society's energy consumption behaviours and indirectly shapes opinions on fossil fuels and receptivity to renewable energy.

An understanding of the socio-technical landscape is relevant, particularly in examining how external pressures or support of an emerging technology, influences society's perception and adoption of such technology. As an illustration, the COP21's position on reduction of emissions could lead to an adjustment of society's energy consumption, or diversification of the sources through which society meets its electricity needs. A price increase resulting from energy scarcity or carbon regulations could also lead to a diversification of investment from fossil fuel to renewable energy.

2.4.2.2 Regimes

A regime refers to the infrastructure prevailing at a given time (Geels, 2002). The regime frontier, or the meso-level, is between the socio-technical landscape and the socio-technical niche as depicted in Figure 2.2. The dominant energy infrastructure, through which energy services are met, forms the regime. Socio-technical regimes often consist of large-scale infrastructure and exhibit lock-in, and path dependence (Geels, 2005a). Transitioning from a regime often poses a great challenge, given the large investment in the form of power cables, transformers, and especially power plants, in the case of energy or electricity infrastructure (Verbong and Geels, 2010).

The challenge of changing socio-technical systems is embedded in their very characteristics, in that they are an embodiment of strong and stable infrastructures and institutions with immense momentum (Lovell, 2007). The size of socio-technical infrastructures, determines the extent of inertia they exert. Researchers describe this inertia as technological lock-in (Schot, Hoogma and Elzen, 1994; Unruh, 2002), entrapment (Walker, 2000), path-dependency (Phillimore, 2001), drop in (Kemp, 1994), and continuity (Dosi, 1982).

Regimes can encounter hurdles depending on the relationship that exists between them and the landscape factors. The reason behind the global campaign to consider alternative or renewable energy for unmet power markets is not solely that fossil fuel resources are finite. An excessive expansion in power capacity through fossil fuels, to promote access and end energy poverty, poses negative consequence on climate change efforts (Bazilian and Pielke Jr, 2013). Such adverse repercussions tend to stifle the expansion of regime technology, and in the case of energy, result in current and future energy projects focusing more on renewable energy rather than intensive carbon energy. A decline in lock-in or path dependence of regimes technologies signals a broader adoption of renewable energy technologies. This chapter evaluates the nature and capacity of regime technology and infrastructure within an unmet electricity market to design an appropriate framework for transition.

2.4.2.3 Niches

Niche technologies can be defined as emerging innovations or technologies that develop to compete and potentially, or eventually, destabilize the regime configuration (Smith, Voß and

Grin, 2010). Socio-technical niches develop in protective spaces from the excessive power of the socio-technical regimes (Hoogma, Kemp, Schot and Truffer, 2004). Niches face regime obstacles that are sometimes insurmountable resulting in a consequent fizzle-out before maturity. The high cost associated with niche technologies is often stated as a major obstacle in demand for such technologies (Geels, 2004a; Hoogma et al., 2004). When it comes to energy, however, the extensive institutional investment in research and development, the learning effect, and the gradual increase in renewable energy scale have contributed to a significant reduction in the unit cost of renewables (Kobos, Erickson and Drennen, 2006; McDonald and Schrattenholzer, 2001). The Global Fund is one such institution, which offers grants to nations advancing the use of renewable instead of fossil fuels, so that they can reduce the unit cost of renewables, making it more competitive (Martinot, 2000).

It is important to examine, critically, the three levels of the multi-level perspective, namely landscape, regime and niches, and their role in a potential transition pathway in unmet electricity markets. The development of niches and the growing landscape pressure in the energy sector, for instance, can be perceived as priming for the emergence and subsequent dominance of a potentially new socio-technical regime that would usher out the present regime.

2.4.3 Innovation system

The energy sector represents a collection of technical and social infrastructure that constitutes a system. The word ‘system’ is widely referenced in this chapter and is usually connected with innovation, technology, energy, electricity, or other terms depicting the constitution of various components. A system is a collection of components, relationships, and attributes (Bo Carlsson, 2002), the sum of which is less than the system as a whole, due to the interdependence of these components (Blanchard, Fabrycky and Fabrycky, 1990). Meadows (2008) defines a system as a set of elements interconnected in a manner that results in a given behaviour or pattern of outcome over time. A system might be described as a collection of individual components operating in synchrony towards an ultimate outcome (Bergek et al., 2008). The components in a system include institutions, objects, actors, devices, and networks of individuals (Carlsson and Stankiewicz, 1991) working together to develop, diffuse, and use new products (Bergek et al., 2008). There are often multiple feedbacks or interrelated units functioning collectively to create dynamism within a system (Geels, 2004a). The degree of dynamics in a system depends on the number of interactions occurring within it.

Innovation systems augment the efficiency or performance of electricity systems through an innovation diffusion process, knowledge transfer, and learning. An innovation system refers to '*a network of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion, and utilisation of variants of a new technology and/or new product'* (Markard and Truffer, 2008). It is considered that the collaboration or synergy of efforts or activities of individual entities in an industry or sector to develop and decentralise a technology (renewable energy technologies). An innovation system occurs under different settings or in different tiers, namely technological innovation (Carlsson, 2003; Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008), national innovation (Freeman, 1995; Lundvall, 1992; Nelson, 1993), sectoral innovation (Breschi and Malerba, 1997; Geels, 2004a; Malerba, 2002), and regional innovation (Asheim and Coenen, 2005; Cooke, Mikel and Goio, 1997; Kubeczko, Rametsteiner and Weiss, 2006). Electricity provision is considered a complex system comprising multiple units working towards a common goal of generating and supplying electric power. The interconnectedness or interdependence of the sub-units upon each other is significant and inseparable, and the output of their interdependence is greater than the sum of the units (Blanchard et al., 1990). Transformation in an electricity system involves one or a combination of tiers of innovation systems.

The ability to transition depends largely on the system of innovation. Even with the readiness of the end-user to transition, upstream innovation must be available for transition to occur. Transition in upstream supply also requires the readiness of end-users to respond or adapt commensurately. This implies that, at the time of the invention and development of a technology, innovators must recognise the market it seeks to serve, and end-users equally ought to be willing, or in the position to, accept and adapt this innovation as a unique, effective, efficient, and affordable technological alternative.

2.4.3.1 Technological innovation system

Technological innovation incorporates the cross application of technology, where new technology is applied to current fields, or existing technology is used in new fields. It is the new and improved products, services, and processes (Freeman, 1989). Technological innovation opens new markets, discovers new resources (Niosi, Saviotti, Bellon and Crow, 1993), and transforms industries. The technological innovation system's goal is to develop, diffuse and use innovation (Edquist, 2011). According to Freeman (1989) technological innovation can be classified into four types. The first type is *incremental innovations*, resulting from quality, performance, adaptability, and design efforts within an industry. The second type is *radical innovations,* where inventions originate from the findings of conscious research and development activities that ultimately bring about complete change in past practice. The third is *change in technological systems*, which occurs when radical innovations cluster. The fourth and last type is *change in techno-economic paradigm*, the type of change that is universal and affects an entire economy. A consumer that does not own a vehicle, and then purchases a hybrid-electric vehicle could be deemed to have leapfrogged over and beyond the fossil fuel vehicle regime into the very latest design in the automotive industry, under the technological innovation system. For a transition from conventional energy to renewable energy to occur, technological innovation needs to be adequately developed to offer services nearly as good, as good or better than the existing dominant technology. The quality of technological innovation could potentially drive transition at a pace and scale that creates a rapid transitioning effect in unmet electricity markets.

2.4.3.2 National innovation system

The national innovation system refers to the categorisation of innovation activities under territorial delimitation such as a common legislation, culture, and language within national borders (Kubeczko et al., 2006). The development of innovation involves coordinated activities of a collection of supporting individual players, within a complex network system, contained in a given institutional framework (Carlsson and Stankiewicz, 1991). Various studies (Freeman, 1995; Lundvall, 1992; Nelson, 1993), have established the national innovation system as the first to apply this view of innovation processes. As an illustration of renewable energy diffusion, local initiatives and elaborate innovation policy were found to be more efficient in Rwanda, compared to the choice of innovation systems technology diffusion framework in Kenya, which failed despite a number of stakeholder training efforts (Tigabu, Berkhout and van Beukering, 2015). This study is interested in developing a framework suitable for unmet electricity markets, to address the challenges associated with a generic transition framework, which has been found ineffective. A national innovation system is relevant in attaining this objective as it offers locally applicable innovative solutions to domestic challenges. National initiatives diffuse faster than external ideas, which may require adjustments to suit local usability.

2.4.3.3 Sectoral innovation system

A sectoral innovation system describes a set of new or existing products or services designed for specific uses, and the group of agents executing both market and non-market interaction to create, produce, and sell those products or services (Malerba, 2002). Similar to the national innovation system, a sectoral innovation system is systematic and made up of a collection of actors in a complex network system (Malerba, 2004) contributing towards its improvement. Innovation in the energy sector is the focus of contemporary discourse. Given the enormous importance of the services electricity can offer, stakeholders in different units of the energy technology spectrum, from conception of a new innovative idea to the testing of a prototype, have a shared interest in producing optimal innovative solutions to energy poverty. The energy sector comprises a collection of both active and peripheral players working to provide ideal energy solutions, including increasing access to electricity for varied services. Integration of innovation across different sectors could improve, the time and speed, of the transition to renewable energy and consequently boost electricity access.

2.4.3.4 Regional innovation system

A regional innovation system is the use of geographic demarcations of regions, and their proximity to innovation processes as the basis for classifying innovation systems. Various regional blocks collaborate by sharing knowledge to provide context-specific solutions for given problems, such as electricity access (Gnansounou, Bayem, Bednyagin and Dong, 2007). Cooke et al. (1997) refer to innovation processes as involving complex network systems of different actors in an institutional framework. The participation of institutional actors in complex systems promotes coordination and decentralisation of innovation pertaining to region specific issues. Energy innovation efforts in regions with unmet electricity need can propel the design and introduction of novel solutions for a society’s needs, relating to electricity services.

Niche innovations emerging through national, technological, sectoral, or regional systems would follow a growth trajectory consistent with technology diffusion (Geels, 2002). The growth trajectory of innovation involves an interlocking interaction of the three multi-level hierarchies namely; landscape, regime, and niches as captured in Figure 2.2 depicting the paths of new technologies.

2.4.4 Strategic niche management

Niches emerge at the micro-level of the multi-level perspective (Geels, 2002). These emerging technologies encounter stiff competition from the dominant regimes, as discussed earlier. Depending on factors such as market conditions, and resilience of technology, niches can grow to catch up with regimes, or they may stagnate, or fizzle out of the market (Geels, 2002). To ensure that viable niche innovations are not crowded out before they are launched, they are developed and nurtured under protection until market conditions and the technology's value proposition can withstand existing market pressure (Geels and Schot, 2007). This process of nurturing and protection of niches is termed strategic niche management. This involves monitoring and evaluating the strengths and weaknesses of an emerging innovation and juxtaposing that with prevailing market conditions to test its viability (Geels, 2002).

The fundamental underpinning of Strategic Niche Management is that, given the immense competitive capability of the regime, niche innovations require a protected space where they can be incubated and nurtured to maturity through a process of experimentation and learning by a network of different actors, including private and public organisations, producers, end-users, and researchers (Caniëls and Romijn, 2006). Amid abundant regime technologies, radical innovations encounter strong resistance from the market environment. This resistance spans technological factors such as the need for complementary technologies to use the new technology; cultural and psychological negativity resulting from insufficient information, and infrastructural factors including the distribution and communication networks; or the large sunk cost of the new technology. Others are the environmental factors including pollution and other repressive waste related issues: to regulatory limitations such as the lack of political will to offer incentives for the adoption of niche technologies (Kemp et al., 1998). The reason for keeping niche technologies in a protected space is to ensure that they are able to overcome the inertia new technologies usually encounter, which consequently cause their failure (Caniëls and Romijn, 2006).

Through strategic niche management, stakeholders at local, regional, national, or even global level can nurture niche technologies by protecting them from the hostile competitive environment in order to grant them the compelling power scale to capture market share (Geels, 2002). In an unmet electricity market such as Africa, there is an already unsatisfied demand, which implies low market saturation and less competition on the supply side, except in cost.

Government could introduce subsidies, for example, as one of the protection mechanisms for niche energy technologies.

2.5 THEORETICAL FOUNDATIONS OF THE TRANSITION FRAMEWORKS

It is also important to recognise the complexity and evolutionary nature of infrastructural transition. The theory of complex systems (Ethiraj and Levinthal, 2004; Kay, Regier, Boyle and Francis, 1999; Rotmans and Loorbach, 2009) and that of evolutionary systems (Foxon, 2011; Safarzyńska, Frenken and van den Bergh, 2012; van den Bergh, 2007) are rooted in how these frameworks emerge.

2.5.1 Complex systems

Complex systems theory is an interdisciplinary theory that includes science, society, nature, as well as technology. Complexity theory provides a framework of analysis for a collection of interconnected units operating in synchrony (Rotmans and Loorbach, 2009). The theory of complex systems centres on the understanding that there is a co-evolutionary relationship within system development. The field of complex systems has attracted research and applications in various fields, including ecology (Kay et al., 1999), economics (Arthur, Durlauf and Lane, 1997), biology (Kauffman, 1990), policy analysis (Rotmans, 2003), and management (Ethiraj and Levinthal, 2004). Energy systems, by design, incorporate a complex system of physical and non-physical interactions, ranging from infrastructure to regulatory framework. It is important to introduce complex system theory into this discussion, to improve understanding of transitions as a complex process and to aid in the framework formulation process.

2.5.2 Evolutionary systems

Evolutionary theory posits that change is as a result of variation, selection, and differential replication (Safarzyńska et al., 2012). This is linked to evolutionary economics, where the feature of variation is represented by innovation, offering diversity in technologies and behaviours; selection is instigated by prevailing competition and regulations; and replication originates from innovation imitation (Safarzyńska et al., 2012). Sustainable transition literature has expanded the theme of technological change to include other factors such as institutions, structure, and societal features of behaviours, norms, and preferences, which reiterates the complexity of transition. Employing evolutionary modelling can be a useful mechanism or technique for appropriately evaluating and understanding change in complex systems. Some techniques of evolutionary modelling are evolutionary computation, agent-based systems, and game theory (Safarzynska and van den Bergh, 2008). Safarzyńska et al. (2012) noted that socio-technical change needs to consider the co-evolution of demand and supply. The concept of an evolutionary system is therefore important towards the objective of framework development.

Besides the technical hindrances to transition, which are largely discussed in this study, there are competing hypotheses that political and socio-cultural issues militate against transition even in unmet markets. In brief, transitions, whether in the fully met or unmet markets, involve multiple stakeholders guided by explicit planning and management, across the multiple levels of landscape, regime, and emergent niche technologies, all contributing to technological, national, and sectoral systems.

2.6 OBSERVATIONS FROM ENERGY TRANSITIONS LITERATURE

Some recent studies on energy transitions (Iizuka, 2014; Szabó, Bódis, Huld and Moner-Girona, 2013) have predicted how energy transitions would emerge. To offer a realistic forecast of energy transition, it is important to review how transitions have occurred in the past. As Grubler (2012) states: ‘History holds important clues for designing policies aiming at another energy transition.’ The lessons of the past offer critical insights for planning and decision-making to shape and determine the future transition paradigm. Review of historical energy transitions suggests some common traits that often accompany transitions in energy (Grubler, 2012). These common transition features, which are discussed in the preceding sections, provide the foundation for decisions relating to future energy transition planning.

2.6.1 Energy transition is bottom-up driven

Energy demand has often surpassed the energy available to the populace (Grubler, 2012). This energy demand and supply gap is even more dominant in developing countries. There has not been a point when the total energy made available has exceeded universal energy needs. This implies that energy deficit has always been a problem. According to Grubler (2012), transitions in energy end-use influence the transitions in the energy sector. The quest for faster travel and in larger groups, for instance, could have led to the emergence of locomotive steam engines, which gradually replaced sailboats and canoes. Richard Trevithick's development of the steam locomotive for sail in 1804 was the birth of a new revolution in the transport industry. Steam locomotion received global recognition following the success of George Stephenson's 1829 engine Rocket, in the Rainhill Trials (Fouquet, 2010). The new locomotives replaced horse-drawn chariots that were hitherto the common means of transport (Fouquet, 2010). These changes in downstream energy services resulted in an increase in the demand for coal. Grubler (2012) concludes that the transition in the upstream energy supply source is a consequence of diversion in energy services from downstream demand, which propelled the development of new technologies to adequately meet contemporary needs and improve efficiency. Similar to many other sectors, the transitions in energy supply can be classified as a demand-pull change, rather than a supply-push cause-effect relationship (Grubler, 2012). Grubler (2012) also acknowledged the multiplicity of factors such as affordability, accessibility, and availability, which might have sustained the transformative changes in supply-side technologies engineered by energy services extension.

2.6.2 Transition in energy is slow

There is a wide consensus among many researchers that energy transition takes decades to occur. In reference to European energy transition in the nineteenth century, Grubler (2012) categorised the transition into three phases: the origin of the innovation, which was referred as the core centre, the early adopters, who were term the rim, and the late adopters, called the periphery. The long-time span between transitions is supported by the fact that it took approximately 160 years to transition from biomass, the major energy of pre-industrial times, to coal. Another 47 to 69 years elapsed before oil technologies gained scale sufficiency to pass through all the transition phases described (Grubler, 2012). Consistent with the observation by Grubler (2012), Wilson and Grubler (2011) as well as Christensen (2013) posit that, energy transitions follow the s-curve technology-diffusion pattern that consists of an experimentation phase, followed by the dominance stage as a result of universal adoption, the steady stage through standardisation, then the emergence of network externalities, saturation, and possible phase-out.

The theory of an energy-transition time-frame is also found in other academic concepts and disciplines, such as: the socio-technical transition (Kern, 2012; Smith et al., 2010), which centres on counteracting the dominance of present systems; ecological modernisation (Buttel, 2000; Hajer, 1995; York and Rosa, 2003) focused on the duration of the regulatory reform process; sociology (Lutzenhiser, 1992; Walker, 2014) emphasising the time it takes for society to change behaviours or routines; and political ecology (Bridge, 2008; Smith, Kern, Raven and Verhees, 2014; Sovacool and Linnér, 2015). The key features and dimensions of these transition approaches are presented in Table 2.1.

Table 2.1: Conceptual approaches to understanding energy transitions

Conceptual Approaches	**Related academic disciplines**	**Primary focus**	**Themes**	**Units of analysis**	**Selected key references**
Socio-technical transitions	Science and technology studies, evolutionary economics, structuration theory	The development or introduction of new technologies leading to new socio-technical configurations	Transition pathways, momentum, path dependency, carbon lock-in, resistance by incumbents	Socio-technical systems, niches, regimes, and landscapes	Geels (2002), Schot and Geels (2008), Kemp et al. (2001), Kern (2012), Hughes (1993),
Ecological modernization theory	Environmental science, environmental sociology, policy studies	Environmental regulation, reform, and governance	Energy transitions, environmental reform, risk society, social movements	Sectors, industries, institutions	Hajer (1995), Buttel (2000), York and Rosa (2003)
Sociology and social practice theory	Sociology, anthropology, cultural theory, Human geography, ecology, political geography	Everyday routines and practices	Changing practices, habits, socialization, normalization	Changing practices, habits, socialization, normalization	Walker (2014), Lutzenhiser (1993)
Political Ecology	Human geography, ecology, political geography	Conflict over natural resources and opposition to change	Contestation, enclosure and exclusion, accumulation by dispossession, global production networks, neoliberalism	Everyday practices or discourses	Sovacool (2013), Bridge (2008), Smith et al. (2005)

Sources: Modified from Sovacool (2016)

These concepts and disciplines support the argument by Grubler (2012) and Smil (2010), who maintain that a long period is required for significant transition to occur.

2.7 LIMITATIONS OF PRESENT TRANSITION FRAMEWORKS IN AFRICAN CONTEXT

Sustainable transition involves the interplay of technology, regulatory frameworks, society, and the market environment. Addressing the multi-dimensionality of sustainable transition and structural change requires theoretical approaches (Geels, 2011). The theoretical underpinnings of present transition frameworks are based on developed countries, which differ in their characteristics from developing countries. From the multi-level perspective (Geels, 2002; Geels and Schot, 2007) to transition management (Kemp, Loorbach and Rotmans, 2007a; Rotmans et al., 2001), technology innovation systems (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007), through to the strategic niche management (Kemp and Rip, 1998; Smith, 2007), these frameworks are primarily contextualised and largely applied in developed countries. Adopting them for developing countries would require adjustment to ensure their applicability. This section identifies and discusses key aspects to consider in the application of these transition frameworks in the context of developing countries. These are: (i) fulfilled, versus unmet, power market; (ii) large-scale versus small scale; (iii) fossil, versus renewable, energy; (iv) time aspect: slow or fast transition; (v) diminishing return versus niche opportunities, and (vi) single, versus multi-dimensional, pressures. These key aspects are further elaborated in the subsections that follow.

2.7.1 Fulfilled versus unmet power market

A fulfilled market refers to the extent to which access to electricity is met in developed countries, as opposed to the limited access found in developing countries. While the existing transition paradigms in energy are built based on a locked-in fossil regime, the deficit in energy services has not been clearly considered in research focused on unravelling potential transition pathways to sustainable energy sources. The reason can partly be attributed to the fact that the frameworks were developed in a context where electricity markets' demands are satisfied. In Africa, however, the size of the unmet power market is approximately 60% of the population, equivalent to about 600 million people (Scott, 2015), offering a vast opportunity for niche energy innovations to flourish. In the absence of conventional path dependent energy infrastructure, there is limited friction on renewable energy growth, hence a bigger opportunity for unmet markets to adopt contemporary renewable energy technologies.

The unmet electricity market in developing countries presents a context that is unique and different from that of developed countries. The low percentage of access to electricity in Africa, largely sub-Saharan Africa (Scott, 2015), is indicative of the vastly unsatisfied market, which is uncommon in developed countries. Developing countries, by nature of their unmet power market, small-scale energy infrastructure, and underdeveloped electricity systems, may face fewer impediments in adapting novel energy technologies, and consequently, less path-dependence than their developed counterparts, who experience lock-in (Iizuka, 2014). This postulation is however contingent on the assumption that the political and socio-cultural issues that could cause transition inertia are averted. A transition from traditional energy sources such as biomass, to commercial fuels such as liquefied petroleum, gas and electricity, is an advancement that improves the standard of living and social well-being (Barnes and Floor, 2003; Leach, 1992). This could reduce potential political and socio-cultural obstacles to transition.

The Sustainable Development Goals advocate for the inclusion of renewable energy in the energy mix electricity generation in pursuit of universal access to modern energy (Giner-Reichl, 2015). Further, the renewed commitments during the COP21 to, proactively, mitigate the climatic effect of CO_2 emissions strengthens the argument that regimes are facing pressures on two fronts, namely: landscape factors and emerging niches. Hence, the potential of niche technologies, such as renewable energy, being adopted at a faster rate in the unmet electricity markets is profound.

2.7.2 Large-scale versus small-scale differences in power markets

Large-scale refers to the scale of energy infrastructure that exists in developed countries in relation to the small-scale and underdeveloped energy infrastructure that characterises developing countries, especially African countries. Developed countries have large-scale energy infrastructure, which presents a transition challenge that developing countries do not encounter. Smil (2010) observes that '*Energy transitions have been, and will continue to be, inherently prolonged affairs, particularly so in large nations whose high levels of per capita energy use and whose massive and expensive infrastructures make it impossible to greatly accelerate their progress even if we were to resort to some highly effective interventions*.' This, in part, highlights the fact that, by sheer size of present regime infrastructure, developed countries' transition to renewable energy would occur at a slower rate than that of developing countries, which lack adequate electricity infrastructure. It is thus possible for energy transition to occur much more rapidly (Sovacool, 2016) in developing countries.

2.7.3 Fossil versus renewable energy focus

Fossil versus renewable refers to the choice between fossil fuels and renewable energy in electricity transition. The opportunities and challenges that characterise transitions from one fossil energy source to another differ from that of a transition from fossil fuel to renewable energy. Despite the challenges associated with knowledge transfer and information dissemination, when it comes to energy transition in the twenty-first century, there are shared global goals, which, in conjunction with the external landscape, facilitate transition in some areas and sectors. Sustainable transition is fast gaining popularity in sectors including energy, transport, and agriculture, as activities in these sectors directly relate to the environment, which is currently the focus of a variety of sustainability campaigns. The pioneers of sustainable transition in the twenty-first century are not the large firms championing regime technologies, but rather a new set of firms with strong commitments to sustainability as a core objective. However, in the absence of concentrated regime technologies, as is the case in unmet electricity markets, sustainability driven enterprises encounter little market friction.

The growing energy needs coupled with the negative consequences of fossil fuel on climate change (Bazilian and Pielke Jr, 2013), would not only make renewable energy a sustainable choice but possibly obligatory, hence the potential for fluidity in transition. Renewable energy opportunities can also be harnessed on smaller scale, a practice common in Germany, where over half of the installed renewable electricity generation capacity belongs to individual citizens and farmers who live close to the power plants (Schmid, Knopf and Pechan, 2016). Electricity through photovoltaic solar energy storage, for example, is most advocated in contemporary discourse, due to the high possibility of tapping power from small rooftop to mini-grid systems. This can be attributed to the quick advancement of knowledge in solar technology and the large-scale opportunities for harnessing solar power in many parts of the globe.

2.7.4 Time aspect: slow versus fast transition rate

This refers to the pace or speed of transition in a fully satisfied market, compared to that of an unmet power market. According to Sovacool (2016), whether or not a transition in an energy system takes a long time to realise, depends on the definition ascribed to it. Therefore, before discussing the limitations of time concept in present energy and socio-technical transition frameworks in an unmet electricity market context, key terms namely *significant transition, society*, and *resources and services* are defined because they are essential in energy transition (Sovacool, 2016). Transition in the dimension of time is assessed on this basis. The purpose of defining these key terms is to limit ambiguity and ensure clarity of scope, and also in response to the recommendation of Sovacool (2016) and Laird (2013), who observed that assumptions contained in definitions are not always clear, though important in demonstrating the design and representation of transitions. *Significant transition* herein implies that people or sectors currently without access to electricity, whether households, commercial, or industrial sectors, can obtain a reliable electricity supply for basic services and functionality of their electrical devices. A transition is also deemed significant when those connected to the electricity grid, but suffering regular outages, can now enjoy more sustainable electricity access after transition. The term *society* is used variously in context to reference the African or the unmet electricity, market. The *resources and services* are the physical elements of generation plants, transmission lines, and end-use tools that use electricity.

While some scholars (Fouquet, 2010; Grubler, 2012; Smil, 2010) are reserved about energy transition and its implications, others (Sovacool, 2016; UN, 2015) are optimists and advocates of a radical transition. Grubler (2012) characterises quick introduction and instantaneous policies as detrimental in simulated innovation, with a predestined transition failure resulting within the new technology deployment arena, and cautions that it takes decades for innovation success to occur. He argues that the size of existing infrastructure makes transition in the sector slow. This observation is relevant to the extent that large-scale energy infrastructure exists within the society or context in reference. In an unmet market, such as Africa, energy infrastructure is relatively small or non-existent, hence the potential for transition to occur faster. This is supported by Sovacool (2016) who affirms that energy transition has, and can, occur in a shorter time than predicted, although it may remain inconspicuous unless assessed based on a given *significance*, *society*, and *energy resource and services.* Pre-existing niche markets could be a catalyst for propelling adoption of innovation in a shorter time (Grubler, 2012).

It is clear, therefore, that the dynamics and pace of technology acceptance in a fulfilled market differs from those of a market with unmet demand. The major difference pertains to infrastructural characteristics - large-scale lock-in for a fully satisfied market versus limited or no ‘regime’ technologies acting as inertia to niche technologies adoption in an unmet market. Given their relatively underdeveloped energy infrastructure, developing economies experience transition at a faster rate and across a broader spectrum of energy sources (Marcotullio and Schulz, 2007). Some major drivers of transition, such as urbanisation, income, education, running water, fuel prices, electrification, and the difficulty in accessing traditional fuels, propel the rate of transition in energy sources (Heltberg, 2004; Pachauri and Jiang, 2008). The broad range of services that electricity provides, compared to the services from traditional energy sources, increases the willingness and rate of acceptance of transition in energy for household and other commercial needs in unmet markets.

The decline in transition time could suggest that, due to advancement in technology and a vastly dynamic demand scenario, future transitions could happen within an even shorter time. The rate of energy transition is different across nations, with developed or large economies experiencing slower transition, and developing economies demonstrating a faster rate of transition.

2.7.5 Diminishing returns versus emerging niche opportunities

Diminishing returns here refer to the change in marginal return of electricity consumed from the newly adopted energy alternative. In developed countries, because of the fully satisfied demand, there is little or no marginal return on a unit of energy consumed. In developing countries, however, the unmet power market creates a higher marginal return on electricity, hence a higher tendency to accept the introduction of alternative energy. Conventional economics (Fiddaman, 2002; Hall and Klitgaard, 2011; Tainter, 1990), generally fail to notice the close association between a resource such as energy and the economy. This is because of the misperception that fossil fuel is available in abundance and, although energy is considered an economic production factor, the possibility of it being inaccessible is not recognised (Sgouridis and Csala, 2014). The pre-existence of niche markets in developing countries is an opportunity for experimenting and scaling up new technologies (Grubler, 2012). With technological, national, regional, and sectoral innovations, the advancement of niche opportunities amidst the vast unmet market could propel the rate of transition.

The marginal return for niche opportunities in an unmet market offers significant incentive for transition to occur quickly. In response to criticisms of the multi-level perspective, Geels (2011) contends that the incentive for the private sector in sustainable transition is low. Though this could easily be thought of as a universal experience in the energy market, in many deregulated electricity markets, e.g. Europe, where there are incentives, active private sector participation exists. Many independent power producers fall into this category because of state support in the form of a subsidy and feed-in-tariffs.

2.7.6 Single versus multi-dimensional influence

It is important to acknowledge that, in existing energy markets, the pressure to transition from the fossil regime to renewable energy is not merely that of landscape activities in the form of international emission regulations, but also the emerging rapid niche growth supported by landscape investments. This is not exactly the same as an intra-regime shift, such as the transition from coal to oil-based infrastructure. With limited external pressure on investors to act, transition in such a context can be sluggish. This observation, though not necessarily unique to unmet electricity markets, is not clearly demonstrated in present transition frameworks. The inadequate supply of electricity also creates a novel influence, distinguishable from that of landscape. This is demand-pull, which increases incentive for investors in niche technologies, especially when backed by statutory guarantees. There is demand for diversified energy services in Africa. Despite the limited electricity access, there is wide adoption of modern technologies such as mobile phones, which cannot be powered as easily or inexpensively by traditional energy. This technology adoption pattern increases the demand for electricity and presents an opportunity for the introduction of some form of renewable energy as an alternative for accelerating electricity access.

2.8 MODIFIED TRANSITION FRAMEWORK FOR UNMET ELECTRICITY MARKETS

The inaptness of existing transition frameworks for the unmet electricity markets is illustrated by the limitations discussed. A modified transition framework that accounts for the unique characteristics of the unmet electricity markets was developed, as shown in Figure 2.3.

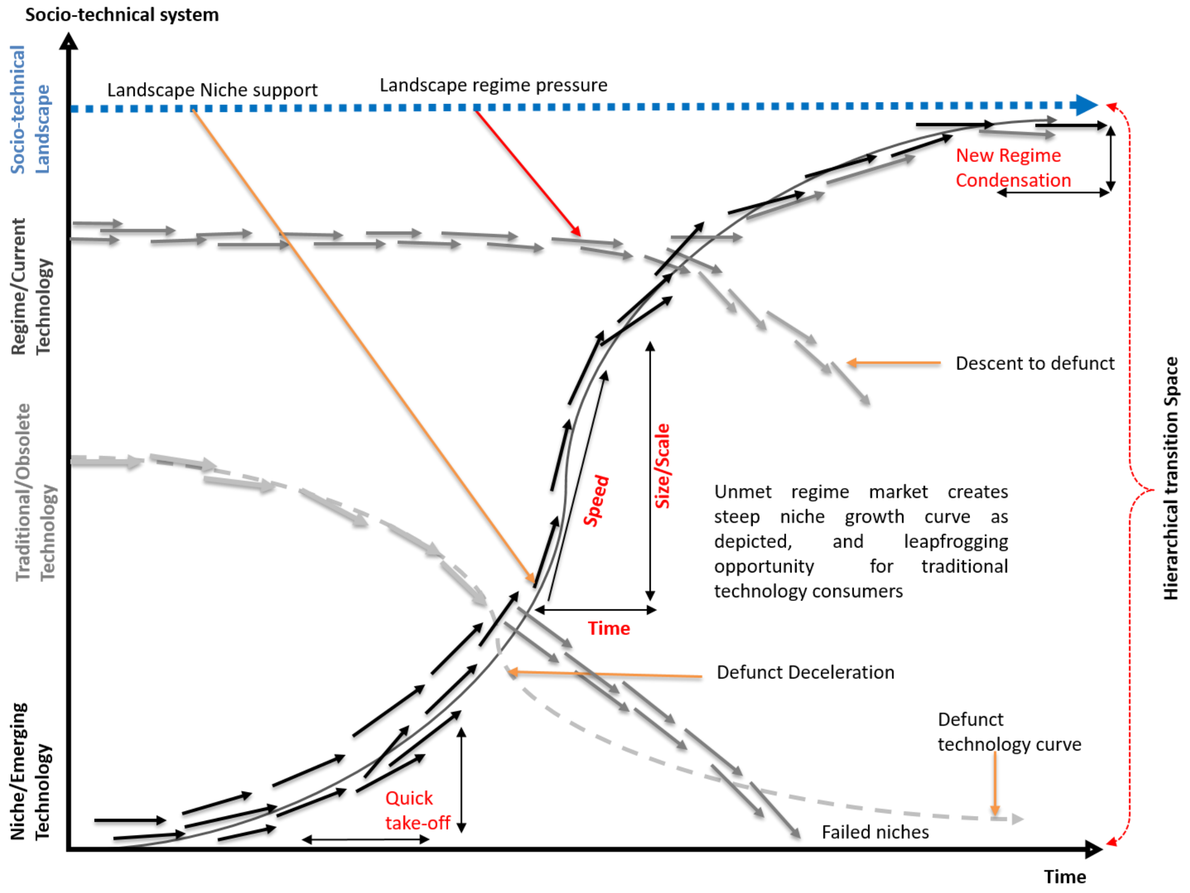


Figure 2.3: Transition framework for unmet electricity markets

Although the dynamic multi-level perspective in Figure 2.2 could be suitably and universally applicable to transitions in fully met energy markets, it falls short of addressing the contextual peculiarities of the unmet energy markets. One major limitation of the multi-level perspective framework is that it fails to recognise that, traditional energy is still largely used in unmet electricity markets, and therefore omits the traditional energy or technology curve (see Figure 2.3). When it comes to unmet markets, therefore, a key piece of information is missing in the contextualisation of the multi-level perspective and, to some degree, its scope of application. The key characteristics in the modified transition framework of the unmet electricity markets are: (i) traditional technology; (ii) defunct deceleration; (iii) the niche technology curve; (iv) the landscape's support for niches; (v) descent to defunct; and (vi) new-regime condensation. These are further discussed in the sections that follow.

2.8.1 Traditional technology

The modified framework in Figure 2.3 captures the existence of a traditional, outdated technology that is still in use in the unmet electricity markets where regime technologies are lacking. Given that regime technologies are already under transition, with the emergence of niches, this is the ideal opportunity to leapfrog the unmet markets into niche technologies. This could be either path-creating or path-skipping leapfrogging, depending on market characteristics and origin of the innovation. The goal is to avoid path-following leapfrogging or worse, technological obsolescence as is the case with outdated technology in unmet markets.

2.8.2 Defunct deceleration

The interaction of traditional and niche technology curves creates a temporal technological instability, which presents opportunity for the unmet market to leapfrog the regime technology to niche technology. The traditional technology curve would experience a rapid deceleration after it intersects with the niche technology curve. This deceleration is termed the defunct deceleration, as new adopters recognise the modernity and extended benefits of the niche technology, compared to the traditional technology or even existing regime technologies. The defunct technologies often do not entirely disappear. Developed countries, for example, continue to consume energy from wood as a vintage technology with unique novelty. This is different from developing countries or unmet energy markets, where traditional energy sources such as wood remain the major energy resource, the excessive consumption of which creates adverse environmental effects, such as deforestation and acceleration of negative climatic conditions.

2.8.3 Niche technology curve

The steepness of the niche innovation curve also highlights the understanding that the rate of innovation, adoption, and landscape pressure and/or support therefore, is one major determinant of the lifespan of present technology. Given the vastly unmet market size, niche technology acceptance and adoption leads to a quick take-off and allows it to capture a large part of the technology market. This is inconsistent in the case of a near-saturation market, as captured in Geels (2002) framework, where niche innovation grows rather slowly because of extensive regime competition.

2.8.4 Landscape support for niches

Another limitation of the multi-level perspective framework is the fact that it does not consider the support that niches receive from landscape development, when it comes to energy transition. Although it appropriately captures the pressures that landscapes such as COP21, Paris Agreement, Copenhagen Accord, among others, exert on conventional regime technologies to transition, when it comes to the support these landscapes extend to propelling the growth of niche innovation, the framework is limited. The modified framework, therefore, recognises this bi-dimensional landscape effect on regimes and niches. Landscapes, besides pressurising regimes to transition, also support the nurturing and dominance of niches such as renewable energy technologies. Beyond transitions in the energy sector, or situations where landscapes do not favour niche creation, (Geels, 2002) the innovation system framework would remain suitable.

2.8.5 Descent to Defunct

Another feature of the modified multi-level innovation systems is that, when regime technologies do interact with the niche technologies, a significant number of the regime technologies would descend towards the defunct curve, because the niche technologies have gained ground and acquired a strong competitive advantage. The regime technologies that survive the niche interactions, especially in an unmet market, would largely consist of those with established large-scale infrastructure. For instance, given that Africa contains large unmet markets, and that those with access to modern energy received that access only recently, the introduction of niche technologies in the satisfied market would result in a gradual decline in regime technologies, especially if investment were limited. On the other hand, they could encounter path-following leapfrogging by adopting niche technologies within a short time of first using regime technologies. The rate and size at which the regime declines to defunct status depends on the benefits of the niche technology, and the length of time the regime technology is in use.

2.8.6 New regime condensation

After a socio-technical regime interacts with niche technologies, a new regime cluster eventually emerges. This clustering of technologies following a peak competition for dominance is termed in this study a regime condensation. It is expected that the new regime cluster would consist mainly of the present niche technology. It takes time for niche technologies to form a dominant regime cluster. The size of present regime technologies in the new condensation is a function of their resilience, the benefits of the niche technology, and the landscape's attitude towards such technologies.

2.9 CONCLUSION

Energy transition, in the context of developing countries in other parts of the world, may not even necessarily be the same as in Africa, irrespective of the extensive features they may share. A strong distinguishable feature could be all that matters in making for dynamic social and infrastructural systems contextually inapplicable. Adopting developed countries' energy transition frameworks for developing countries would require adjustment to ensure their applicability. The abundance of renewable energy resources across an unmet electricity market such as that in Africa, presents the opportunity for a unique transition framework for analysis of a situation and the transition to renewable energy technology. This study identified five key aspects for consideration in the application of these transition frameworks in the context of a developing country, namely: (i) fulfilled versus unmet power market; (ii) large-scale versus small scale; (iii) fossil versus renewable; (iv) time aspect – slow or fast; and (v) diminishing return versus niche opportunities.

The limitations embedded in current transition frameworks are a clear indication of their unsuitability for unmet electricity markets. A modified transition framework that accounts for the unique characteristics of the unmet electricity markets was developed, which includes these characteristics: (i) traditional technology; (ii) defunct deceleration; (iii) the niche technology curve; (iv) landscape support for niches; and (v) new regime condensation.

The limitations of present transition frameworks, the unique features of the unmet electricity markets, and the eventual transition framework presented in this study demonstrate that energy transition in sub-Saharan Africa can occur rapidly. Given the large unmet market size and rising environmental concerns, developing countries can and should avoid the mundane pattern of transition in energy system by leapfrogging to renewable energy for electricity services. Scholars in the field of energy transition are also encouraged to undertake studies to test the robustness of this framework in other developing countries within or outside the African continent.

Chapter 3 investigates the key drivers of energy leapfrogging and assesses how unmet electricity markets in Africa can leapfrog from traditional energy to renewable energy without passing through conventional energy.

CHAPTER TWO REFERENCES

ACKERMAN, L. S. 1982. Transition management: An in-depth look at managing complex change. *Organizational Dynamics,* 11**,** 46-66.

ADLER, G. & WEBSTER, E. 1995. Challenging transition theory: The labor movement, radical reform, and transition to democracy in South Africa. *Politics and Society,* 23**,** 75-75.

ARAÚJO, K. 2014. The emerging field of energy transitions: Progress, challenges, and opportunities. *Energy Research & Social Science,* 1**,** 112-121.

ARTHUR, W. B., DURLAUF, S. N. & LANE, D. A. 1997. *The economy as an evolving complex system II*, Addison-Wesley Reading, MA.

ASHEIM, B. T. & COENEN, L. 2005. Knowledge bases and regional innovation systems: Comparing Nordic clusters. *Research Policy,* 34**,** 1173-1190.

BARNES, D. F. & FLOOR, W. M. 2003. Rural Energy in Developing Countries: A Challenge for Economic Development1. *Annual Review of Energy and the Environment,* 21**,** 497.

BAZILIAN, M. & PIELKE JR, R. 2013. Making energy access meaningful. *Issues in science and technology,* 29**,** 74.

BERGEK, A., JACOBSSON, S., CARLSSON, B., LINDMARK, S. & RICKNE, A. 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy,* 37**,** 407-429.

BLANCHARD, B. S., FABRYCKY, W. J. & FABRYCKY, W. J. 1990. *Systems engineering and analysis*, Prentice Hall New Jersey;.

BO CARLSSON, S. J., MAGNUS HOLMÉN, ANNIKA RICKNE 2002. Innovation systems: analytical and methodological issues. *Research Policy* 31**,** 233-245.

BRESCHI, S. & MALERBA, F. 1997. *Sectoral innovation systems: technological regimes, Schumpeterian dynamics, and spatial boundaries*.

BRIDGE, G. 2008. Environmental economic geography: a sympathetic critique. *Geoforum,* 39**,** 76-81.

BUTTEL, F. H. 2000. Ecological modernization as social theory. *Geoforum,* 31**,** 57-65.

CALDWELL, J. C. 1976. Toward a restatement of demographic transition theory. *Population and development review***,** 321-366.

CALLON, M. 1999. Actor-network theory—the market test. *The Sociological Review,* 47**,** 181-195.

CANIËLS, M. & ROMIJN, H. Strategic niche management as an operational tool for sustainable innovation: guidelines for practice. Schumpeter Conference, 2006. 21-24.

CARLSSON, B. 2003. Innovation systems: a survey of the literature from a Schumpeterian perspective. *Paper for the Elgar Companion to Neo-Schumpeterian Economics, June*.

CARLSSON, B., JACOBSSON, S., HOLMÉN, M. & RICKNE, A. 2002. Innovation systems: analytical and methodological issues. *Research policy,* 31**,** 233-245.

CARLSSON, B. & STANKIEWICZ, R. 1991. On the nature, function and composition of technological systems. *Journal of evolutionary economics,* 1**,** 93-118.

CHAPPIN, E. J. & DIJKEMA, G. P. 2010. Agent-based modelling of energy infrastructure transitions. *International journal of critical infrastructures,* 6**,** 106-130.

CHESNAIS, J.-C. 1992. The demographic transition: Stages, patterns, and economic implications. *OUP Catalogue*.

CHRISTENSEN, C. 2013. *The innovator's dilemma: when new technologies cause great firms to fail*, Harvard Business Review Press.

COOKE, P., MIKEL, G. U. & GOIO, E. 1997. Regional innovation systems: Institutional and organisational dimensions. *Research Policy,* 26**,** 475-491.

DAVISON, R., VOGEL, D., HARRIS, R. & JONES, N. 2000. Technology leapfrogging in developing countries-an inevitable luxury? *The Electronic Journal of Information Systems in Developing Countries,* 1**,** 1-10.

DE SOYSA, I., ONEAL, J. R. & PARK, Y.-H. 1997. Testing power-transition theory using alternative measures of national capabilities. *Journal of Conflict Resolution,* 41**,** 509-528.

DIJKEMA, G. P. J. & BASSON, L. 2009. Complexity and Industrial Ecology. *Journal of Industrial Ecology,* 13**,** 157-164.

DOSI, G. 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. *Research policy,* 11**,** 147-162.

EDQUIST, C. 2011. Systems of innovation: perspectives and challenges. *African Journal of Science, Technology, Innovation and Development (AJSTID),* 2**,** 14-43.

ELZEN, B., GEELS, F. W. & GREEN, K. 2004. *System innovation and the transition to sustainability: theory, evidence and policy*, Edward Elgar Publishing.

ETHIRAJ, S. K. & LEVINTHAL, D. 2004. Modularity and innovation in complex systems. *Management Science,* 50**,** 159-173.

FIDDAMAN, T. S. 2002. Exploring policy options with a behavioral climate–economy model. *System Dynamics Review***,** 243–267.

FOUQUET, R. 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy,* 38**,** 6586-6596.

FOXON, T. J. 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecological Economics,* 70**,** 2258-2267.

FREEMAN, C. 1989. *Technology policy and economic performance*, Pinter Publishers Great Britain.

FREEMAN, C. 1995. The 'National System of Innovation'in historical perspective. *Cambridge Journal of economics*, 19, 5-24.

FRENK, J., BOBADILLA, J. L., STERN, C., FREJKA, T. & LOZANO, R. 1991. Elements for a theory of the health transition. *Health transition review*, 21-38.

GEELS, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31, 1257-1274.

GEELS, F. W. 2004a. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research policy*, 33, 897-920.

GEELS, F. W. 2004b. *Understanding system innovations: a critical literature review and a conceptual synthesis*.

GEELS, F. W. 2005a. Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. *Technological forecasting and social change*, 72, 681-696.

GEELS, F. W. 2005b. *Technological transitions and system innovations: a co-evolutionary and socio-technical analysis*, Edward Elgar.

GEELS, F. W. 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, 1, 24-40.

GEELS, F. W. & SCHOT, J. 2007. Typology of sociotechnical transition pathways. *Research policy*, 36, 399-417.

GIDDENS, A. 2009. *The politics of climate change*, Cambridge, Polity.

GINER-REICHL, I. 2015. Renewable energy in international and regional governance: Propelling development in Africa. *Energy Research & Social Science*, 5, 116-119.

GNANSOUNOU, E., BAYEM, H., BEDNYAGIN, D. & DONG, J. 2007. Strategies for regional integration of electricity supply in West Africa. *Energy Policy*, 35, 4142-4153.

GRUBLER, A. 2012. Energy transitions research: Insights and cautionary tales. *Energy Policy*, 50**,** 8-16.

HAJER, M. A. 1995. *The politics of environmental discourse: ecological modernization and the policy process*, Oxford, Clarendon Press.

HALL, C. A. & KLITGAARD, K. A. 2011. *Energy and the wealth of nations: understanding the biophysical economy*, Springer Science & Business Media.

HALLOCK, J. L., THARAKAN, P. J., HALL, C. A., JEFFERSON, M. & WU, W. 2004. Forecasting the limits to the availability and diversity of global conventional oil supply. *Energy*, 29**,** 1673-1696.

HAMILTON, J. D. 2008. Understanding crude oil prices. National Bureau of Economic Research.

HEKKERT, M. P., SUURS, R. A. A., NEGRO, S. O., KUHLMANN, S. & SMITS, R. E. H. M. 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74**,** 413-432.

HELTBERG, R. 2004. Fuel switching: evidence from eight developing countries. *Energy Economics*, 26**,** 869-887.

HOOGMA, R., KEMP, R., SCHOT, J. & TRUFFER, B. 2004. *Experimenting for sustainable transport: the approach of strategic niche management*.

IEA 2011. World Energy Outlook 2011. Paris: OECD/IEA.

IIZUKA, M. 2014. *Diverse and uneven pathways towards transition to low carbon development: The case of diffusion of solar PV technology in China*, Maastricht Economic and social Research Institute on Innovation and Technology (UNU-MERIT) & Maastricht Graduate School of Governance.

JACOBSSON, S. & BERGEK, A. 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environmental Innovation and Societal Transitions*, 1**,** 41-57.

JEFFERSON, M. 2014. Closing the gap between energy research and modelling, the social sciences, and modern realities. *Energy Research & Social Science*, 4**,** 42-52.

KANAGAWA, M. & NAKATA, T. 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. *Energy Policy*, 36**,** 2016-2029.

KAUFFMAN, S. A. 1990. Requirements for evolvability in complex systems: orderly dynamics and frozen components. *Physica D: Nonlinear Phenomena*, 42**,** 135-152.

KAY, J. J., REGIER, H. A., BOYLE, M. & FRANCIS, G. 1999. An ecosystem approach for sustainability: addressing the challenge of complexity. *Futures*, 31**,** 721-742.

KEMP, R. 1994. Technology and the transition to environmental sustainability: the problem of technological regime shifts. *Futures*, 26**,** 1023-1046.

KEMP, R. 2010. The Dutch energy transition approach. *International Economics and Economic Policy*, 7**,** 291-316.

KEMP, R., ARIE, R. & JOHAN, S. 2001. Constructing transition paths through the management of niches. *In Path dependence and creation.* . Lawrence Erlbaum.

KEMP, R., LOORBACH, D. & ROTMANS, J. 2007a. Transition management as a model for managing processes of co-evolution towards sustainable development. *The International Journal of Sustainable Development & World Ecology*, 14**,** 78-91.

KEMP, R. & RIP, A. 1998. *Technological change. IN RAYNOR, S. & MALONE, EL (Eds.) Human choice and climate change.* , Columbus, Battelle Press.

KEMP, R., ROTMANS, J. & LOORBACH, D. 2007b. Assessing the Dutch Energy Transition Policy: How Does it Deal with Dilemmas of Managing Transitions? *Journal of Environmental Policy & Planning*, 9**,** 315-331.

KEMP, R., SCHOT, J. & HOOGMA, R. 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology analysis & strategic management*, 10**,** 175-198.

KERN, F. 2012. Using the multi-level perspective on socio-technical transitions to assess innovation policy. *Technological Forecasting and Social Change,* 79**,** 298-310.

KERN, F. & SMITH, A. 2008. Restructuring energy systems for sustainability? Energy transition policy in the Netherlands. *Energy Policy,* 36**,** 4093-4103.

KIRK, D. 1996. Demographic transition theory. *Population studies,* 50**,** 361-387.

KOBOS, P. H., ERICKSON, J. D. & DRENNEN, T. E. 2006. Technological learning and renewable energy costs: implications for US renewable energy policy. *Energy policy,* 34**,** 1645-1658.

KUBECZKO, K., RAMETSTEINER, E. & WEISS, G. 2006. The role of sectoral and regional innovation systems in supporting innovations in forestry. *Forest Policy and Economics,* 8**,** 704-715.

LAIRD, F. N. 2013. Against transitions? Uncovering conflicts in changing energy systems. *Science as Culture,* 22**,** 149-156.

LAW, J. 1992. Notes on the theory of the actor-network: Ordering, strategy, and heterogeneity. *Systems practice,* 5**,** 379-393.

LEACH, G. 1992. The Energy Transition. *Energy policy***,** 116-123.

LEMKE, D. & REED, W. 1996. Regime types and status quo evaluations: Power transition theory and the democratic peace. *International Interactions,* 22**,** 143-164.

LINZ, J. J. & STEPAN, A. 1996. *Problems of democratic transition and consolidation: Southern Europe, South America, and post-communist Europe,* Baltimore, JHU Press.

LOORBACH, D. 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance,* 23**,** 161-183.

LOORBACH, D. & ROTMANS, J. 2010. The practice of transition management: Examples and lessons from four distinct cases. *Futures,* 42**,** 237-246.

LOVELL, H. 2007. The governance of innovation in socio-technical systems: the difficulties of strategic niche management in practice. *Science and Public Policy,* 34**,** 35-44.

LUNDVALL, B.-A. 1992. *National systems of innovation: An analytical framework*.

LUTZENHISER, L. 1992. A cultural model of household energy consumption. *Energy,* 17**,** 47-60.

MACKENBACH, J. 1994. The epidemiologic transition theory. *Journal of Epidemiology and Community Health*, 48**,** 329-331.

MALERBA, F. 2002. Sectoral systems of innovation and production. *Research policy,* 31**,** 247-264.

MALERBA, F. 2004. *Sectoral systems of innovation: concepts, issues and analyses of six major sectors in Europe,* Cambridge, Cambridge University Press.

MARCOTULLIO, P. J. & SCHULZ, N. B. 2007. Comparison of energy transitions in the United States and developing and industrializing economies. *World Development*, 35**,** 1650-1683.

MARKARD, J. & TRUFFER, B. 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy*, 37**,** 596-615.

MARTINOT, E. 2000. Renewable energy markets and the Global Environment Facility. *Financial Times, Renewable Energy Report***,** 18-22.

MCDONALD, A. & SCHRATTENHOLZER, L. 2001. Learning rates for energy technologies. *Energy policy,* 29**,** 255-261.

MEADOWCROFT, J. 2009. What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sciences*, 42**,** 323-340.

MEADOWS, D. H. 2008. *Thinking in systems: A primer*, Chelsea Green Publishing.

MEADOWS, D. H., MEADOWS, D. L., RANDERS, J. & BEHRENS, W. W. 1972. *The limits to growth: a report to the club of Rome,* New York, Potomac Associates.

MEIR, A. 1986. Demographic transition theory: A neglected aspect of the nomadism-sedentarism continuum. *Transactions of the Institute of British Geographers***,** 199-211.

MILLER, C. A., RICHTER, J. & O'LEARY, J. 2015. Socio-energy systems design: A policy framework for energy transitions. *Energy Research & Social Science,* 6**,** 29-40.

MITCHELL, C. L. 2008. Altered landscapes, altered livelihoods: the shifting experience of informal waste collecting during Hanoi's urban transition. *Geoforum,* 39**,** 2019-2029.

NEE, V. 1989. A theory of market transition: From redistribution to markets in state socialism. *American Sociological Review***,** 663-681.

NELSON, R. R. 1993. *National innovation systems: a comparative analysis*, University Press.

NIELSEN, J. R., HOVMØLLER, H., BLYTH, P.-L. & SOVACOOL, B. K. 2015. Of "white crows" and "cash savers:" A qualitative study of travel behavior and perceptions of ridesharing in Denmark. *Transportation Research Part A: Policy and Practice,* 78**,** 113-123.

NIOSI, J., SAVIOTTI, P., BELLON, B. & CROW, M. 1993. National systems of innovation: in search of a workable concept. *Technology in society,* 15**,** 207-227.

OFFE, C. & ADLER, P. 1991. Capitalism by democratic design? Democratic theory facing the triple transition in East Central Europe. *Social Research***,** 865-892.

OMRAN, A. R. 1971. The epidemiologic transition: a theory of the epidemiology of population change. *The Milbank memorial fund quarterly,* 49**,** 509-538.

PACHAURI, S. & JIANG, L. 2008. The household energy transition in India and China. *Energy policy,* 36**,** 4022-4035.

PAINULY, J. P. 2001. Barriers to renewable energy penetration; a framework for analysis. *Renewable energy,* 24**,** 73-89.

PEARCE, D. W., MARKANDYA, A. & BARBIER, E. 1989. *Blueprint for a green economy,* London, Earth scan Publication Limited.

PHILLIMORE, J. 2001. Schumpeter, Schumacher and the greening of technology. *Technology Analysis & Strategic Management,* 13**,** 23-37.

RAVEN, R. & GEELS, F. 2010. Socio-cognitive evolution in niche development: comparative analysis of biogas development in Denmark and the Netherlands (1973–2004). *Technovation,* 30**,** 87-99.

ROLAND, G. 2002. The political economy of transition. *The Journal of Economic Perspectives,* 16**,** 29-50.

ROTMANS, J. 2003. Transition management: key to a sustainable society. Assen Van Gorcum.

ROTMANS, J., KEMP, R. & VAN ASSELT, M. 2001. More evolution than revolution: transition management in public policy. *Foresight,* 3**,** 15-31.

ROTMANS, J. & LOORBACH, D. 2009. Complexity and Transition Management. *Journal of Industrial Ecology,* 13**,** 184-196.

SAFARZYŃSKA, K., FRENKEN, K. & VAN DEN BERGH, J. C. 2012. Evolutionary theorizing and modeling of sustainability transitions. *Research Policy,* 41**,** 1011-1024.

SAFARZYNSKA, K. & VAN DEN BERGH, J. C. 2008. Evolutionary modelling in economics: a survey of methods and building blocks. The Papers on Economics and Evolution.

SARRICA, M., BRONDI, S., COTTONE, P. & MAZZARA, B. M. 2016. One, no one, one hundred thousand energy transitions in Europe: The quest for a cultural approach. *Energy Research & Social Science,* 13**,** 1-14.

SCHMID, E., KNOPF, B. & PECHAN, A. 2016. Putting an energy system transformation into practice: The case of the German Energiewende. *Energy Research & Social Science,* 11**,** 263-275.

SCHOT, J., HOOGMA, R. & ELZEN, B. 1994. Strategies for shifting technological systems: the case of the automobile system. *Futures,* 26**,** 1060-1076.

SCOTT, A. 2015. Building Electricity Supplies in Africa for Growth and Universal Access. *Working Paper, The New Climate Economy*.

SGOURIDIS, S. & CSALA, D. 2014. A Framework for Defining Sustainable Energy Transitions: Principles, Dynamics, and Implications. *Sustainability,* 6**,** 2601-2622.

SHACKLEY, S. & GREEN, K. 2007. A conceptual framework for exploring transitions to decarbonised energy systems in the United Kingdom. *Energy,* 32**,** 221-236.

SMIL, V. 2010. *Energy transitions: history, requirements, prospects,* Santa Barbara, ABC-CLIO.

SMITH, A. 2007. Translating sustainabilities between green niches and socio-technical regimes. *Technology Analysis & Strategic Management,* 19**,** 427-450.

SMITH, A., KERN, F., RAVEN, R. & VERHEES, B. 2014. Spaces for sustainable innovation: Solar photovoltaic electricity in the UK. *Technological Forecasting and Social Change,* 81**,** 115-130.

SMITH, A., VOß, J.-P. & GRIN, J. 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. *Research policy,* 39**,** 435-448.

SOVACOOL, B. K. 2009. Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. *Energy Policy,* 37**,** 4500-4513.

SOVACOOL, B. K. 2016. How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science,* 13**,** 202-215.

SOVACOOL, B. K. & HIRSH, R. F. 2009. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy,* 37**,** 1095-1103.

SOVACOOL, B. K. & LINNÉR, B.-O. 2015. *The political economy of climate change adaptation,* Basingstoke, Palgrave Macmillan.

SZABÓ, S., BÓDIS, K., HULD, T. & MONER-GIRONA, M. 2013. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. *Renewable and Sustainable Energy Reviews,* 28**,** 500-509.

TAINTER, J. 1990. *The collapse of complex societies,* Cambridge Cambridge University Press.

TIGABU, A. D., BERKHOUT, F. & VAN BEUKERING, P. 2015. The diffusion of a renewable energy technology and innovation system functioning: Comparing bio-digestion in Kenya and Rwanda. *Technological Forecasting and Social Change,* 90**,** 331-345.

TUKKER, A. 2005. Leapfrogging into the future: developing for sustainability. *International Journal of Innovation and Sustainable Development,* 1**,** 65-84.

UNFCCC, C. 1992. United Nations Framework Convention On Climate Change. *Kyoto Protocol.* Kyoto: UN.

UN. 2015. Conference of the Parties. Framework Convention on Climate Change, 2015 Paris. UN.

UNRUH, G. C. 2002. Escaping carbon lock-in. *Energy policy,* 30**,** 317-325.

VAN DEN BERGH, J. C. 2007. Evolutionary thinking in environmental economics. *Journal of Evolutionary Economics,* 17**,** 521-549.

VERBONG, G. P. J. & GEELS, F. W. 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technological Forecasting and Social Change,* 77**,** 1214-1221.

WALKER, G. 2014. The dynamics of energy demand: Change, rhythm and synchronicity. *Energy Research & Social Science,* 1**,** 49-55.

WALKER, W. 2000. Entrapment in large technology systems: institutional commitment and power relations. *Research policy,* 29**,** 833-846.

WEITZMAN, M. L. 1993. Economic transition: can theory help? *European Economic Review,* 37**,** 549-555.

WILSON, C. & GRUBLER, A. Lessons from the history of technological change for clean energy scenarios and policies. Natural Resources Forum, 2011. Wiley Online Library, 165-184.

YORK, R. & ROSA, E. A. 2003. Key challenges to ecological modernization theory institutional efficacy, case study evidence, units of analysis, and the pace of eco-efficiency. *Organization & Environment,* 16**,** 273-288.

3 CHAPTER THREE: LEAPFROGGING TO RENEWABLE ENERGY: THE OPPORTUNITY FOR UNMET ELECTRICITY MARKETS[2]

3.1 CHAPTER OVERVIEW

This chapter answers the second research objective: to investigate leapfrogging to renewable energy as an opportunity for accelerating electricity access in unmet markets. It discusses the different types, drivers, and paradigms of leapfrogging. A journal article published in the South African Journal of Industrial Engineering titled: '*Leapfrogging to renewable energy: the opportunity for unmet electricity markets'* was based on this chapter, which assesses how unmet electricity markets in Africa can leapfrog from traditional energy to renewable energy without passing through the conventional energy stage.

Abstract

Electricity plays a crucial role in the socio-economic development of any country. However, over one billion people, mainly located in Africa, lack access to electricity. The vastly unmet electricity markets in Africa accentuate the limited energy infrastructure currently available in the sub-region. The objective of the chapter is to identify the potential trajectories for unmet electricity markets in Africa to leapfrog directly to renewable energy as they strive to accelerate electricity access. This objective was achieved through an in-depth literature review on technology leapfrogging, to establish the potential and opportunities for a rapid transition in energy. From the review, the key drivers of renewable energy leapfrogging in unmet electricity markets were identified as follows: the need to achieve sustainability targets, the availability of renewable energy resources on the scale of sufficiency, growing investment in renewable energy, a maturing niche for renewable technologies, a weakening renewable energy cost hypothesis, and growing population and urbanisation. The chapter further reports on the conceptualisation of three potential transition paradigms, namely; Revolutionary*, Scattered, and Coned* pathways. These paradigms were defined by the pace and magnitude of transition that can be observed, and depend on the intensity of the identified drivers in any specific unmet

---

[2] BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., 2017. Leapfrogging to renewable energy: the opportunity for unmet electricity markets. *The South African Journal of Industrial Engineering*, *28*(4), pp.32-49.

electricity market. In the chapter, it was argued that the unmet electricity markets in Africa provide an opportunity for leapfrogging over and beyond the fossil-intensive energy regime, to a renewable energy regime.

Keywords: *Leapfrogging; Renewable energy; Unmet electricity markets; Sustainable development.*

3.2 INTRODUCTION

Globally, society is increasingly energy-reliant, resulting in fast-paced energy demands, especially in the form of electricity. Electricity is essential for providing most daily energy services such as cooking, heating, lighting, cooling, and for powering electric devices. Since 2000 however, the number of people without access to electricity in Africa has increased by approximately 200 million (IEA, 2014a) due to, among other things, a growing population and rapid urbanisation. This has resulted in Africa being the most electricity-deprived region in the world. In recognition of the intensifying energy problem, the United Nations pursues universal access to modern energy by 2030 as one of the sustainable development goals (SDGs) (UN, 2015a). Energy has, therefore, become a topical subject in recent discourse, appearing in the spotlight of both academic and non-academic research, given the varied services provided through electricity (Shyu, 2014; Scott, 2015; Abdul-Salam and Phimister, 2016; Corrêa da Silva, de Marchi Neto and Silva Seifert, 2016; Kitzing, Katz, Schröder, Morthorst and Møller Andersen, 2016; Panos, Densing and Volkart, 2016).

As part of the efforts to expand and decentralise electricity access, a growing body of research on energy transition (Fouquet, 2010; Geels, 2002; Grubler, 2012; Kemp, Rotmans and Loorbach, 2007; Sovacool, 2016b), has emerged. A transition to renewable energy, especially, is gaining momentum as a conduit to universal energy access for all. Furthermore, leapfrogging to renewable energy is considered a potential route to achieving energy security (Burlamaqui and Kattel, 2016; Amankwah-Amoah, 2015; Schroeder and Chapman, 2014; Szabó, Bódis, Huld and Moner-Girona, 2013; Binz, Truffer, Li, Shi and Lu, 2012; Goldemberg, 2011; Zerriffi and Wilson, 2010). Considering the long-term benefits of generating electricity from renewable sources, some developed countries are effectively harnessing their renewable energy resources for electricity services. As an illustration, about 95% of Norway's electricity is generated through hydropower (García-Gusano, Iribarren, Martín-Gamboa, Dufour, Espegren and Lind, 2016); Denmark is one of the leading countries with wind-generated power (REN21, 2014); and Germany has significantly increased its solar power (REN21, 2014), notwithstanding the country's limited solar resources. This, however, is not the case with developing countries, especially in Africa where the potential of renewable energy resources, such as solar, hydro, wind, geothermal, and biomass, is high.

There are different factors driving energy transitions; these include, inter alia, environmental protection, energy security, and health hazards. However, when it comes to a renewable energy transition, contextual limitations and opportunities play a key role. For instance, the transition that occurred in Germany, following the decommissioning of nuclear plants and the growth in solar PV from less than one gigawatt (1 GW) to twenty-four gigawatts (24 GW) between 2004 and 2014 (Morris and Pehnt, 2012), is not comparable with a transition to renewable energy for electricity production in Africa. Prior to the nuclear decommissioning and introduction of solar PV, Germany already had a 100% electricity access rate. It therefore took almost a decade to expand the country's solar capacity, given the low sense of urgency. Similarly, other countries that are leading in renewable energy technology developments, such as Denmark, the Netherlands, Italy, Japan, and United States, have 100% electricity access rates. Their transition motives differ from those of Africa, where more than half the population do not have access to electricity (Scott, 2015).

Developing countries, unlike their developed counterparts, neither have fully satisfied electricity markets, nor 'laden' with large-scale infrastructure that could act as inertia to transition. There is therefore a higher sense of urgency to build electricity infrastructure in developing countries. These contextual differences make the potential of renewable energy leapfrogging in Africa more compelling. This study investigates the potential drivers, and examines the possible trajectories of leapfrogging in unmet electricity markets. This investigation was achieved through a process of literature review and context analysis. The study contends that leapfrogging to renewable energy is an opportunity to accelerate electricity access in unmet markets, particularly in Africa.

The rest of the chapter is organised as follows: First, an overview is presented of Africa as an unmet electricity market. The section magnifies the limited nature of electricity access on the continent. The next section discusses the concept of leapfrogging as a form of transition, followed by the different types of leapfrogging. The potential for leapfrogging to renewable energy in unmet electricity markets is then assessed, highlighting the key drivers of leapfrogging. The ensuing section presents conceptualised leapfrogging paradigms, and discusses the potential pathways of leapfrogging to renewable energy. Finally, conclusions are drawn from insights on leapfrogging in unmet electricity markets and opportunities for the implementation of rapid electricity access in Africa are presented.

3.3 UNMET ELECTRICITY MARKETS IN AFRICA

In Africa, a lack of access to energy is an endemic problem, causing firms and households to resort to self-owned means of meeting their energy needs for basic services. About 6% of power generation capacity in sub-Saharan Africa originates from own generation, while in lower-income countries, and the western part of the continent, this number is almost doubled (Steinbuks and Foster, 2010). This is irrespective of the fact that such self-generated power costs more than the supply from national power systems (Steinbuks and Foster, 2010). (Steinbuks and Foster) conclude that the drive for a firm to own a power generation plants stem from the unreliability of the national power system, the size of the firm, the sector or industry within which the firm operates, and the firm's tendency to export. Self-generation, especially through fossil fuels is, however, unsustainable as a long-term substitute as it increases overheads and undermines return on investment.

Energy access describes an individual, household, or entity's initial supply connection, with a power consumption that then rises gradually to that of a regional average (IEA, 2011). The UN Secretary General's Advisory Group on Energy and Climate Change (AGECC, 2010) defines energy access as '*a basic minimum threshold of modern energy services for both consumption and productive uses. Access to these modern energy services must be reliable and affordable, sustainable and, where feasible, from low greenhouse gas emitting energy sources*'. The Asian Development Bank (ADB, 2010) observes that energy access includes making electricity available to households, the improved supply and delivery of energy services, modern fuels and/or heating, and finance in order to access energy.

There is no standard definition of an unmet electricity market. This study defines an unmet electricity market considering the characteristics of modern energy access, namely that energy should be accessible to a basic minimum threshold, affordable, reliable, sustainable, and environmentally friendly. Following these features, a definition of an unmet electricity market is derived from the United Nation's Advisory Group on Energy and Climate Change (AGECC, 2010). The AGECC define a lack of energy access as applicable to people who do not have access to any, not even the basic minimum threshold of affordable, reliable, sustainable, and environmentally-friendly modern energy services for consumption and production activities. Unmet electricity market in this chapter refers to the number or proportion of households, as well as commercial, and industrial electricity demand that remains unsatisfied. It includes those that are connected to some form of grid but do not have a reliable supply. Reliability, in this context, refers to a consistent and uninterrupted supply of electricity for at least five out of the seven days in a week. This definition is important, in order to recognise households that may be connected to a grid of some sort but do not get electricity. A connection to a power grid therefore does not equal electricity access, since power outages are a relatively frequent occurrence in Africa (Scott, 2015).

The UN's Sustainable Energy for All (SE4ALL) goal of ensuring universal access to energy by 2030 would be unrealisable should the current trend of investment persist. It is estimated that some 600 million people in Africa alone would still live without electricity access by 2030, if the current business-as-usual scenario continues (Scott, 2015). This is consistent with observation by Eberhard, Foster, Briceño-Garmendia, Ouedraogo, Camos and Shkaratan (2008) less than a decade ago, that sub-Saharan Africa is in a power crisis. The fact that many households are neither connected to the national power grid, nor has access to off-grid power, highlights the electricity problem in Africa. The inefficiencies in Africa's electricity system are also evident even among those connected to the grid, who still experience rampant power outages (Scott, 2015). The economic implication of this unreliable electricity supply is estimated to account for a 2% decline in GDP, and as a result, productivity and output levels fall (Scott, 2015). The Africa Progress Panel (2015) estimates the power outages to result in a 2%-4% GDP decline. This is consistent with the earlier conclusions by Andersen and Dalgaard (2013), that every percentage increase in power outage causes GDP per capita to decline by 2.86% in the long-run.

The extent of Africa's electricity deficit is demonstrated in Figure 3.1, where the highlighted depth of colour on the map, from light blue to deep blue, reveals the intensity of energy inadequacy, while the number in the yellow boxes depict the size of the population, in millions, who do not have access to electricity. Ghana, for example, remains one of the countries in

Africa where a significant number of people, approximately four million, are still not connected to national, regional, or local electricity grids. Data from International Energy Agency (IEA) and Bank (2017) highlights Africa's low electricity access with countries such as Chad, Malawi, Burundi, the Central African Republic, Democratic Republic of Congo, and Sierra Leone, less than 20% of the entire population as having access to electricity.

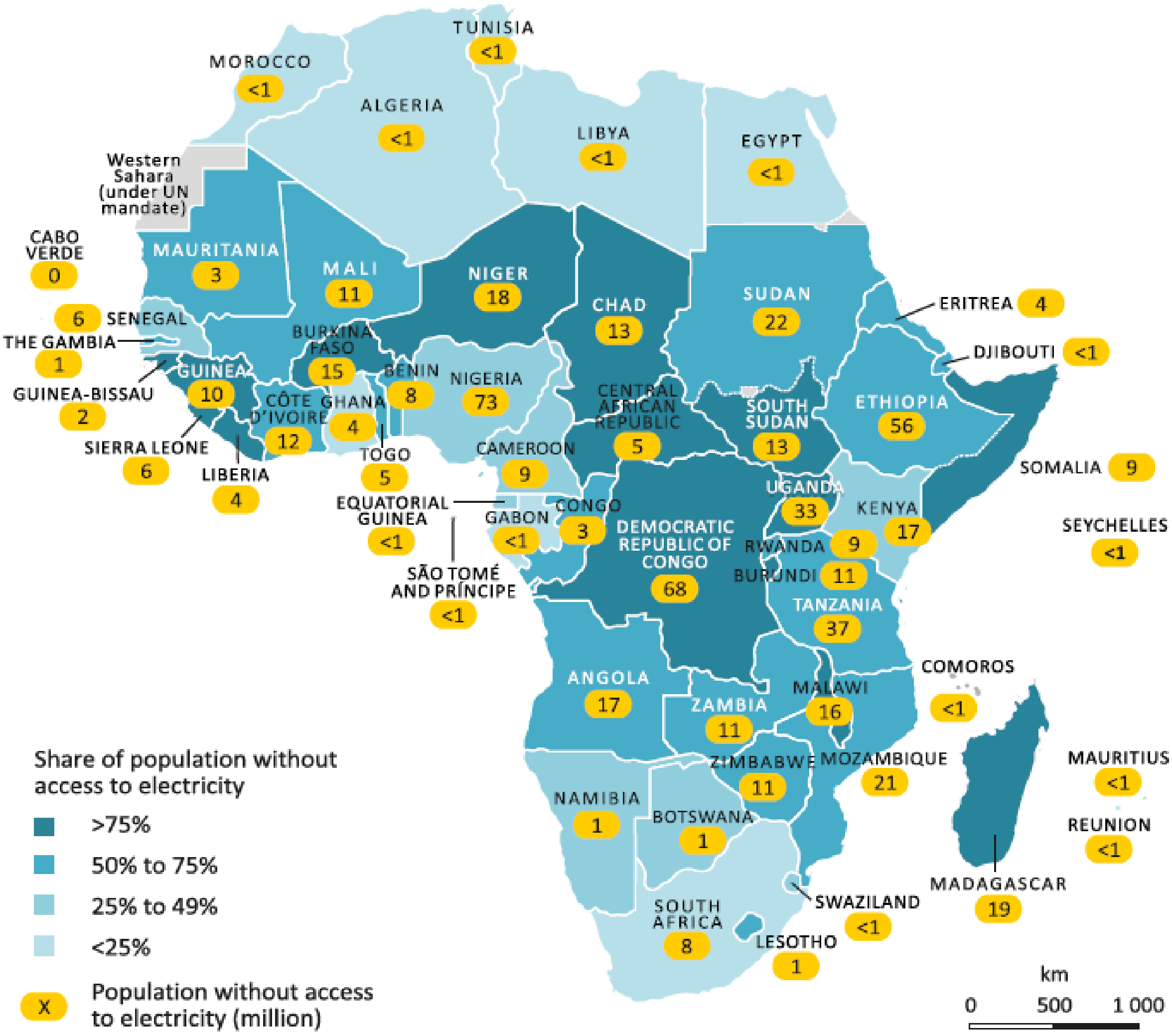


Figure 3.1: Electricity access in Africa – 2016

Source: (IEA, 2017)

The UN's Sustainable Energy for All (SE4ALL) goal of ensuring universal access to energy by 2030 would be unrealisable should the current trend of investment persist. It is estimated that some 600 million people in Africa alone would still live without electricity access by 2030, if the current business-as-usual scenario continues (Scott, 2015). This is consistent with observation by Eberhard, Foster, Briceño-Garmendia, Ouedraogo, Camos and Shkaratan (2008) less than a decade ago, that sub-Saharan Africa is in a power crisis. The fact that many households are neither connected to the national power grid, nor has access to off-grid power, highlights the electricity problem in Africa. The inefficiencies in Africa's electricity system are also evident even among those connected to the grid, who still experience rampant power outages (Scott, 2015). The economic implication of this unreliable electricity supply is estimated to account for a 2% decline in GDP, and as a result, productivity and output levels fall (Scott, 2015). The Africa Progress Panel (2015) estimates the power outages to result in a 2%-4% GDP decline. This is consistent with the earlier conclusions by Andersen and Dalgaard (2013), that every percentage increase in power outage causes GDP per capita to decline by 2.86% in the long-run.

The lingering electricity problem in Africa appears immune to the mediations implemented so far. This persistent undersupply of electricity is largely attributable to the limited financial resources allocated to the sector. Indeed, energy is a capital-intensive investment (Sovacool, 2013). Castellano, Kendall, Nikomarov and Swemmer (2015) estimate that USD835 billion would be required to ensure electricity access to all in Africa. Other studies (Bazilian, Nussbaumer, Rogner, Brew-Hammond, Foster, Pachauri, Williams, Howells, Niyongabo and Musaba, 2012; IEA, 2014b) estimate that a total investment in excess of USD800 billion is needed to attain universal electrification by 2030, without factoring in the financial requirements for the operation and maintenance of the existing electricity systems. It is clear that the current annual investment of USD8 billion in electricity across Africa is certainly inadequate to support the power generation requirements needed to address the growing electricity demand (Scott, 2015). An annual investment of USD45 billion would be needed to ensure universal access to modern energy by 2030 (IEA, 2011), and USD46 billion by 2040 (IEA, 2014a).

Szabó et al. (2013) observed that a conventional large-scale centralised power infrastructure with grid extension system has been unsuccessful in Africa. Reliance only on grid extension would not be sufficient to attain the universal electrification target by 2030 (Bhattacharyya and Palit, 2016). The scale and infrastructural requirements of the conventional energy system involves longer installation time and stretches the limited financial capacity of developing countries. In areas where the system is installed, challenges such as inadequate transmission capacity, and frequent breaks in transmission are experienced, resulting in significant difference between a plant's installed capacity and its productivity. The idea of investing in distributed off-grid electricity systems in Africa is thus relevant for two main reasons: firstly, there is excessive stress on the national transmission lines, which carry power for distribution over long distance. Secondly, the continent is characterised by countries with sparsely populated rural settlements, which makes distributed power generation, compared to a centralised generation system, more efficient (Szabó et al., 2013).

In Africa, fossil energy constitutes a large portion of the source of fuel for electricity systems, although vast opportunities exist for the generation of electricity from renewable and sustainable sources. According to Scott (2015), a total of 85% of Africa's electricity was generated through fossil fuels in 2012. In sub-Saharan Africa it is projected that, under a business as usual scenario, 81 gigawatts (GW) of power will be added by 2040, mainly from fossil fuels (Scott, 2015). The goal of universal access to modern energy in Africa thus appears challenging.

3.4 LEAPFROGGING AS A FORM OF TRANSITION

The concept of leapfrogging is gaining popularity in the transition discourse, especially in the sustainable energy arena. The concept is not novel in academic literature (Gallagher, 2006; Goldemberg, 1998; Lee and Lim, 2001; Murphy, 2001; Perkins, 2003; Szabó et al., 2013). It emerged as the rate of invention of new technologies increased and the potential to transition from one product or service to another became greater. As a result, the possibility for some consumers to entirely skip a 'generation' of technologies to novel and modern ones (Goldemberg, 1998) emerges. Leapfrogging is generally defined as a development strategy whereby industrialising nations skip conventional economic growth stages, by adopting contemporary resource–efficient technologies in order to reduce post-consumption repercussions, such as pollution (Perkins, 2003). Leapfrogging, according to Lee and Lim (2001) is a form of catching-up with contemporary technology. Hobday (1995) refers to leapfrogging as the situation where users of a vintage form of a given technology skip the current dominant form of that technology, and the excessive investment requirements, and go directly to its modern form. A common example of leapfrogging technology is telecommunication devices. Most developing countries leapfrogged to mobile telephones without completely accessing the line telephone system, which was the dominant form of virtual communication (Mu and Lee, 2005).

There are different opinions on the capacity of countries to leapfrog regime technologies. In the case of international leapfrogging, for example, Tukker (2005) and Gallagher (2006) surmised that new adopters, such as developing countries, often rely upon their developed counterparts for new energy solutions, until domestic capabilities become adequate to produce and integrate advanced energy technologies. Gallagher (2006) further argues that, due to the limited technological capabilities for complex innovations in large-scale socio-technical systems, energy technology leapfrogging in developing countries is challenged by policy inconsistency, unwillingness of developed countries to transition, and limited domestic capabilities. Contrary to the observation of Gallagher (2006), Lee and Lim (2001) posit that late adopters of a technology do not simply follow the path of technological development of the pioneers, but may entirely skip some stages of an emerging technology and create paths to improve upon it. Developing countries, by nature of their small-sized infrastructure, can easily adopt new and/or emerging energy technologies that are more advanced, hence evading the resource-intensive path of conventional energy development that developed countries have experienced (Goldemberg, 1998).

The success of energy technology leapfrogging could originate from the global interest in reducing emissions, and the growing pressure from the socio-technical landscape entities (IEA, 2015; UN, 2015). The pursuit of renewable energy quotas in the total energy mix, as part of the Sustainable Development Goals (ICSU and ISSC, 2015), could potentially drive successful leapfrogging in energy technology. Every economy can be regarded a beginner in the emerging techno-economic paradigm and, hence, has the potential to leapfrog (Perez, 1988). The national, regional, and sectoral innovation systems are grounds of support to this observation (Carlsson, 2003).

3.4.1 Types of leapfrogging

Lee and Lim (2001) identify three forms of leapfrogging, namely: path skipping, path creating, and path following. Gallagher (2006) has a different view and only considers the first two forms as leapfrogging, and regards path following as a gradual form of transitioning. Given that a key characteristic in the definition of leapfrogging is rapid transition, and skipping stages of conventional practice or technology, this study takes a similar view to that of Lee and Lim (2001) and regards all three forms as leapfrogging. The following of conventional pathways may be brief, and adopting new technology within short timeframes qualifies as a form of leapfrogging. Each of the three forms of leapfrogging is depicted in Figure 3.2 and further elaborated on in the sub-sections that follow.

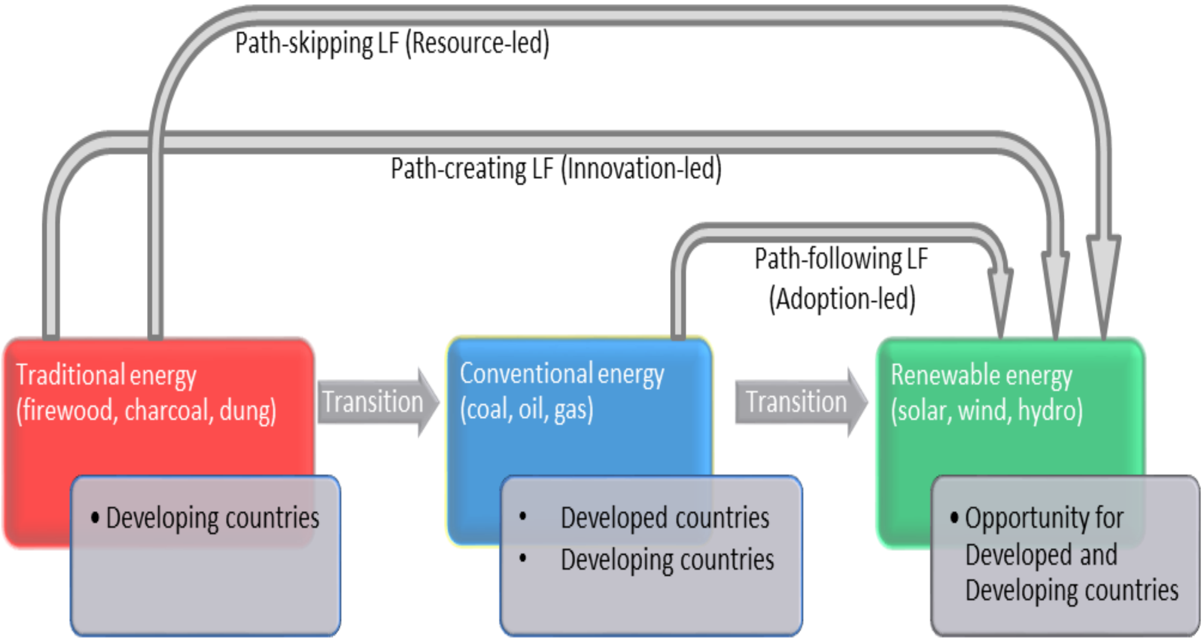


Figure 3.2: Types of Leapfrogging

3.4.1.1 Path Skipping

Path skipping is the quintessential form of leapfrogging - skipping over generations of technology. Since Africa has a low electricity access rate, and a large unmet electricity market, immediately introducing renewable energy technologies such as solar photovoltaic, wind, and hydro, which would result in skipping the conventional fossil fuels for the provision of electricity, would constitute technological leapfrogging described by Lee and Lim (2001) as path skipping, and by Gallagher (2006) as skipping over generations of technology. Another example, as stated earlier, is the adoption of mobile phones (wireless) in Africa, without first going through the conventional landline (wired) regime. In the energy sector, this type of leapfrogging involves jumping to renewable energy without experiencing the dominant energy source regime, which is fossil energy. It could also be perceived as skipping the dominant mode of delivering electricity from centralised grid transmission and distribution, to decentralised mini-grids and stand-alone electricity systems. The path skipping method of leapfrogging can be perceived as a resource-led leapfrogging, because a country that is endowed with the resources for modern technology can easily skip conventional technology based on such an advantage as resource accessibility.

3.4.1.2 Path creating

Path creating as a form of leapfrogging implies that late-adopters explore their own path of technology development by creating a new path, after they have been following the path of the initial adopters (Lee and Lim, 2001). This type of leapfrogging is characterised by skipping over a generation of technologies and, consequently, leading in the production, adoption, or utilisation of such technology (Gallagher, 2006). An example is the emergence of the Korean steel industry, which leapfrogged, and overtook leading steel producers, to become the industry leader (Gallagher, 2006). In the energy sector, this leapfrogging would include advancing to become the leader in renewable energy technology. For instance, if Africa commits to, and succeeds in, fulfilling universal energy access by providing the excess market demand with renewable energy, the continent would become the leader in renewable energy access by share to total demand. This would fulfil the second definition of leapfrogging by Gallagher (2006). With the Path creating, a nation's ability to innovate quickly and more efficiently can propel it to become a market leader in a given technology.

3.4.1.3 Path following

Path following is a traditional form of change, whereby late adopters of a technology follow the same path as the forerunners, but in a shorter time (Lee and Lim, 2001). This is usually because the adopter's technology is out-dated, hence the need to transition to a 'new conventional' technology. Because late-adopters use the technology for a brief period before moving on to the next conventional technology, their transition is regarded as a slow or weak form of leapfrogging. Path following is a weak form of leapfrogging because the user may not necessarily champion innovation, or be the most endowed with the resources for the technology, but they leapfrog to the latest technology for reasons such as quick diffusion, and therefore use the existing technology for a shorter time before transitioning.

3.4.2 Differentiating leapfrogging from technical change

Leapfrogging is not the same as technical change, even if the outcome is similar. In the energy sector, for example, not every sustainable clean energy transition is regarded as leapfrogging. The act of encouraging the use of sustainably clean technologies that do not require a skip in generation of conventional technologies is therefore not considered leapfrogging (Gallagher, 2006). The act of government policy to encourage consumers to choose the most efficient, available, and affordable fuel alternative among the existing conventional fuel types is a form of technical change, and not leapfrogging. For example, petroleum and natural gas are both contemporary fossil fuel types. If a national policy results in the migration from one to the other, it is considered a transition or technical change, because both are conventional energy, and there is no leap in generations of regime technologies.

National policy, however, can be an impetus for leapfrogging. An example is the case of Brazil, where the state stimulated the adoption of ethanol-fuelled vehicles by introducing disincentives for conventional gasoline-fuelled vehicles. This is considered leapfrogging, because ethanol fuelled vehicles were a new and emerging technology introduced into a market dominated by conventional gasoline-fuelled automobiles (Goldemberg, 1998). Leapfrogging can also differ in context of country and industry (Lee and Lim, 2001). For example, while Goldemberg (1998) considers the ethanol-fuelled vehicles in Brazil as a form of leapfrogging, Gallagher (2006) questions the effectiveness of the adoption of ethanol-fuelled automobiles in China.

3.5 LEAPFROGGING UNMET ELECTRICITY MARKETS TO RENEWABLE ENERGY

Universal access to modern energy in Africa is not an easy goal, considering current trends. The demand for energy services in the form of electricity for household and commercial purposes has never been resolved across the continent (Bastakoti, 2003; IEA, 2009; IEA, 2011). Studies forecasting electricity access for the next two decades (IEA, 2011; Scott, 2015) suggest that the current trend of development in electricity system would not lead to sustainable electricity access. Although the total installed power capacity is expected to increase significantly, especially in developing countries, the population growth in these areas would offset the additional capacity and intensify energy insecurity.

Notwithstanding the present gloomy electricity environment in Africa, there are opportunities for a brighter future and more sufficient power. Renewable energy innovation is fast growing, offering energy alternatives to developing countries that would allow them to speed up electricity access. Various key driving factors makes it possible to leapfrog the conventional energy, to renewable energy for the purposes of electricity generation, in the context of an unmet electricity market. These factors includes: the global goals of a sustainable energy future and universal electricity access, the abundance of renewable energy resources, especially in Africa, the financial commitment to invest in renewable energy, the growing renewable energy technology, the declining cost of renewables, and rapid urbanisation and population growth. These drivers are depicted in Figure 3.3.

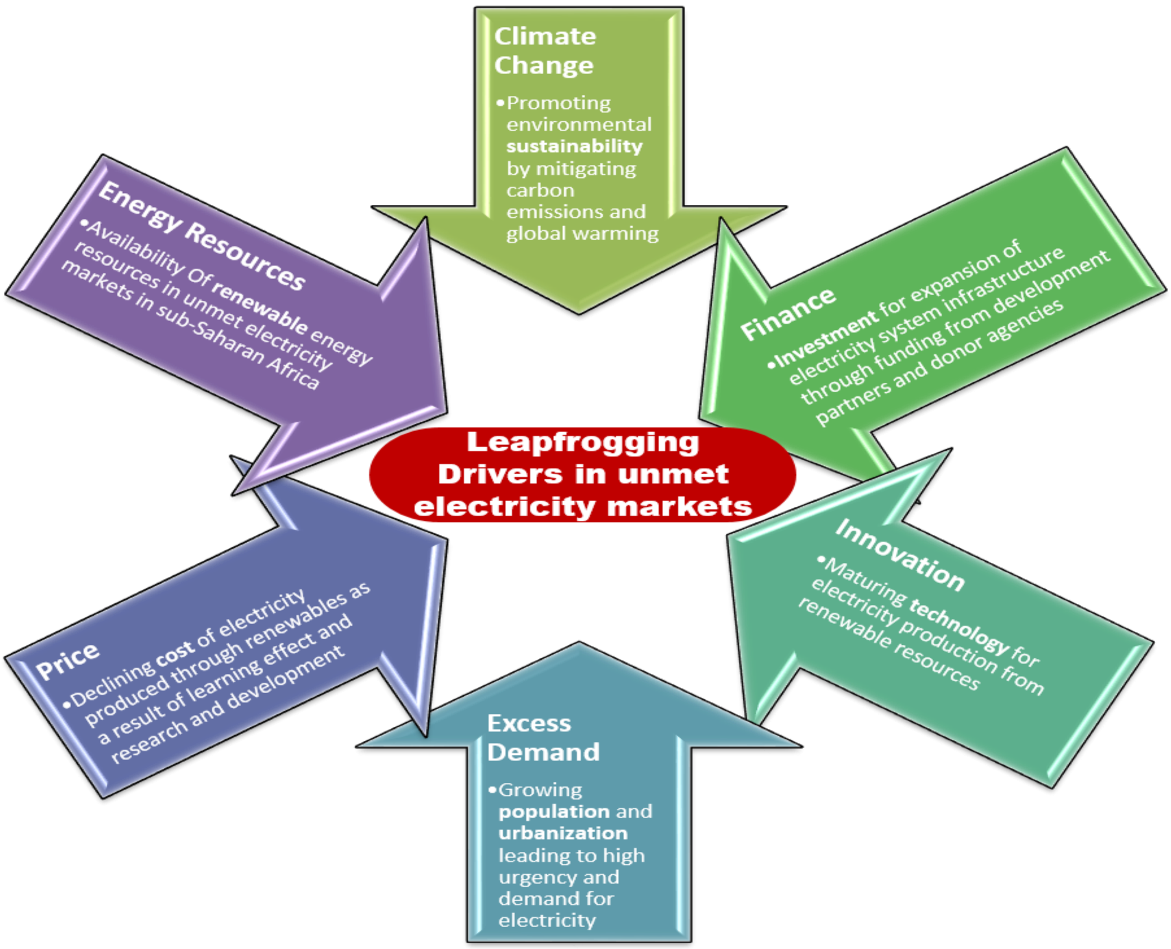


Figure 3.3: Leapfrogging Drivers in unmet electricity markets

The key drivers of leapfrogging conventional energy from traditional energy to renewable energy, in the context of unmet electricity markets, especially in Africa, are summarised in

Figure 3.3. While these factors are essential, and boost the potential for leapfrogging to occur in an unmet electricity market context, they do not represent an exhaustive list of the potential drivers for such a transition. Only some of these drivers may be identified when further categorising unmet electricity markets into sub-units and niches. Though these factors would potentially become an impetus for leapfrogging in unmet electricity markets, they are not peculiar to satisfied markets. Driving factors such as climate change and innovation, for example, will most likely also be found in fully satisfied markets. Excess demand and renewable energy resources, however, are highly common drivers in unmet electricity markets in Africa.

3.5.1 Sustainable energy goals and targets

The transition from traditional biomass to coal, and eventually to oil, accelerated in the mid twentieth century. This transition propelled the new industrial revolution, which saw many presently developed countries placed on the road to rapid growth and innovation. Obviously, the era of the new industrial revolution created a competitive global market of national traders whose major trade commodity was determined by comparative and absolute cost advantages. Transition to renewable energy in the twenty-first century, however, seems to be pursued as global co-operative objective where sustainable energy initiatives are extensively promoted at international level. This is evident in the United Nation's treaties, namely the Framework Convention on Climate Change (UNFCCC, 1992), the Kyoto Protocol (UN, 1998), the Copenhagen Accord (2009), the Cancun Agreement (UN, 2011) and the recent Paris Agreement (UN, 2015). The active role of the international community in championing a globally sustainable energy environment can be attributed to, among other things, the burgeoning benefits of renewable energy and the adverse consequences (e.g. health and climate change) of fossil fuels. An estimated 4.3 million people died from exposure to polluted air in household environments in 2012, with most of this number recorded in developing countries (WHO, 2014). The presence of international organisations such as the United Nations and the World Bank, and the extensive number of national bodies and initiatives advocating transition to sustainable energy is a major incentive for developing countries to leapfrog to renewable energy. The broad stakeholder spectrum in the global sustainability agenda has motivated many countries, including those in Africa, to set renewable energy targets in their overall energy development plans. This is a clear sign that, despite the limitations that may hinder the competitiveness of renewable energy, a growing opportunity for leapfrogging is apparent, and is being sustainably driven.

3.5.2 Available renewable energy resources and scale sufficiency

Besides the technological and innovative constraints of renewable energy transition emphasised in literature (Smil, 2010), there is also the issue of limited availability of renewable energy resources and the unpredictability of weather conditions (Smil, 2010). The viability of the argument pertaining to weather predictability is, however, constantly diminishing, due to rapid advancements in technology capable of adjusting to weather variations and performing other complex tasks such as the tracking of sunrays, in the case of solar technology. In addition, there is limited variation in seasonality across the African continent, hence fewer seasonal challenges to renewable energy. Most of the continent, by nature of its geographical position, records sunshine on most days annually, averaging 325 days in a year (KPMG, 2015). Africa, compared to most part of the global North, is thus favourably positioned for renewable energy, especially electricity production, with abundant resources and opportunities in solar, wind, hydro, biomass, and geothermal energy (Asami and Nawfal, 2015). According to Asami and Nawfal (2015), while the total installed power capacity in 2014 was 150 gigawatts, solar PV and wind potential in the continent is 300,000 gigawatts and 250,000 gigawatts respectively, a clear depiction of resource abundance.

Renewable energy technology is also scale efficient, even when installed in smaller units. New technology that offers higher economies of scale reduces leapfrogging tendencies (Mody and Sherman, 1990). Mature networks, which are common in developed countries, constrain the potential for leapfrogging due to the inertia created by investment sunk in conventional infrastructure (Mody and Sherman, 1990). Strangely, (Mody and Sherman) also found that leapfrogging to electronic technologies was absent in countries with low network maturity. They concluded that the scale of investment required to leapfrog is far greater than the capabilities of developing countries. The findings of Mody and Sherman (1990) do not, however, annul the argument of leapfrogging potential in developing countries, for the following reasons: the type of technology studied (telephone) differs from other technologies (e.g. energy) in both scale and functionality, and the context, time and location, is different. The contention that there is higher leapfrogging potential in developing countries is evident in the penetration of mobile money services, which is a mobile phone-based financial service without a bank account. As of 2015, sub-Saharan Africa accounts for 52% of active mobile money services (GSMA, 2015) globally. Unlike the fossil energy alternatives, whose return on investment increases with economies of scale, maximizing investment returns on renewable energy is not heavily dependent on economies of scale. Wind, solar, and mini-hydro opportunities scattered across Africa therefore increase the chances of leapfrogging to renewable energy in the region, since installing them in smaller units does not sufficiently diminish their returns, as it would with fossil alternatives.

3.5.3 Growing investment in renewable energy

As part of initiatives to alleviate energy poverty in Africa, some regional blocs on the continent are promoting regional integration through energy trading to expand electricity generation. The initiatives, which constitute regional blocs of power markets, include: Southern Africa Power Pool (SAPP); Eastern Africa Power Pool (EAPP); Central Africa Power Pool (CAPP) and Western Africa Power Pool (WAPP) (Gnansounou, Bayem, Bednyagin and Dong, 2007). In addition, governmental development agencies from developed countries, as well as other international bodies, are investing in the African energy sector, and significant donations are specifically earmarked for renewable energy expansion in the region. Some of these financial initiatives are listed in Table 3.1.

Table 3.1: Funding initiatives alleviating renewable energy investment challenges

Project	Goal and Description
Power Africa Initiative - Electrify Africa Act, 2015 - (United States Government)	The project`s goal is to improve access to affordable and reliable electricity in sub-Saharan Africa. It also aims to provide power services for 50 million rural and urban dwellers by 2020 through the installation of 30,000 megawatts of clean energy generation.
Energy Africa Campaign (United Kingdom´s Department for International Development)	Started in 2015 and centred on energy access for rural communities that are not connected to the national grid, it invests in off-grid energy firms and helps them overcome regulatory barriers, foster innovation and deliver solar energy systems to promote universal access to energy by 2030.
New Deal for Energy in Africa (African Development Bank)	A decade-long project launched in 2015 to promote universal access to energy in Africa by 2025. It also engages in providing technical assistance for energy utility restructuring, de-risking and making funds accessible for energy projects, boosting regional interconnections, and advising on efficient energy sector regulation.
Electrification Financing Initiative (European Union)	This project is set to launch in 2016 to boost off-grid energy access for rural sub-Saharan African communities. It serves as a financing conduit for market

	development and private sector initiatives to promote sustainable energy solutions across the region.
Sustainable Energy Fund for Africa	The project supports small and medium-scale renewable energy and energy efficient projects in Africa.
Africa-EU Renewable Energy Cooperation Programme (RECP)	The programme goal is to increase renewable energy use and access to modern energy for about 100 million people by 2020. It also supports Africa with policy advice, private sector co-operation, capacity development, etc.
African Renewable Energy Fund (AREF)	This is a private equity fund investing in small and medium-scale renewable energy projects in Africa. It also assists governments in meeting their renewable energy and carbon emission targets.
Capital Access for Renewable Energy Enterprises Programme (CARE2)	A financing programme that aims to expand renewable energy markets in selected African countries by augmenting capital to businesses. It is supported by the Swedish International Development Cooperation Agency.
ACP-EU Energy Facility	This is a co-financing instrument for extending sustainable energy access in impoverished rural communities in African.
Sustainable Energy Fund for Africa (SEFA)	A Danish government commitment administered by the African Development Bank to support small- and medium-scale clean energy and energy efficiency projects in Africa through grants for technical assistance and capacity building, investment capital, and guidance.

Sources: Mendoza (2016); REN21 (2014)

Other funding initiatives for clean and sustainable energy access in Africa include the EU-Africa Infrastructure Trust Fund (ITF), Energy, Eco development and Resilience in Africa (EERA), the African Energy Leaders Group, the African Renewable Energy Alliance (AREA), and Lighting Africa. These projects create multi-stakeholder platforms for information exchange on policies, regulatory frameworks, and financial tools to facilitate renewable energy technology development, its adoption, and expansion in Africa.

3.5.4 Maturing niche renewable technologies

The pattern of development of a new technology from inception to extinction differs, depending on various factors affecting it at different stages of its lifespan. These factors include the unique consumer need it serves, the cost involved, relative benefits of consuming an alternative, and the satisfaction it provides relative to other prevailing technologies (Grubler, 2012). These factors not only determine how quickly the technology is accepted among consumers, but also how long it remains relevant to them. New technology is more likely to scale up faster if it offers better performance and efficiency, and is more affordable than the incumbent technology. Late adopters can transition easily and faster to such novel technology due to the experiences of early adopters and the declining cost, based on technology improvement (Wilson, 2009). The rapid adoption of mobile phones in Africa is an embodiment of the rapid transition route for late adopters. Developing countries in Africa can replicate the fast transition experienced in mobile telecommunication within its energy and electricity generation sector, through accepting renewables, as niches gain growth momentum. Fast transition for late adopters is observed across industries; in the transport sector literature (Grubler, 2012) and the supply end-use technologies sector (Wilson, 2012). In a market where there is an existing niche segment, as is the case with renewables in Africa, it could offer new technologies an opportunity to test their viability. Further ground for scaling up to new technology is the comparative advantage (Wilson, 2009). The global concern regarding sustainability and the investment initiatives from international agencies encourage advancement of niche energy technologies in developing countries. Kenya, for example, is one of the top five countries globally to have increased geothermal power significantly in 2013 (REN21, 2014). The growing niche technologies in Africa are an indication that the region is poised to leapfrog the present fossil energy regime.

3.5.5 Weakening renewable energy cost hypothesis

It is widely argued that renewables are costly, relative to fossil energy, without factoring in weight of subsidies, context, and technology specifics. To demonstrate an appropriate cost comparison of different energy options, it is important to understand how much households without electricity access presently spend on accessing main energy services. These services include lighting, cooking and water heating, space heating, cooling, communications, and earning a living (Action, 2010). It is also essential that a cost comparison of fossil energy and renewable energy is not simply assessed based on production unit cost, but investigates overall cost elements - Levelised Cost of Electricity (LCOE). A sensitivity analysis by Carbon Tracker (2016) using the Levelised Cost of Electricity suggests that the global average costs of renewable power is lower than that of power generated from fossil fuels, which predicts even more cost-resilient renewable energy plants by 2020. Without factoring in health benefits, energy security cost, environmental cost, and other opportunity costs, Figure 3.4 depicts the consistent decline in solar cost since 1977.

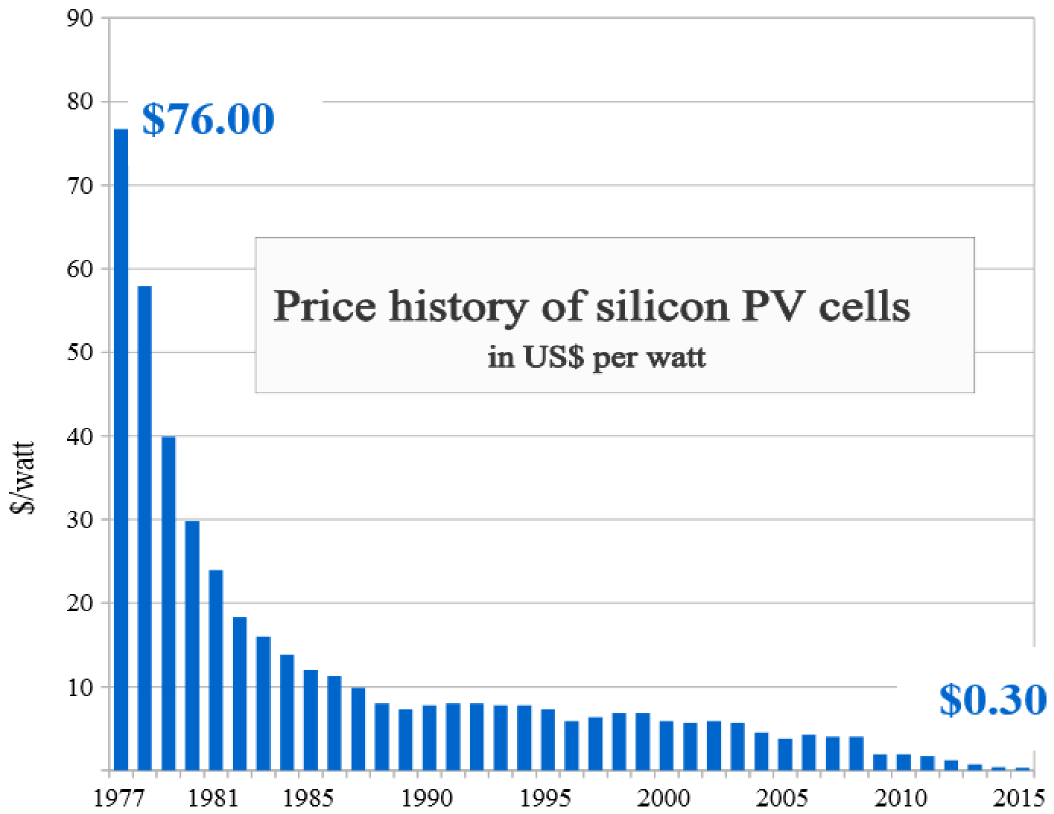


Figure 3.4: Solar Power Cost from 1977 to 2015

(Source: Bloomberg New Energy Finance (2016)

The transmission of electricity from a national grid source to a remote and low-density population settlement might not be justifiable when compared to the provision of stand-alone or mini-grid renewable energy. According to Szabo, Bódis, Huld and Moner-Girona (2011), for the greater portion of rural dwellers who live within 100 kilometres of an existing grid system, solar PV could still prove an economically feasible option, as opposed to grid extension. In their study of two electricity deficit countries, namely Nigeria and Ethiopia, Nerini, Broad, Mentis, Welsch, Bazilian and Howells (2016) concluded that stand-alone and mini-grid systems are cost effective for providing electricity access to the least populated remote areas. To expound on the cost of renewable energy technologies in relation to fossil, it is important to critically assess and analyse the opportunity cost of living without electricity at all, due to inaccessible power supply from the national grid or fossil energy sources, vis-a-vis accessing electricity from the presently 'expensive' renewables, the cost of which is continually declining. Though there is an argument, that renewable energy is expensive, hence possesses little incentive for investors, the evidence to support that claim is little or non-existent when assessed in the context of a market which currently has no electricity while renewable energy opportunities prevail therein. It is even less cogent when one considers the improvement in the quality of life, education, economic opportunities, and usability of modern technologies (e.g. computers instead of typewriters, computers for learning, communication, health programmes, etc.) largely driven by access to electricity. The correlation between electricity access and real per capita Gross Domestic Production (Adom, 2011), economic development (Eshun and Amoako-Tuffour, 2016), and human development index (UNDP, 2015) deepens the relevance of electricity access. It therefore appears that to live without electricity access would cost more compared to using electricity accessed through ‘costly’ renewable sources, as the benefits accrued through access would be forfeited. Despite the emphasis on the distinguishing cost differences and limitations of renewables in relation to fossil energy, which has been the focus of some recent studies such as those of Stram (2016), when accessed on the basis of opportunity cost, provision of electricity via renewable energy is justified.

3.5.6 Growing population and urbanisation

The global population is estimated to almost double by the end of this century (UN, 2015b). Keho (2016) identifies population and urbanisation as one of the key drivers of energy consumption, and, given its relatively higher population growth compared to developed countries, Africa is set to record significant increase in energy and electricity demand. The number of people that would still live without electricity by 2030, under a business as usual scenario, is projected by some scholars to be about 600 million (Scott, 2015) and others project 822 million (Pachauri, Rao, Nagai and Riahi, 2012). With this additional population without access to electricity, coupled with the presently limited fossil energy resources, the need for rapid integration of renewable energy in the total energy mix is compelling. Pessimists regarding renewable energy usually question the efficacy of renewables as a substitute for the present fossil regime because of cost and capacity factors. Amid ever-expanding cities and increasing technological reach around the world, execution of basic services increasingly depends on energy. A growing number of consumer appliances and devices are powered by electricity. To satisfy this increasing need for energy, the exploration and adoption of renewable energy technologies is becoming less of a choice and more of an obligation to meet basic societal needs.

3.6 RECONCEPTUALISING LEAPFROGGING PARADIGMS

A conceptual leapfrogging framework based on the types, and the potential drivers, of leapfrogging can be described. The framework would capture how a typical case of leapfrogging would emerge, depending on the extent to which such potential drivers of leapfrogging are present in the given context. Contextualising a framework for leapfrogging in emerging economies, Binz et al. (2012) observed that there is a need to assess the performance of technological innovation systems based on three main categories. These are; the industrialising country context, the scale of international innovation capacity beyond the contextual scope, and the interplay between the global and contextual dimensions of technological innovation systems. They further highlighted the role of other entities such as universities, research institutes, and other organisations or actors that might influence the effect of global technological innovation systems on local innovation. Binz et al. (2012) also identified six leapfrogging pathways: International competition, global innovation, foreign direct investments, isolated regime formation, export oriented leapfrogging, and low leapfrogging potential. These leapfrogging trajectories, unlike the three types of leapfrogging illustrated in Figure 3.5, outline how innovation develops depending on its point of origin and scope of reach. This categorisation highlights the combination of factors that determine the advancement of a new technology innovation, but does not necessarily describe what leapfrogging entails.

Though the concept of leapfrogging involves a form of change fuelled by innovation, most leapfrogging concepts are mainly focused on technological innovation (Gallagher, 2006; Lee and Lim, 2001; Murphy, 2001; Soete, 1985; Szabó et al., 2013). Technological innovation is a precursor to leapfrogging, but is not the sole determinant. Leapfrogging requires more than the development of a new technology (Murphy, 2001). This implies that the social aspects of change are thus relevant and should be considered in order to leapfrog successfully. In addition, society needs to recognise an added value in the new innovation, relative to the prevailing alternatives (Tigabu, Berkhout and van Beukering, 2015). Transition management is therefore crucial for introducing niche technologies in a market of regime technologies or one lacking them. Innovation and niche development need to be linked with the social context they are intended for, especially when there is a supply push technology. This study conceptualises two major dynamics essential for characterising leapfrogging trajectories in electricity markets.

These are *pace* and *magnitude,* where the *pace* is considered as either fast or slow and the *magnitude* as either large or small. A combination of these descriptions illustrates three paradigms of leapfrogging, namely *Revolutionary, Coned,* and *Scattered*; then a fourth paradigm, considered as conventional Transition, as illustrated in Figure 3.5.

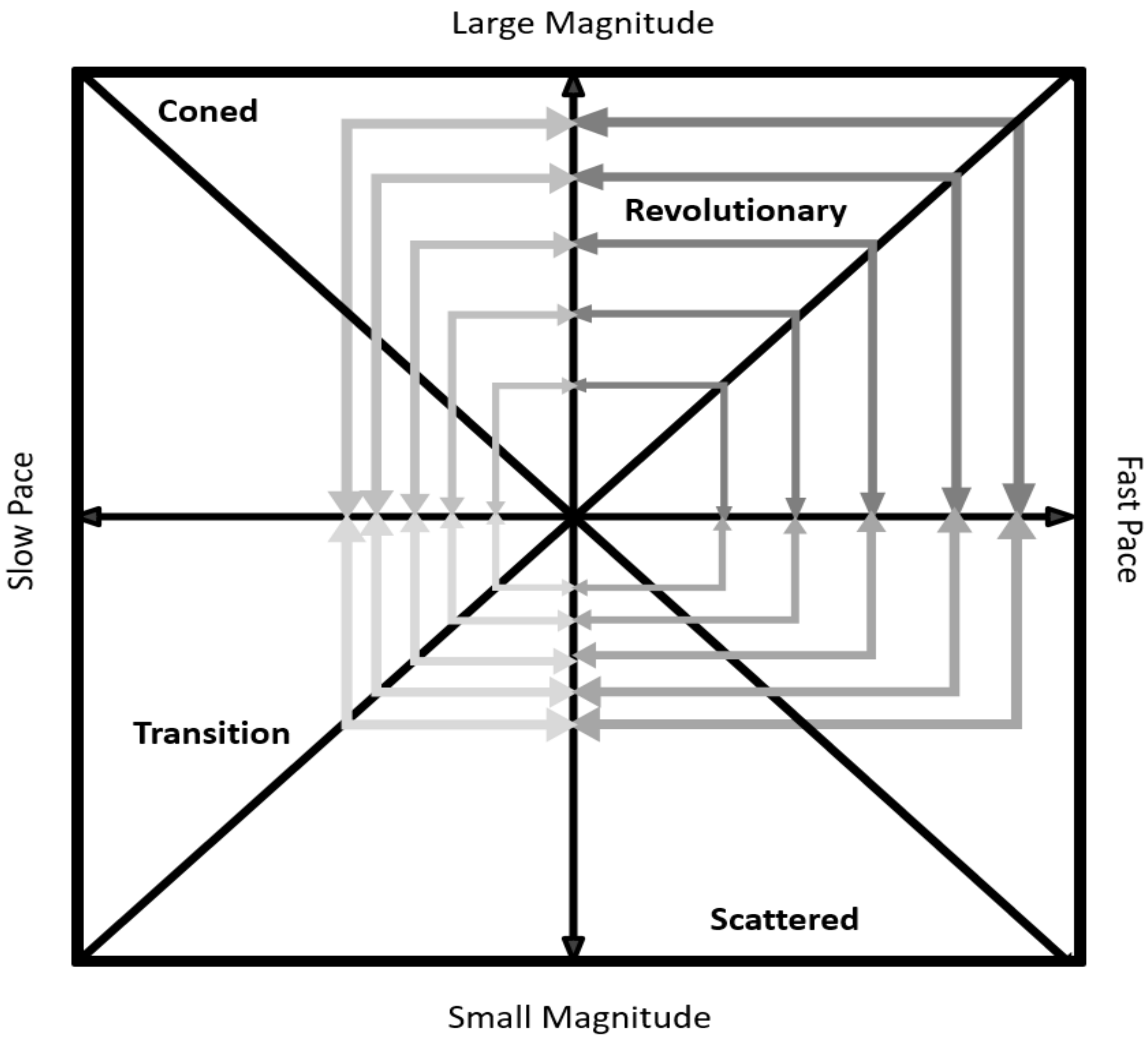


Figure 3.5: Conceptualised leapfrogging trajectories

The conceptualisation of leapfrogging in Figure 3.5 suggests that some essential elements, such as the size and performance of the existing market infrastructure and the unmet market demand, can steer a transition that would seemingly require a longer period, to assume a revolutionary leapfrogging paradigm. Some of these essential elements for leapfrogging are evident in the literature (Levin and Thomas, 2016; Sovacool, 2016a; Szabó et al., 2013). Critical to the success of leapfrogging is the availability of the new technology or resource to provide an improved service bundle. The paradigms of leapfrogging conceptualised are discussed below.

3.6.1 Revolutionary leapfrogging

Revolutionary (Strong) leapfrogging refers to a situation where the transition from one technology, and the adoption of a novel one, happens quickly and on a large scale, due to the characteristics of the new technology compared to the current technology, as well as the capabilities of the adopter. The transition from traditional energy such as biomass, to modern and clean energy such as renewable energy, can happen on a large scale if the context under consideration bears some key features. Some of these features include: (i) limited large-scale infrastructure of conventional energy; (ii) unmet demand for energy; and (iii) affordable cost and availability of renewable energy (EC, SE4All and UN., 2012), and unreliable capacity of the existing infrastructure. These features imply that transition in the described context can occur at a faster pace and on a larger scale. This form of transition is also regarded in this study as a strong form of leapfrogging. A close example is Kuwait's discovery of oil, which led to a quick change in their mode of transport from camels and donkeys to modern auto motives within a five-year period (Al-Marafie, 1989). The tendency to achieve a revolutionary leapfrogging successfully is greater when resources are available, and the adopter innovative.

3.6.2 Scattered leapfrogging

Scattered leapfrogging is a transition with some characteristics of revolutionary leapfrogging, except that the magnitude of change is small. This could be because of an existing large-scale infrastructure that takes time to be decommissioned. There is no resource problem preventing the building of infrastructure, but the available capacity of the existing infrastructure diminishes the need for the creation of a new one on a large scale. Hence, small additions of new technology are experienced, but at a faster rate than would otherwise have occurred. This form of leapfrogging is also described in this study as *medium*, as it involves fast-paced creation of small and distributed instances of new technology.

3.6.3 Coned leapfrogging

Coned leapfrogging is a form of transition that involves movement from existing socio-technical systems to a novel one. Given the large-scale existing infrastructure that needs to be changed, the magnitude of change is large, hence occurs at a slower pace. This is a weak form of leapfrogging, since the adoption of the new technology occurs over a longer period. An example would be constructing a large hydroelectric power to supply a large town that has been dependent on abundant traditional energy, such as wood fuels.

3.6.4 Conventional transition

Conventional transition is a form of transition which occurs when a variety of natural influences cause humanity to adjust and adapt. Given that major natural transition takes decades to occur, conventional transition is very slow, with small changes that occur over time. The seemingly small nature of their occurrence may seem insignificant, but the accumulated effect may be large. Conventional transition is not regarded as leapfrogging, as it does not involve a skip in pace or magnitude during the transition process. An example can be found in Canada, where the state of Ontario transitioned from coal for electricity production, to a cluster of renewable energy sources including solar and hydro, between 2003 and 2014, which eventually led to the shutdown of about 7,573 MW of coal capacity. A similar transition situation was found in The Netherlands and France, where natural gas for electricity production rose from 2% in 1959 to 50% in 1971, and nuclear grew from 4% in 1974 to 40% in 1982 (Sovacool, 2016b). The features of the leapfrogging paradigms are summarised in Table 3.2.

Table 3.2: Characteristics of leapfrogging paradigms

		Pace	
		Fast	**Slow**
Magnitude	**Large**	<u>Revolutionary (Strong) leapfrogging</u> - Small-scale current infrastructure - Unreliable current infrastructure - Unmet market needs - Available and affordable alternatives	<u>Coned (Weak) leapfrogging</u> - Large-scale current infrastructure - Declining current infrastructure - Limited and expensive alternatives
	Small	<u>Scattered (Medium) leapfrogging)</u> - Small-scale current infrastructure - Unmet market needs - Available and affordable alternatives	<u>Transitional (Conventional) leapfrogging</u> - Large-scale current infrastructure - Reliable current infrastructure - Fully satisfied market - Less affordable alternatives

3.7 CONCLUSIONS

Over-reliance on conventional energy would hinder the attainment of the Sustainable Development Goal, which relates to universal access to modern energy. This study examined the potential of, and opportunity for, leapfrogging to renewable energy in unmet electricity markets in Africa. Africa is characterised by a relatively small energy infrastructure, which is accentuated by the size of its unmet electricity markets. The region, therefore, does not need to burden itself with dirty fossil energy to attain universal electricity access. The study identified, the pursuit of universal access to electricity, the financial inflow from development partners, the abundance of its renewable energy resources, and the declining cost of renewable technology as the drivers of leapfrogging. Other drivers of Africa's readiness to leapfrog to renewable energy include the continuous improvement in technology efficiency, and the growing demand for electricity propelled by the increasing population and urbanisation.

Having identified the key features illuminating the path of renewable energy leapfrogging in unmet electricity markets, the trajectory of leapfrogging was reconceptualised in three paradigms namely: revolutionary, coned, and scattered. These paradigms are based on the particular combination of the pace and magnitude of change in a given transition setting. The pace and magnitude of change depend on the level of existence of the potential leapfrogging drivers discussed. Specific countries in the sub-region, for example, may have greater financial strength, enabling them to undertake large-scale renewable infrastructure development at a slower pace. Others, more endowed with distributed renewable energy resources, however, would find it ideal to build small-scale infrastructure at a faster pace. This means that different pathways for energy technology development, adoption, and absorption would eventually emerge. Generally, the African electricity market is largely suitable for the three leapfrogging paradigms described.

Inasmuch as there are vast opportunities for Africa's unmet electricity market to leapfrog to renewable energy, there remain foreseeable hindrances that ought to be addressed to ensure an efficient transition environment. In socio-technical systems, like energy, the challenges to leapfrogging can be rather multi-faceted. They not only require market preparedness to adopt new technology, but also the innovative readiness to provide the required technology. Some notable challenges include an awareness of the political environment, in order to stimulate its readiness and receptivity towards renewable energy as the way forward, internal financial commitment to undertake renewable energy investment beyond what is received in aid and donations from development partners. There is also the need for technical training to improve upon renewable energy innovation, technology cost and efficiency, liberalisation of the energy market to attract private sector participation, and strategic policy fine-tuning for commitment to renewable energy objectives and targets.

It is imperative that renewable energy leapfrogging in Africa be pursued with a consciousness of these potential challenges. For a start, market liberalisation, specifically deregulating the production of electricity and incentivising active private sector participants in the energy sector, would encourage competitiveness and, consequently, contribute to the expedition of electricity access. This would also alleviate the excessive capital burden on governments and public institutions as they endeavour to provide adequate energy. Ironically, the intensity of these challenges is mitigated by the gravity of the problem, a large 'awaiting' demand market. There is a significant payoff for those leapfrogging through path skipping and path creating, as there is for early market entrants or technology adopters. The penalty for path following leapfrogging is the difficult choice between abandoning old technological infrastructures before they exhaust their useful lifespan, or remaining stuck in obsolescence. The former can be observed in telecommunication, where late adopters of landline models underused such infrastructures following the emergence and rapid diffusion of mobile phones.

This study has attested to the need for energy transition in Africa, as well as the urgent need to expedite integration of renewable energy in the overall energy mix. Opportunely, global interest in energy sustainability and environmental safety has awoken the energy sector to the merits of renewable energy, where new electricity systems can be built on the foundation of renewable energy flows, instead of the present fossil energy stocks. Extensively, global stakeholders, and not just those within the continental market, are actively participating in the search for a quick redress to the energy problem in unmet electricity markets, such as Africa. These opportunities serve as a springboard to leapfrog unmet electricity markets to a new era where electricity would be accessed largely through renewable sources, and thereby contribute towards avoiding the adverse climatic consequences of the current high fossil fuel dependency.

Access to funding was identified as one of the main impediments to achieving universal electricity access in Africa. Chapter 4 investigates the funding gap in Africa's electricity market.

CHAPTER THREE REFERENCES

ABDUL-SALAM, Y. & PHIMISTER, E. 2016. The politico-economics of electricity planning in developing countries: A case study of Ghana. *Energy Policy*, 88**,** 299-309.

ACTION, P. 2010. Poor people's energy outlook 2010. Rugby: Practical Action.

ADB, A. D. B. 2010. Guidelines for Estimating Asian Development Bank (ADB) Investments in Access to Energy Projects. .

ADOM, P. K. 2011. Electricity consumption-economic growth nexus: the Ghanaian case. *International Journal of Energy Economics and Policy*, 1**,** 18.

AFRICA PROGRESS PANEL 2015. Power People Planet: Seizing Africa's energy and climate opportunities. Africa Progress Report: Africa Progress Panel.

AGECC, U. 2010. Energy for a sustainable future: summary report and recommendations. *UN (United Nations)/The Secretary-General's Advisory Group on Energy and Climate Change. New York, USA.*

AL-MARAFIE, A. 1989. Assessment of oil and natural gas resources in Kuwait. *Energy*, 14**,** 1-7.

AMANKWAH-AMOAH, J. 2015. Solar Energy in Sub-Saharan Africa: The Challenges and Opportunities of Technological Leapfrogging. *Thunderbird International Business Review*, 57**,** 15-31.

ANDERSEN, T. B. & DALGAARD, C.-J. 2013. Power outages and economic growth in Africa. *Energy Economics*, 38**,** 19-23.

ASAMI, M. & NAWFAL, S. 2015. AFRICA POWER SECTOR: Planning and Prospects for Renewable Energy. *IRENA - SYNTHESIS REPORT.* Abu Dhabi IRENA.

BASTAKOTI, B. P. 2003. Rural electrification and efforts to create enterprises for the effective use of power. *Applied Energy*, 76**,** 145-155.

BAZILIAN, M., NUSSBAUMER, P., ROGNER, H.-H., BREW-HAMMOND, A., FOSTER, V., PACHAURI, S., WILLIAMS, E., HOWELLS, M., NIYONGABO, P. & MUSABA, L. 2012. Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. *Utilities Policy,* 20**,** 1-16.

BHATTACHARYYA, S. C. & PALIT, D. 2016. Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? *Energy Policy,* 94**,** 166-178.

BINZ, C., TRUFFER, B., LI, L., SHI, Y. & LU, Y. 2012. Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China. *Technological Forecasting and Social Change,* 79**,** 155-171.

BLOOMBERG NEW ENERGY FINANCE 2016. New Energy Outhlook 2016. *https://about.bnef.com/*.

BURLAMAQUI, L. & KATTEL, R. 2016. Development as leapfrogging, not convergence, not catch-up: towards Schumpeterian theories of finance and development. *Review of Political Economy***,** 1-19.

CARBON TRACKER 2016. End of the load for coal and gas? *http://www.carbontracker.org/wp-content/uploads/2016/09/End-of-the-load-for-coal-and-gas_Exec-Summary_web-6.pdf*.

CARLSSON, B. 2003. Innovation systems: a survey of the literature from a Schumpeterian perspective. *Paper for the Elgar Companion to Neo-Schumpeterian Economics, June*.

CASTELLANO, A., KENDALL, A., NIKOMAROV, M. & SWEMMER, T. 2015. Brighter Africa: The growth potential of the sub-Saharan electricity sector. Mckinsey.

CORRÊA DA SILVA, R., DE MARCHI NETO, I. & SILVA SEIFERT, S. 2016. Electricity supply security and the future role of renewable energy sources in Brazil. *Renewable and Sustainable Energy Reviews,* 59**,** 328-341.

EBERHARD, A., FOSTER, V., BRICEÑO-GARMENDIA, C., OUEDRAOGO, F., CAMOS, D. & SHKARATAN, M. 2008. Underpowered: the state of the power sector in Sub-Saharan Africa. *Background paper.* World Bank.

EC, SE4ALL & UN. 2012. Sustainable Energy For All Action Plan.

ESHUN, M. E. & AMOAKO-TUFFOUR, J. 2016. A review of the trends in Ghana's power sector. *Energy, Sustainability and Society,* 6**,** 1-9.

FOUQUET, R. 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy,* 38**,** 6586-6596.

GALLAGHER, K. S. 2006. Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry. *Energy Policy,* 34**,** 383-394.

GARCÍA-GUSANO, D., IRIBARREN, D., MARTÍN-GAMBOA, M., DUFOUR, J., ESPEGREN, K. & LIND, A. 2016. Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. *Journal of Cleaner Production,* 112**,** 2693-2696.

GEELS, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy,* 31**,** 1257-1274.

GNANSOUNOU, E., BAYEM, H., BEDNYAGIN, D. & DONG, J. 2007. Strategies for regional integration of electricity supply in West Africa. *Energy Policy,* 35**,** 4142-4153.

GOLDEMBERG, J. 1998. Leapfrog energy technologies. *Energy Policy,* 26**,** 729-741.

GOLDEMBERG, J. 2011. Technological leapfrogging in the developing world. *Georgetown Journal of International Affairs***,** 135-141.

GRUBLER, A. 2012. Energy transitions research: Insights and cautionary tales. *Energy Policy,* 50**,** 8-16.

GSMA 2015. State of the Industry Report - Mobile Money. GSMA.

HOBDAY, M. 1995. Innovation in East Asia. *Books*.

ICSU & ISSC 2015. Review of Targets for The Sustainable Development Goals: The Science Perspective. Paris: International Council for Science (ICSU).

IEA 2009. Cities, towns & Renewable Energy: Yes In My Front Yard. *International Energy Agency*. Paris: OECD/IEA.

IEA 2011. World Energy Outlook 2011. Paris: OECD/IEA.

IEA 2014a. The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems. Paris: OECD/IEA.

IEA 2014b. World Energy Outlook 2014. Paris: OECD/IEA.

IEA 2015. World Energy Outlook 2015 Paris: OECD/IEA.

IEA 2017. World Energy Outlook 2017: From Poverty to Prosperity. *Special Report.* Paris: OECD/IEA.

INTERNATIONAL ENERGY AGENCY (IEA) & BANK, W. 2017. Sustainable Energy for All 2017—Progress toward Sustainable Energy. Washington, DC: World Bank.

KEHO, Y. 2016. What drives energy consumption in developing countries? The experience of selected African countries. *Energy Policy*, 91**,** 233-246.

KEMP, R., ROTMANS, J. & LOORBACH, D. 2007. Assessing the Dutch Energy Transition Policy: How Does it Deal with Dilemmas of Managing Transitions? *Journal of Environmental Policy & Planning*, 9**,** 315-331.

KITZING, L., KATZ, J., SCHRÖDER, S. T., MORTHORST, P. E. & MØLLER ANDERSEN, F. 2016. The residential electricity sector in Denmark: A description of current conditions.

KPMG 2015. Power in Africa. *Sector report*. KPMG.

LEE, K. & LIM, C. 2001. Technological regimes, catching-up and leapfrogging: findings from the Korean industries. *Research policy*, 30**,** 459-483.

LEVIN, T. & THOMAS, V. M. 2016. Can developing countries leapfrog the centralized electrification paradigm? *Energy for Sustainable Development,* 31**,** 97-107.

MENDOZA, N. B. 2016. 6 initiatives tackling African electrification <devex.com-6 initiatives tackling African electrification.pdf>.

MODY, A. & SHERMAN, R. 1990. Leapfrogging in switching systems. *Technological forecasting and social change,* 37**,** 77-83.

MORRIS, C. & PEHNT, M. 2012. Energy Transition: The German Energiewende. *Heinrich Böll Stiftung.* Berlin.

MU, Q. & LEE, K. 2005. Knowledge diffusion, market segmentation and technological catch-up: The case of the telecommunication industry in China. *Research policy,* 34**,** 759-783.

MURPHY, J. T. 2001. Making the energy transition in rural East Africa: Is leapfrogging an alternative? *Technological Forecasting and Social Change, ,* 68**,** 173-193.

NERINI, F. F., BROAD, O., MENTIS, D., WELSCH, M., BAZILIAN, M. & HOWELLS, M. 2016. A cost comparison of technology approaches for improving access to electricity services. *Energy,* 95**,** 255-265.

PACHAURI, S., RAO, N., NAGAI, Y. & RIAHI, K. 2012. Access to modern energy: Assessment and outlook for developing and emerging regions. *Laxenburg: IIASA*.

PANOS, E., DENSING, M. & VOLKART, K. 2016. Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030. *Energy Strategy Reviews,* 9**,** 28-49.

PEREZ, C. 1988. *New technologies and development,* London, Pinter.

PERKINS, R. 2003. Environmental leapfrogging in developing countries: A critical assessment and reconstruction. *Natural Resource Forum,* 27**,** 177-188.

REN21 2014. Renewables 2014 Global Status Report. *Tech. Rep.* Paris: REN21.

SCHROEDER, P. M. & CHAPMAN, R. B. 2014. Renewable energy leapfrogging in China's urban development? Current status and outlook. *Sustainable Cities and Society,* 11**,** 31-39.

SCOTT, A. 2015. Building Electricity Supplies in Africa for Growth and Universal Access. *Working Paper, The New Climate Economy*.

SHYU, C.-W. 2014. Ensuring access to electricity and minimum basic electricity needs as a goal for the post-MDG development agenda after 2015. *Energy for Sustainable Development,* 19**,** 29-38.

SMIL, V. 2010. *Energy transitions: history, requirements, prospects,* Santa Barbara, ABC-CLIO.

SOETE, L. 1985. International diffusion of technology, industrial development and technological leapfrogging. *World Development,* 13**,** 409-422.

SOVACOOL, B. K. 2013. *Energy & ethics: justice and the global energy challenge,* New York, Palgrave Macmillan.

SOVACOOL, B. K. 2016a. Differing cultures of energy security: An international comparison of public perceptions. *Renewable and Sustainable Energy Reviews,* 55**,** 811-822.

SOVACOOL, B. K. 2016b. How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science,* 13**,** 202-215.

STEINBUKS, J. & FOSTER, V. 2010. When do firms generate? Evidence on in-house electricity supply in Africa. *Energy Economics,* 32**,** 505-514.

STRAM, B. N. 2016. Key challenges to expanding renewable energy. *Energy Policy,* 96**,** 728-734.

SZABO, S., BÓDIS, K., HULD, T. & MONER-GIRONA, M. 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environmental Research Letters,* 6**,** 034002.

SZABÓ, S., BÓDIS, K., HULD, T. & MONER-GIRONA, M. 2013. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. *Renewable and Sustainable Energy Reviews,* 28**,** 500-509.

TIGABU, A. D., BERKHOUT, F. & VAN BEUKERING, P. 2015. The diffusion of a renewable energy technology and innovation system functioning: Comparing bio-digestion in Kenya and Rwanda. *Technological Forecasting and Social Change,* 90**,** 331-345.

TUKKER, A. 2005. Leapfrogging into the future: developing for sustainability. *International Journal of Innovation and Sustainable Development,* 1**,** 65-84.

UN 1998. Kyoto Protocol to The United Nations Framework Convention on Climate Change

UN 2011. Conference of Parties. Durban: UN.

UN 2015a. *Transforming our world: the 2030 Agenda for Sustain able Development* http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

UN 2015b. World Population Prospects: The 2015 Revision *Department of Economic and Social Affairs - Population Division.* New York: UN.

UNDP 2015. *Human Development Report 2015*.

UNFCCC, C. 1992. United Nations Framework Convention On Climate Change. *Kyoto Protocol.* Kyoto: UN.

UN. 2015. Conference of the Parties. Framework Convention on Climate Change, 2015 Paris. UN.

WHO 2014. Burden of disease from household air pollution for 2012. Geneva: World Health Organization.

WILSON, C. 2009. Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios.

WILSON, C. 2012. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy,* 50**,** 81-94.

ZERRIFFI, H. & WILSON, E. 2010. Leapfrogging over development? Promoting rural renewables for climate change mitigation. *Energy Policy,* 38**,** 1689-1700.

4 CHAPTER FOUR: EXAMINING THE FUNDING GAP IN UNMET AFRICAN ELECTRICITY MARKETS[3]

4.1 CHAPTER OVERVIEW

The chapter addresses the third objective of the study: to explore the potential of private sector finance to bridge the funding gap and expedite universal electricity access. This was motivated by the estimates of studies, that Africa's annual power sector investment is less than half the amount required to ensure that it attains universal access by 2030. A system dynamics model of Africa's electricity access, dubbed the AFELA model, was developed to assess electricity access and investment trends as well as the funding gap in Africa. The model considers different scenarios that provide key insights on how the funding gap could be closed.

Abstract

A growing number of people in Africa still do not have access to electricity. This phenomenon threatens the realisation of the United Nation's Sustainable Development Goal pertaining to energy. Factors attributed to Africa's low electricity access include limited financial resources at the dispensation of governments to execute the capital-intensive infrastructure required to develop the power sector. This chapter examines the funding gap in the African electricity market, and explores the potential of private sector finance as a conduit to bridge the gap and expedite the attainment of universal access to electricity. This was achieved by developing the Africa Electricity Access (AFELA) model, using system dynamics. AFELA comprises three sub-models, namely: Electricity Access, Electricity Capital Investment, and Electricity Supply Capacity. Four scenarios were examined to determine the fastest transition to universal electricity access in Africa. The scenarios were the Baseline scenario, Economies of scale scenario, Capacity utilisation factor scenario, and Electricity access investment scenario. The results showed that the Electricity Access Investment Scenario, which entails an increase in the

[3] BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Assessing the funding gap of Africa's Unmet Electricity Markets. *Energy for Sustainable Development*

annual power investment by two per cent of GDP, is the most viable way to universal electricity access. The budget constraints of national governments that are mandated to provide electricity, and the limited funds available from multilateral and bilateral aids, imply that investment from the private sector is vital.

Keywords: *Africa; Electricity access; Private finance; Investment; Incentives.*

4.2 INTRODUCTION

Africa is characterised by large unmet power markets with no grid connections, and even the population connected to the power grid suffer frequent power outages. The World-Bank (2016) estimates that Africa experiences power outages eight times a month, on average, with an outage lasting an average of four hours, and altogether costing businesses approximately 5.4% losses in annual sales. This translates to a reduction of Gross Domestic Product (GDP) by 2% (Scott, 2015). Many firms in Africa therefore, because of the unreliable nature of grid supply, tend to supplement their power needs and boost stability of power supply for their activities through self-owned or shared stand-by power generators (World-Bank, 2016).

Africa's unmet electricity market does not reflect its energy potential. The IEA (2016a) estimates gas and coal deposits for over 400 and 600 years, respectively, recoverable oil for the next century, and there is a variety of renewable energy potentials. The IEA (2014) also projects Africa's technical hydropower capacity as 283 GW, which can generate about 1200 terawatt hours (TWh) yearly. The total wind potential is estimated at about 1300 GW (Mandelli, Barbieri, Mattarolo and Colombo, 2014), a capacity that exceeds, several fold, the present power required for universal electricity access across the continent. Solar potential is vast, especially in the southern and northern belts, while geothermal potential ranges from 10 to 15 GW (IEA, 2014). Evidently, the total energy resources on the continent far exceed what is required for full electricity access. While the abundance of energy resources in Africa is now established, the inadequacy of electric power does suggest absence of other crucial resources for electricity infrastructure.

The main challenges of Africa's power sector, as Duarte, Nagarajan and Brixiova (2010) noted, includes limited generation capacity, unreliable services, low electrification, high cost of electricity, low electricity consumption, and a large financing gap. Buttressing on finance as a key barrier to electricity access, Trimble, Kojima, Perez Arroyo and Mohammadzadeh (2016) also noted the inadequacy of finance, deteriorating power plants, and the poor revenue collection as key challenges in the electricity sector. A number of the other challenges can be addressed with adequate finance.

Finance is a non-peculiar resource often deemed scarce for undertaking capital-intensive investment such as constructing power plants especially in developing country context. The growing financing gap in the power sector is a priority for governments (Crousillat, Hamilton and Antmann, 2010). While, through different studies, the Africa Progress Panel (2015); Castellano, Kendall, Nikomarov and Swemmer (2015); IEA (2014) have reiterated the extent of energy poverty in Africa, and forecasted the trend of this problem over the next couple of decades, scanty findings are offered on navigating the finance barriers in order to accelerate energy access. Until now, the energy access budget in developing countries has been dominated by public finance, mainly from domestic government budgetary allocations, and multilateral and bilateral aids from development partners.

In 2009, the IEA (2011) calculated that, of the US$ 9.1 billion investment towards electricity access, the funding sources were 30% public funding, 34% multilateral aid, 22% private finance, and 14%bilateral aid. Four years later, in 2013, the total investment had increased to US$13.1 billion, and comprised 37% for public funding, 33% multilateral aid, 18% private finance, and 12% bilateral aid (IEA, 2015). Funding from governments and aid agencies has so far proven insufficient and less than effective for surmounting the electricity inadequacy in Africa. Private sector financing is considered a potential remedy. Although there had been increased investment in the power sector between 2009 and 2013, the share of private finance had declined.

It is important therefore, to understand the key drivers of private investment in the power sector, especially in Africa where investment is most needed. This study evaluates the trend of investment in the power sector, quantifies the amount of investment required for universal electricity access in Africa, and then assesses the sort of environment that would, attract private investors to invest in the electric power sector, and consequently lead to elimination of the finance barrier in the sector.

4.3 OVERVIEW OF THE ELECTRIC POWER SECTOR IN AFRICA

Africa has five power-pool markets: the Southern Africa Power Pool (SAPP), Eastern Africa Power Pool (EAPP), Central Africa Power Pool (CAPP), Western African Power Pools (WAPP), and North African power pool known as the Comité Maghrébin de l'Electricité (COMELEC). They were created to promote power trade at various stages. According to the Infrastructure Consortium for Africa (ICA), the creation and integration of the power markets could potentially result in a reduction of the yearly operation and development cost by approximately US$2 billion, equivalent to 5% of systems costs (ICA, 2011). Castellano et al. (2015), also forecast that sub-Saharan Africa alone would accumulate a net saving of US$41 billion on generation capital spending through regional integration by 2030. The regional power exchange across national borders is, however, limited. The total power trade across countries is less than 8% of total power production (Castellano et al., 2015). This situation is not surprising, as most countries are unable to meet the domestic market requirements or to prevent unplanned outages.

The reason for poor integration of the power markets in Africa transcends the inadequate domestic market supply. A key contributor to their inefficiency is the inconsistency on the part of the purchasing nation in adhering to debt accrued from power supplied. The West Africa Gas Pipeline (WAGP), which runs through and supplies gas to Benin, Togo, and Ghana, is an illustration of this pitfall of consumer country default on the timely paying of the supplier country. Supply from the pipeline is also intermittent, owing to offshore damage - as was the case in 2011, when a ship anchor severed the pipeline and vandalism, which occurs at the Niger Delta (IEA, 2014). Notwithstanding the challenges, initiatives such as the WAGP also present immense potential. The pipeline is estimated to have reduced Ghana's weighted average electricity generation cost by over 10% (IEA, 2014).

The Africa Progress Panel observed that, the continent has yet to build approximately two-thirds of the energy infrastructure required by 2030 (Africa Progress Panel, 2015). The projected power capacity required to meet the unmet African markets by 2030 is 610 GW, of which the regional power pool distribution would appear as follows: North Africa would require 318 GW, 150 GW in Southern Africa, 62 GW for West Africa, 55 GW in East Africa, and 25 GW for the Central Africa region.

4.4 CONTEXTUALIZING ELECTRICITY ACCESS AND INVESTMENT IN AFRICA

Energy and electricity access is often described with various contextual connotations. The United Nation Secretary-General's Advisory Group on Energy and Climate Change (AGECC) classifies energy access into three main levels: basic human needs, productive uses, and modern society needs (AGECC, 2010). The first level of energy access addresses such primary needs as electricity for basic uses including lighting, health, education, communications and other community services, through which means the average energy consumed per person per year ranges between 50 to 100 kWh. The second level of access has, in addition to the first level, energy for improved productivity in agriculture, commerce, and transport services. The third level, or the needs of modern society, extends the first and second levels to include other household appliances, more cooling and heating requirements, private transportation, and an average electricity use of about 2000kwh per person per year (AGECC, 2010). The average consumption per person per year in Africa is estimated as 620 kwh (IEA, 2014), while a majority of the populace has yet to attain electric energy for first level needs. Electricity is an input in the production process, and the access to it can attract private investors, creating opportunity for advancements in internal economic operations (KPMG, 2015). The development of the private sector depends on the availability of infrastructure. Africa's lack of adequate energy infrastructure for reliable power supply is, therefore, a hindrance to the growth of the private sector (Kaberuka, 2011), and requires immediate attention.

The campaign for universal access to modern energy includes clean energy for cooking, transportation, industrial and agricultural operations and electricity generation. Embedded within this objective is the attempt to reduce the fossil fuel consumption, which remains the largest energy source for electric power in Africa. However, data from the ICA indicates an increasing investment in gas-fuelled thermal power in Africa, despite the higher operating costs involved (ICA, 2011). This investment trend could be due to (i) the large initial capital requirement for constructing large renewable power plants, in relation to the cost of fossil-fuelled plants, and (ii) the relatively shorter completion time of some fossil-fuelled power plants compared to renewable power plants, such as those for hydroelectric power, amid growing agitation for expansion in electricity access. The transition to low carbon electricity generation can be challenging; however, the low level of energy access in Africa reduces the inertia and presents opportunity for rapid transition (Batinge, Musango and Brent, 2017). The advocacy for concerted efforts to increase the share of renewable energy in power investments stems not only from climate protection, but is also due to economic and health benefits from such investment decisions. For instance, in 2012, household air pollution-related death cases in Africa were estimated at 600 000 (WHO, 2014). The evidence for the case that investment towards clean electricity generation be targeted at renewable energy is therefore compelling.

Infrastructural deficit is a common development challenge that characterises African countries. The magnitude of this deficit is estimated at $US93 billion annually (Foster and Briceño-Garmendia (2010). The power sector deficit alone is about 40% of this annual figure, buttressing the fact that the power sector investments are far from adequate. The growth in power demand over the next two decades requires an estimated annual investment of US$45 billion (IRENA, 2015). Emphasising the infrastructural deficit in the power sector, Eberhard, Gratwick, Morella and Antmann (2016) surmised that Africa requires in excess of US$40 billion annually, of which about $US28 billion is for investment in capital (approximately US$14 billion for new power generation capacity yearly) and the rest for operations and maintenance. The investment requirements in Africa's power sector is equivalent to 6% of the continent's GDP and, given the present paltry average spending of about US$11 billion (2.7% of GDP) on energy access, a lot more investment is required.

It is apparent from the figures that the capital responsibility that rests upon national governments is overwhelming. Private sector participation to share the financial burden of African power sector is indispensable if the continent is to achieve the UN goal of universal energy access by 2030. Indeed, key bilateral investors are making gainful investments in the African power sector with China being the major bilateral trade investor. Since 2010, China's investment in the power sector has led to the installation of 7 GW power from different energy sources, and an additional 10 GW is expected by 2020. This will lead to a total of 17 GW power capacity installation from Chinese investment, equivalent to 10% of the existing capacity in sub-Saharan Africa (IEA, 2016a). Despite these efforts, a lot more investment is still required. This prompts the redrafting of state policies pertaining to energy provision to involve private entity participation to boost the availability of finance to undertake the expansion of electricity access.

4.4.1 Why private finance is limited in African electricity sector

A multiplicity of factors deters the private sector from investing in the African power sector. These factors include: (i) a regulatory dimension manifested in issues of tariff settings, service standards, and private entry conditions (Muzenda, 2009); (ii) conflicts with public agencies to remedy, which Brown, Stern, Tenenbaum and Gencer (2006) proposed rules, to pre-empt and govern the energy sector to promote private participation; (iii) the nature of incentive schemes available to private investors; and (iv) the corrupt acts perpetuated by state agents tasked to procure private finance. Corruption distorts financial investments, detracts the efficiency state and business, and destroys the appeal of private investments (Bergara, Henisz and Spiller, 1998). Electricity losses through substandard transmission and distribution also significantly undermine Africa's power sector efficiency. Transmission losses are often the result of substandard transformers and cable lines, while distribution losses are attributable to human conduct including cable theft, theft through meter tampering and illegal connections (Golden and Min, 2012). The inability of public stakeholders to reduce the transmission losses to an acceptable minimum, and effectively collect revenue from consumers to offset power sector expenditures has been a major obstacle to securing the necessary capital needed for infrastructural expansion. Although electricity provision is still largely the mandate of public institutions, an active private sector role remains critical for attaining a universal electricity access status in Africa. Reforms in countries such as the UK, Germany, and Belgium, have provided the private sector the opportunity to cooperate or lead in the electricity generation (Karan and Kazdağli, 2011). The onus rests on national policy-making structures to ensure that a friendly climate for investment is created through implementation of regulatory reforms, ensuring that the power sector is solvent, and promises or guarantees of a positive return on investment. The preceding section offers some strategies for attracting private investment in the sector.

4.4.2 Strategies to facilitate investments in electricity generation

The obligation to provide electricity infrastructure is primarily imposed on state and public institutions. However, public agencies often engage private sector entities at different levels and capacities to assist in meeting the mandate of providing goods and delivering services (Delmon, 2009), independently or jointly with national institutions. The UN Secretary General in 2011 launched the Sustainable Energy for All (SE4All) initiative (Sovacool, 2013), a nonprofit body to engage with governments and civil society groups, and collaborate with private entities to develop energy catalogues geared towards accelerating energy access. The African Energy Leaders Group, a community of leaders from both public and private sectors also commits to champion sustainable energy transition in Africa, and promote universal energy access through public-private partnership and commercial regional power pools in support of the SE4ALL objectives. Different other mechanisms can be instituted to assuage private sector risks in providing essential utilities (Kaberuka, 2011). Some of these mechanisms are discussed next.

4.4.2.1 Regulatory reforms

There has been conspicuous advocacy for privatisation in the last decade of the twentieth century, to induce competition in the electricity sector (Stridbaek, 2006). Electricity generation output increases with privatisation, when there are independent regulations in the market. There are many instances around the globe where reforms have been implemented in the electricity sector to augment capital availability. In Asia, China carried out reforms to attract investment from the private sector (Li and Dorian, 1995). The struggles of government to provide adequate electricity to meet demand drove Colombia to embark on reform, which allowed Independent Power Producers (IPP) to investment in the sector (Lefevre and Todoc, 2000). In Africa, Ghana has been able to secure funding from the World Bank following reforms in the power sector (Saunders, 1993). This shifted the country's reliance on guaranteed loans from multiple donors and foreign governments for finance to construct generation plants and transmission facilities (Edjekumhene, Amadu and Brew-Hammond, 2001; Turkson and Wohlgemuth, 2001). Following findings from its study in 1995, which established that active private sector participation improves the performance of public enterprises, the World Bank has made reforms a condition for its lending in the power sector (Bacon, 1995; Bouille, Dubrovsky and Maurer, 2001; Galal and Shirley, 1995).

Theoretically, it is an optimal choice for governments to abdicate their duties in the electricity sector and confer that responsibility to private entities on make more public funding available for other development needs (Wamukonya, 2003). It has since come to light, that privatisation of power sector operations does not necessarily amount to significant savings for funding other sectors, nor does it create the expected capital flow in the electricity sector (Wamukonya, 2003). Zhang, Parker and Kirkpatrick (2008), investigated electricity generation response through privatisation, competition, and regulation of the sector's operations and concluded that, privatisation and regulatory reforms alone are not adequate to increase electricity production unless combined with competition in the sector. Counteracting the challenges of electricity access in Africa, therefore, requires the introduction of reforms that encourages competition, especially in monopolistic state-regulated power sectors (Zhang et al., 2008; Scott, 2015). The creation of competition in electricity generation instigates improvement in performance (Zhang et al., 2008), reflected through delivery of a quality service. According to Lamech and Saeed (2003), a legal framework of their rights and obligations, and enforcement on and commitment by consumers to pay for utilities provided, an independent regulatory entity, and government and multilateral guarantees, are typical key motivators for the private sector to invest in the power sector. Private investors would prefer to invest in a deregulated market rather than a regulated market because, in a regulated electricity market, when there is uncertainty surrounding electricity prices, the tendency for intervention from a state regulator is high, especially when the price rises. This reduces investors' expected revenue and discourages them from investing in power generation (Neuhoff and De Vries, 2004). In a deregulated electricity market, the state entity, with limited direct influence on price, can mitigate the consumer price burden by way of subsidising without compromising investors' confidence in the market. Potential risks can also be hedged through the introduction of an effective regulatory framework as a sign of good faith, especially in a monopolistic power market (Zhang et al., 2008), to motivate the private sector to assume an active investment role in the electricity sector.

4.4.2.2 Electricity market liberalisation

Private investment is one of the pillars for developing a stable supply of power (Nagayama, 2009). The upsurge in liberalisation stems, in part, from the urgent need to increase private finance to address capacity issues in the power sector, and to mitigate inefficiencies characterising state ownership of utility institutions. Most electricity markets in industrialised countries are liberalised (Boom, 2003). A liberalised electricity market eliminates some bottlenecks such as the delays associated with a centralised planning process (Castro-Rodriguez, Marín and Siotis, 2009). Although electricity market liberalisation in the developed world started over two decades ago, it remains highly regulated in Africa. The task of transforming a regulated electricity market to a deregulated one is complicated and difficult (Woo, King, Tishler and Chow, 2006). Some countries are in a more advanced stage of liberalisation than others. These stages or degree of liberalisation according to Nagayama (2009) ranges from a monopolistic model where there is no competition; to a single buyer model where competitive bidding occurs at the upstream generation level; or a wholesale market model; and finally a retail model. The state of development of a country, Nagayama (2009) cautioned, is important for determining a suitable model of liberalisation. Heeding this advice, and considering the state of the electric power market environment in many African countries, a single buyer model of liberalisation would attract private investors and thus alleviate the financial responsibility and operational burden such a capital-intensive infrastructure levies on a state-owned enterprise.

4.4.2.3 Incentive schemes

Governments also institute different incentive policies purposely to motivate private sector firms towards investment in electricity access. The Feed-In-Tariff (FIT) mechanism is one such frequently used incentive tool for attracting investment in power generation. The returns of this mechanism are often fixed in nature, and therefore contrary to the competition that characterises a liberalised power market (Alishahi, Moghaddam and Sheikh-El-Eslami, 2012). The units and cost of electricity generated, rather than market price, is the basis of FIT incentives. It offers a guarantee to firms by limiting the risk associated with modern technology or power generated through renewables (Lipp, 2007). Another form of incentive is the market–based incentive, which is often variable in nature and responds to electricity price changes. A fixed incentive mechanism has attracted investment and expansion of generation capacities due to its risk aversion. An incentive system, which has proven vital in many sectors, should also be used as a key negotiating mechanism with private investors in the power sector investment expansion strategy as Muzenda (2009) observed. The existence of a variable payment incentive tool, according to Barforoushi, Moghaddam, Javidi and Sheikh-El-Eslami (2010), does not automatically boost investment in power. While investment from the private sector is imperative to the increase in the electricity access rate in Africa, and offers realistic chances for achieving universal electricity access by 2030, liberalisation and incentives in the power market must take precedence.

4.4.2.4 Independent power producers (IPP) and public private partnerships (PPP)

In the wake of increased concerted efforts to limit carbon emissions, innovative incentives become the conduit to attract private sector investment in renewable energy to complement the electricity supply. One such innovative incentive tool is the Renewable Energy BID (REBID) that South Africa adopted. Bids totalling 1415.5 MW, comprising wind, solar photovoltaic, concentrated solar power, biomass, biogas, and small hydro, among other forms of renewable energy were obtained from private investors in 2011 (Fritz, 2012). A second bid call attracted 1043.9 MW of bids, and the accumulative investments from private sector through these bids created a robust platform for a smart grid in South Africa (Fritz, 2012). National governments can also introduce subsidies for utility services as a way of alleviating the cost burden of consumers of such utilities while ensuring that the investment cost is recovered. Different subsidy schemes exist in the electricity sector to ensure sustainability of investment capital and protection of consumers (Muzenda, 2009). Clark, Davis, Eberhard, Gratwick and Wamukonya (2005), noted these to include direct subsidies extended to IPPs, and lifeline tariffs, where only a limited amount of electricity is subsidised (e.g. Ghana, Uganda, Mali, Tanzania), and cross-subsidisation (e.g. South Africa).

Another strategy to acquire private funds for power infrastructure is through public private partnership (PPP). The partnership between private and public sector to construct electricity generation infrastructure can be based on Design-Build-Finance-Operate-Maintain (DBFOM) which can be categorised into various forms such as: Build Operate Transfer (BOT), Build Own Operate (BOO), Management contracts, Leasing, Cooperative arrangements, and Joint ventures (Grimsey and Lewis, 2007). One key advantage of the PPP is it that brings the discipline that private ownership exudes, which is critical to limit electricity losses and instil a good management culture in the power sector (Littlechild, 2000). Countries are recognising the potential role of active private sector participation and resources for developing the energy sector, and Africa, with its limited financial strength for infrastructural expansion needs to assume a lead role in opening its electricity market for the flow of private finance. The next section introduces the methodological approach to assessing Africa’s power sector and state of electricity access.

4.5 METHOD

Different methods are applied in the assessment and planning of the electricity sector, and private sector financing. These methods include, for example, linear programming models used to experiment on the transfer of ownership of a power plant (Bunn, Larsen and Vlahos, 1993), the fully modified ordinary least squares (FM OLS) method used to analyse the time varying behaviour of electricity demand elasticity (Adom and Bekoe, 2013), the structural time series method for assessing the effect of endogenous and exogenous economic factors on electricity demand (Ackah, Adu and Takyi, 2014), the long-range energy alternative planning (LEAP) model for assessing bioenergy use, and the hierarchical lexicographic programming method for planning the extension of electricity access (Abdul-Salam and Phimister, 2016). These methods generally lack essential relational feedback processes among key variables within the sector. The system dynamics modelling method, however, takes cognisance of these feedback processes, and is therefore useful for assessing the state of electricity access in Africa. This study also aims to ascertain the development of the sector in the future, based on different scenarios, for which system dynamics modelling is often used.

The system dynamics modelling approach is not new to the electricity sector. Dyner and Larsen (2001) applied the methodology to understand the changes required in the planning methods used in monopolistic, as against deregulated, electricity markets. The method has also been used to propose an improved mechanism for electric power capacity payment (Assili, DB and Ghazi, 2008), assess the electricity access gap (Batinge, 2015), and analyse the decentralisation and the network effect of electric power generation (Kubli and Ulli-Beer, 2016). Ahmad, Mat Tahar, Muhammad-Sukki, Munir and Abdul Rahim (2016) investigated the contributions system dynamics modelling made in the electricity sector and concluded that policy assessment (mainly at the national level), such as attracting investment from the private sector, and expanding generation capacity, are the two major electricity sector issues modelled using the system dynamics approach. A list of applications in the electric power sector is also found in the work of Ford (1997).

In the broader energy sector, the application of system dynamics modelling is even more prominent. From understanding the energy market dynamics and economic indicators (Naill, 1977), to energy development and energy structure testing (Chi, Nuttall and Reiner, 2009;

Connolly, Lund, Mathiesen and Leahy, 2010) through the environmental aspect of energy and CO_2 emissions (Anand, Vrat and Dahiya, 2006; Feng, Chen and Zhang, 2013), energy technology sustainability assessment (Musango and Brent, 2011), and energy security resulting from supply and demand in country specific cases (Shin, Shin and Lee, 2013; Wu, Huang and Liu, 2011), this approach has proven useful. In fact, Andrew Ford, a forerunner in energy research using system dynamics modelling, points out that '…my experiences with energy industry modelling convinced me that the ability to simulate the information feedback in the system is a truly unique feature of the system dynamics approach' (Ford, 1997). In a similar context, Bunn, Dyner and Larsen (1997) noted: 'for markets in transition, where strategic imbalances exist, system dynamics has a useful role to play in developing a better understanding of processes, which might shape their evolution.' This methodology fits with the nature of the electricity sector problem herein investigated; it is dynamic, with multiple stakeholders, variables, and different sectors with extensive interdependence. Subsequently a simulation model was constructed using Vensim DSS version 6.3, developed by Ventana Systems Inc.

4.6 THE AFRICAN ELECTRICITY ACCESS (AFELA) MODEL

The African Electricity Access (AFELA) model was developed to assess the continent's power and electricity requirements. The model contains three sub-models, namely: (i) electricity access, (ii) electricity supply capacity, and (iii) electricity capital investment. The basic model setup is represented in *Table 4.1*, and a more detailed description of these sub-models is presented in the sub-sections.

Table 4.1: Model setting

Model setup	
Initial Time	*2001*
Final Time	*2040*
Time Step	*0.0625*
Saveper	*1*
Units for Time	*Year*
Integration Type	*Euler*

The simulation period for the model is from 2001 until 2040. The result from 2001 to 2015 was compared with the historical data obtained from UNSD (2017) and the IEA (2016b) to access the model's validity against data. Upon establishing confidence in the results through calibration, the simulation time is then extended to 2040, to understand the likely future pattern of electricity access, under business as usual (referred to as base run). The computation is done sixteen times (the time step) in a year to enhance accuracy, and the results are saved annually. The Euler integration method is used in the model simulation, because it gives the simplest and fastest solution.

4.6.1 Model feedback loops, structure, and equations

The model boundary defines the list of endogenous variables, those that represent the main internal variables in the feedback loops; exogenous variables, which are external parameters or constants influencing endogenous variables; and excluded variables that are considered to be less relevant, because they fall outside the scope or boundaries of the model. The AFELA model boundary is illustrated by the various sub-model causal feedback loops captured in Figure 4.1.

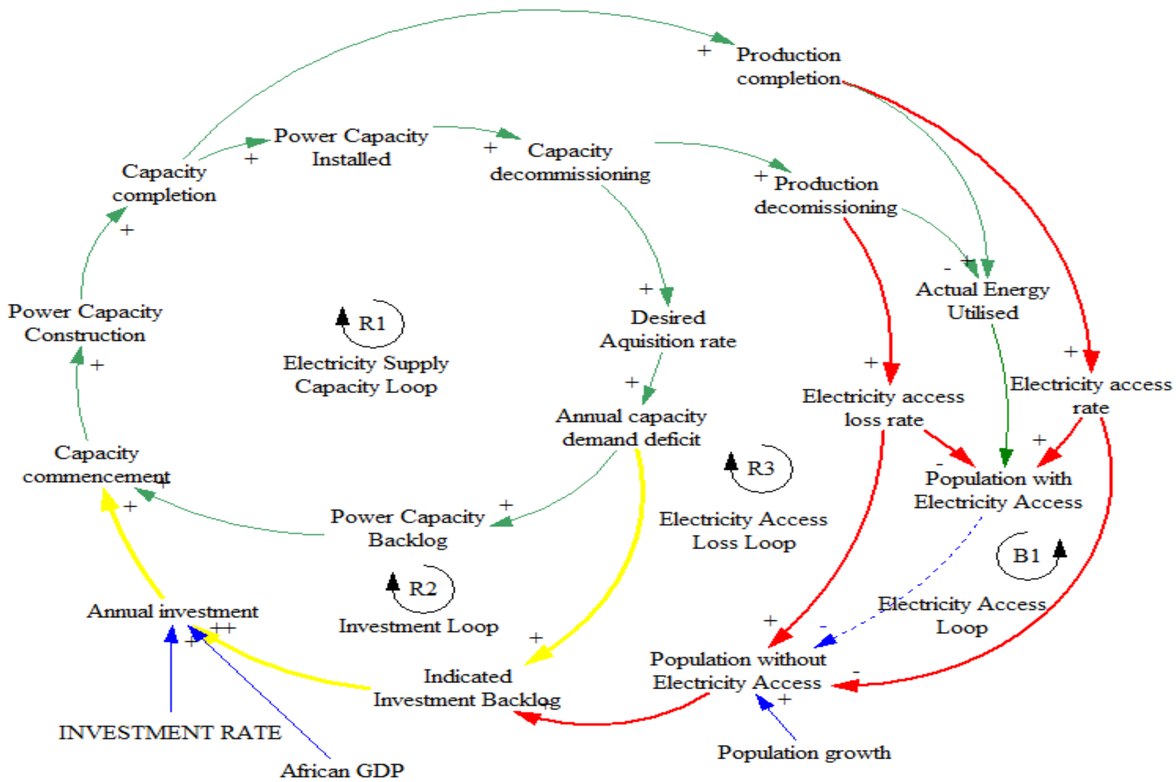


Figure 4.1: Causal loop diagram of Africa's power sector

A causal loop diagram is a useful tool for illustrating feedback structure; how the variables in a model are related, with arrows from one variable (cause) to another (effect). A causal loop diagram presents a brief model boundary, with key feedbacks more essential than clouding in detailed specification of individual components (Sterman, 2000). The causal loop diagram of the AFELA model (see Figure 4.1) captures the feedback processes among key variables in the model. Four key feedback loops were identified as; electricity supply capacity loop, investment loop, electricity access loss loop, and electricity access loop.

The ***electricity supply capacity loop*** (R1) is core to the overall causal loop diagram. It takes into account the capacity backlog, capacity commencement, capacity construction, capacity installed, capacity decommissioning, desired acquisition rate, and annual capacity demand deficit, which ultimately accumulates in the capacity backlog. This sector interacts with the investment sector when new investments lead to capacity backlog depletion and with the access sector when population growth and access loss results in capacity backlog accumulation.

The ***investment loop*** (R2) is an extension of the power supply loop to show the feedback from the indicated annual demand deficit to the indicated investment backlog, annual investment, and then back to the capacity commencement. This loop captures the financial flow into infrastructural developments, and links the capacity sector to the access sector.

The ***electricity access loop*** (R3) builds on both the electricity supply capacity loop and investment loop. It extends from the capacity decommissioning to production decommissioning, through to the electricity access loss rate, population without electricity access, and then to the indicated investment backlog.

The ***electricity access loop*** (B1) is one of the key, and only counteracting, loops of the four main loops identified. Essentially, it is the outermost loop in the structure, extends upon the electricity supply capacity loop, the investment loop, and the electricity access loss loop. The key additional variables include the production completion, actual energy used, electricity access rate, population with electricity access, population without electricity access, and then to the indicated investment backlog. When more investment is made, the capacity availability increases, resulting in an increase in the population with electricity access, and a decrease in population without access.

4.6.1.1 Electricity access sub-model structure and equations

A model boundary chart captures the scope of the model by detailing the variables, which are computed endogenously, those included exogenously, and those excluded entirely. The boundary chart is a word picture of the model and explicitly highlights the endogenous, exogenous and excluded variables (Sterman, 2000). A boundary chart for the electricity access sub-model is presented in Table 4.2.

Table 4.2: AFELA model: electricity access sub-model boundary

Endogenous	Exogenous	Excluded
Electricity access sub-model		
Total Population	Initial Population without Electricity Access	Income
Total access rate	Initial Population with Electricity Access	
Population without Electricity Access	Average consumption per access person	
Population with Electricity Access	Reference Electricity Price	
Average consumption per person	Net Population growth rate	
Electricity access rate	Effect of Price on Consumption TABLE	
Electricity access loss rate	Time Step	
Population growth		
Effect of price on consumption		
Electricity price		
Price change		
Reserve Energy Coverage		

The sub-model comprises two key stocks, namely: population with electricity access, and population without electricity access. There are also three key flows: electricity access rate, electricity access loss rate, and population growth. The stock of population without electricity access decreases as more people gain access to electricity through energy generated from new plants completion, and increases as population grows or people lose access to electricity as a result of plant decommissioning. The parameters, sources, and values in this sub-model are shown in Table 4.3.

Table 4.3: Electricity access sub-model parameters

Parameter	Units	Value	Source
Initial Population without Electricity Access	People	523,320,000	(IEA, 2002)
Initial Population with Electricity Access	People	310,000,000	(IEA, 2002)
Average consumption per access person	GWh/People	0.00131	Author's estimation
Reference Electricity Price in kWh	US$/kWh	0.5	(AfDB, 2013)
Net Population growth rate	Dmnl/year	0.0252	(UN, 2015)
Effect of Price on Consumption TABLE	Dmnl	graph	Author's formulation
Time Step	Year	*0.0625*	Author's setting

Population with access increases as people gain access to electricity, and decreases as access is lost. The key parameters in the electricity access sub-model are the net population growth rate and the average consumption per access person. The equations for the key sub-model variables include the electricity access rate (EAr):

$$EAr = Max\ [Min\ \left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0] \quad (1)$$

where *PCp* is the production completion, that is, the energy produced from new power capacity completed in a given year; *TS* is the time step, *PwA* is the population without electricity access, and *AvCp* is the average consumption per person. The maximum constraint in the equation ensures that the stock of population without electricity access remains non-negative while the minimum constraint limits the flow rate to that group.

The average consumption per person in the model is not based on the conventional per capita income formulation. Africa's electricity consumption per capita is estimated as 620 kWh per year (AfDB, 2013). However, given that only a fraction of the total population have electricity access; using average per capita, which expresses access over the entire population, would understate the average electricity demand per person. The average electricity consumed per person is thus expressed as a function of the price effect on consumption, and the initial average consumption per person (this is calculated by dividing the population with access at start time by the energy used at the start time). This results in estimation of the average electricity consumption per capita over time, with an initial value of approximately 1,130 kWh per annum, a figure still far below the global average of 2,730 kWh in 2009 (AfDB, 2013). This formulation diminishes the error that arises from using population as the basis for estimating electricity needs for the entire economy (of which residential consumption constitutes a smaller fraction compared to industry and commercial sectors), and also caters for growth in consumption emanating from any change in the economic status of individuals. The electricity access loss rate (*EALr*) is:

$$EALr = Min\ \left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right] \quad (2)$$

where *PCd* is the production decommissioning, the energy lost when power capacity is decommissioned in a given year, and *PnA* is the population with electricity access. The minimum constraint here ensures that when the population with electricity access is zero, no person can lose access to electricity. The population growth rate (Pg) is:

$$PGr = TP * nPgr \tag{3}$$

where *TP* is total population, and *nPgr* is the net population growth rate. The population without electricity access (PwA), a key variable of the model, depends on three key flows: the population growth rate, the population who lose electricity access, and the electricity access rate. The PwA is computed as:

$$PwA = PwA_{int} + \int [(TP * nPgr) + Min\left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right] - Max[Min\left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0]]dt \tag{4}$$

where PwA_{int} is the initial population without electricity access, *Pg* is the population growth, *EALr* is the electricity access loss rate, and *EAr* is the electricity access rate. The population with electricity access (PnA) is formulated as:

$$PnA = PnA_{int} + \int [Max[Min\left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0] - Min\left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right]]dt \tag{5}$$

where PnA_{int} is the initial population with electricity access. These are the equations for the key stocks and flows in the electricity access sub-model. A detailed snapshot of the sub-model structure is depicted in Figure 4.2

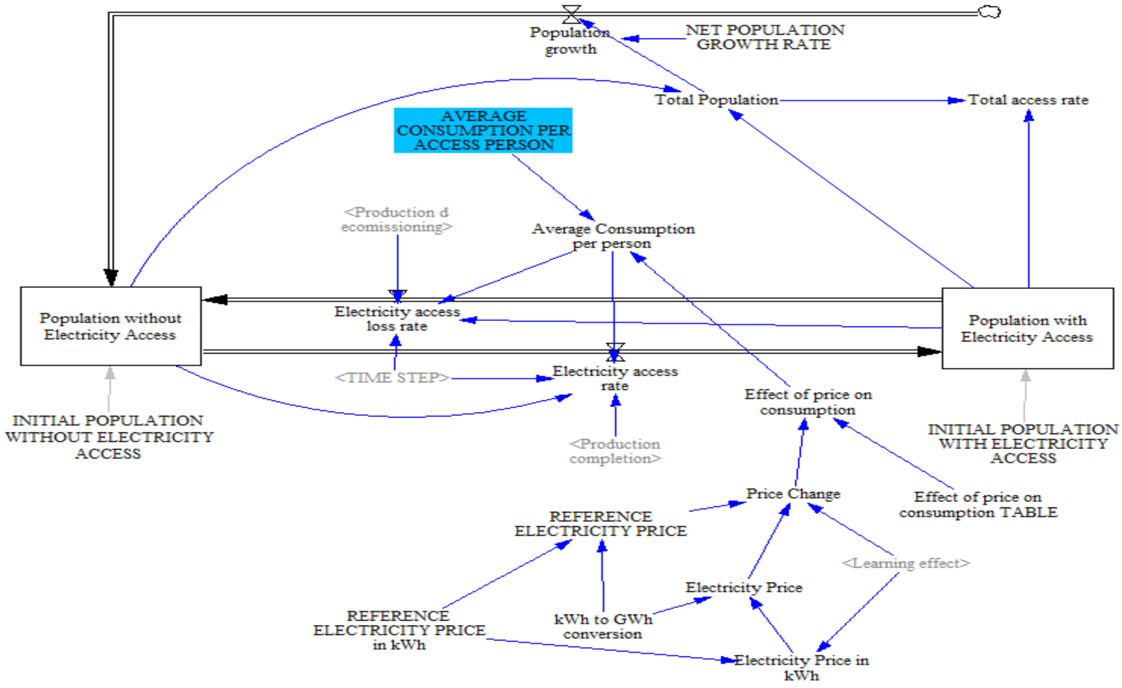


Figure 4.2: Electricity access sub-model

4.6.1.2 Electricity capital investment sub-model structure and equations

The electricity capital investment sector illustrates the financial requirements for the installation of power capacity in Africa. This sector determines how many new power projects are commissioned for construction, based on the financial resources/investment available. The boundary chart of this sub-model in Table 4.4 shows the endogenous, exogenous, and excluded variables.

Table 4.4: AFELA model: electricity capital investment sub-model boundary

Endogenous	**Exogenous**	**Excluded**
Electricity capital investment sub-Model		
African GDP	Initial GDP	Politics
Indicated Investment Backlog	Initial Investment Backlog	Inflation
Cumulative Investment	Initial Cost per GW Unit	
Indicated Annual Investment	GDP growth rate	
Annual Investment	Learning rate	
Cost per GW Unit	Investment rate	
GDP growth	Investment rate policy	
Learning Effect		

This sub-sector comprises two key stocks: indicated investment backlog, and African GDP. A third stock called cumulative investment was created to compute the total investment made during the simulation period. There are also two key flows: annual investment, and indicated annual investment. A third flow, GDP growth, calculates the yearly change in African GDP. The stock of indicated investment backlog calculates the total financial needs in US$ billions over the simulation period. It increases or decreases when there is a positive or a negative difference between the indicated annual investment and the annual investment, respectively. An essential focus of the model is the rate of annual investment (an outflow from the indicated investment stock), and how this rate would respond to policies such as change in regulations or incentives offered to private firms. It is expected that the annual investment would increase, resulting in increased cumulative investment. The key assumptions made on the parameters in this sub-model include learning rate, the initial cost per GW unit, and initial investment backlog. The parameters, sources, and values in this sub-model are listed in Table 4.5.

Table 4.5: Electricity capital investment sub-model parameters

Parameter	Units	Value	Source
Initial GDP	US$	1,208,500,000,000	(IEA, 2002)
Initial Investment Backlog	US$	300,000,000,000	Author's estimation
Initial Cost per GW Unit	US$/GW	2,000,000,000	Author's estimation
GDP growth rate	Dmnl/year	0.046	(OECD, 2016)
Learning rate	Dmnl	0.05	Author's estimation
Investment rate	Dmnl/year	0.01	(Rosnes and Shkaratan, 2011)

The electricity capital investment sector of the AFELA model captures a core aspect of this study; the finance gap of Africa's electricity sector, and how state and market policies can incentivise and increase the flow of private sector finance into the power sector.

The main sources of finance for investment in the energy sector are already identified as domestic governments, bilateral and multilateral aid, and private sector financing. The model assumes a limitation on the extent of foreign aid granted to Africa, and also on the national budgetary allocations for expanding electricity access. Private sector financing therefore becomes the focus area through which additional funding can be attracted into the energy sector. The size of investment from this private funding is a function of market conditions, and national policies including incentives to attract private investments.

The main equations used for this sub-model are those for the annual investment flow, the indicated annual investment flow, and the indicated investment backlog stock. One key variable of this sector is the annual investment rate (AIr) given as:

$$AIr = Min\left[\left(GdP * \left(Ir + step(Irs, 2020)\right)\right), \left(\frac{IiB}{TS}\right)\right] \quad (6)$$

where *GdP* is African GDP, *Ir* is the investment rate, *Irs* is the investment rate sensitivity, a policy parameter to assess the effect of a change in the investment rate, and *IiB* is the indicated investment backlog. The indicated annual investment (IIr), the amount that ought to be invested into the electricity sector annually, is given as:

$$IIr = CGu * CDd \quad (7)$$

but *CGu is:*

$$((intCGu + step(CGWS, 2020)) *L) \quad (8)$$

hence,

$$IIr = (intCGu + (step(CGus, 2020)) * L) * CDd \quad (9)$$

where $_{int}CGu$ is initial cost per GW unit, *CGus* is the cost per GW unit sensitivity, *L* is the learning effect, and *CDd* is the annual capacity demand deficit. The cost per unit is a constant value representing an average cost of installing a GW unit of power. The average GW cost is not decoupled into the different energy sources. Instead it was attributed a value based on the average cost of the leading power sources from which electricity is generated in Africa. Since the electricity supply sub-model did not unbundle the different sources, this fixed unit cost improves consistency in the forecast. Differentiated unit pricing would require unbundling the generation mix to ensure accuracy, a task rather in-depth and demanding beyond the scope of this research.

The indicated investment backlog (IiB) is the stock of capital investment (in US$) that should have been made towards electricity access in Africa. Because of financial constraints, the investment deficit accumulates into a stock of indicated investment backlog. This stock is computed as:

$$IiB = IiB_{int} + \int \Big[(intCGu + (step(CGus, 2020)) * L) * CDd - Min\left[\left(GdP * \left(Ir + step(Irs, 2020)\right)\right), \left(\frac{IiB}{TS}\right)\right]\Big] dt \quad (10)$$

The amount of investment made annually throughout the simulation accumulates into the cumulative investment (CmI). While this is not a key stock in the model, it gives a clear insight of the total investment made in the power sector at any given point of the simulation. The formulation for this stock is:

$$CmI = \int Min\ \left[\left(GdP * \left(Ir + step(Irs, 2020)\right)\right), \left(\frac{IiB}{TS}\right)\right] dt \qquad (11)$$

The amount of investment made in the power sector in Africa is assumed to be a fraction of the total Gross Domestic Product (GdP). The GdP changes annually, as the growth rate changes.

$$GdP = GdP_{init} + \int [GdPg]dt \qquad (12)$$

The GdP_{init} stands for the initial GdP, and $GdPg$ is the annual GDP growth. The capital investment sub-model in Figure 4.3 indicates the variables and parameters that affect the annual investment.

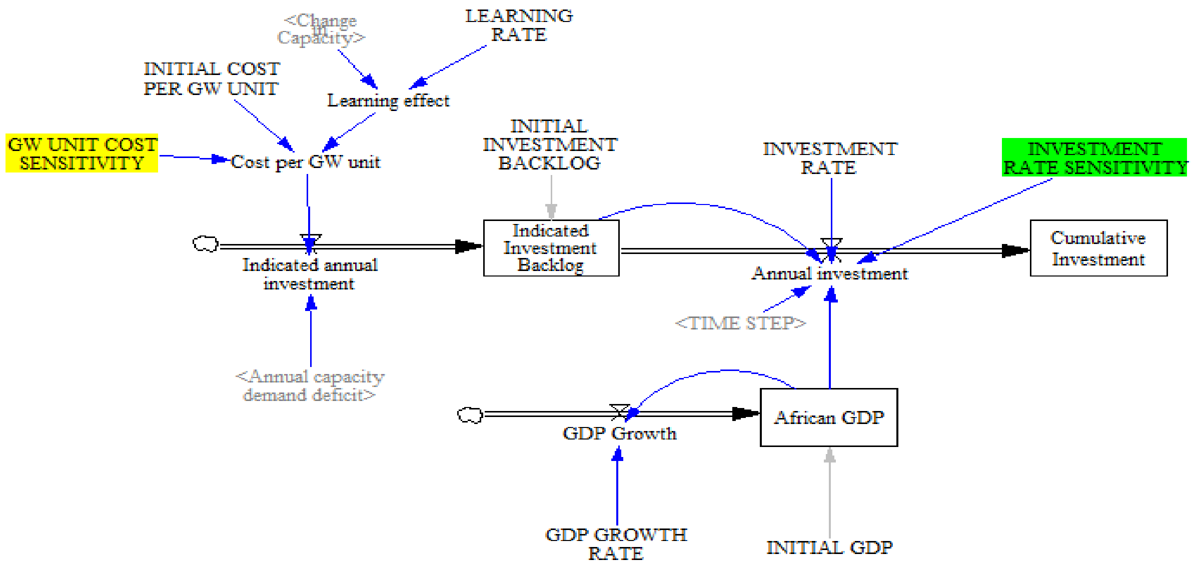


Figure 4.3: Electricity capital investment sub-model

4.6.1.3 Electricity supply capacity sub-model structure and equations

This sub-model contains five key stocks: power capacity backlog, which is the outstanding capacity needed at any given point in time of the simulation; power capacity construction - the total amount of power capacity that is under construction; power capacity installed, which is the total amount of power installed and generating energy; actual energy used - the total amount of energy consumed each year, not including transmission losses; and power capacity decommissioned, which is the capacity discarded and is no longer in use. The boundary for this sub-model is defined by the variables in Table 4.6.

Table 4.6: AFELA model: electricity supply capacity sub-model boundary

Endogenous	**Exogenous**	**Excluded**
Power Capacity Backlog	Initial Capacity Backlog	Climate change
Power Capacity Construction	Initial Capacity Construction	Environmental factors
Power Capacity Installed	Initial Capacity Installed	Import and exports
Power Capacity Decommissioned	Average Plant Life	Weather
Annual capacity demand deficit	GW to GWh conversion	
Capacity commencement	Utilisation factor	
Capacity completion	Construction time	
Capacity decommissioning	Capacity adjustment time	
Indicated new capacity requirement	Supply line adjustment time	
Desired supply line	Initial Production	
Desired acquisition rate	Expected acquisition delay	
Expected capacity loss		
Expected capacity addition		
Capacity gap		
Desired capacity		
Hours in a year		
Actual Energy Utilised		
Production completion		
Production decommissioning		
Change in capacity		

There are also six key flows, including the annual capacity demand deficit, the capacity commencement, capacity completion, production completion, capacity decommissioning, and production decommissioning. The annual capacity demand deficit is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity, after accounting for the supply line. The annual amount of new capacity initiated for construction as a result of investments made, is the capacity commencement. Capacity completion is the annual amount of power capacity that is completed and commissioned for use; the production completion calculates the amount of energy generated for the newly completed capacity; capacity decommissioning is how much capacity is written-off annually; and the production decommissioning is the amount of energy lost because of the capacity decommissioning. This also translates to loss of electricity access. Besides the key stocks and flows, certain assumptions are also made about key parameters in this sub-model. These are shown in Table 4.7.

Table 4.7: Electricity supply capacity sub-model parameters

Parameter	Units	Value	Source
Initial Capacity Backlog	GW	112	Author's estimation
Initial Capacity Construction	GW	15	Author's calibration
Initial Capacity Installed	GW	101	(Department-of-Economic-and-Social-Affairs, 2006)
Average Plant Life	Year	60	Author's calibration
GW to GWh conversion	GWh/GW	8760	Standard computation
Utilisation factor	Dmnl	0.48	(Department-of-Economic-and-Social-Affairs, 2006)
Construction time	Year	3	Author's calibration
Capacity adjustment time	Year	1	Author's estimation
Expected acquisition delay	Year	2	Author's estimation
Supply line adjustment time	Year	1	Author's estimation
Initial Production	GWh	407370	(Department-of-Economic-and-Social-Affairs, 2006)

The AFELA model's estimation of the utilisation factor takes cognisance of the losses from transmission and distribution. These losses are not separated, but rather embedded in the formulation, because of limited access to the information required for explicit presentation. An increase in investment leads to increase in the total energy used, which amounts to an increase in the electricity access rate. The annual capacity demand deficit (*CDd*) is equivalent to the indicated capacity requirement, which is calculated as the maximum of the Supply line adjustment (Sla), and desired acquisition rate (Dar), expressed as a fraction of the supply line adjustment time (Slt). The *CDd* is therefore defined as:

$$CDd = \left(\frac{Max(Sla\,,\ Dar)}{Slt}\right) \qquad (13)$$

The capacity commencement (*CCo*) is a function of the power capacity backlog (*PcB*), the annual investment (*AIr*), and the cost per GW unit (*CGu*) and is given by:

$$CCo = Max\ [Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right], 0] \qquad (14)$$

Capacity completion (CCp) is a function of the power capacity construction (IPCC) and the construction time (Ct):

$$CCp = \left(\frac{PcC}{Ct}\right) \qquad (15)$$

The capacity decommissioning (PCd) is given as:

$$PCd = \left(\frac{PcI}{AvPl}\right) \qquad (16)$$

where *PcI* is the power capacity installed, and *AvPl* is the average plant life. The production completion (PCp) is a function of the capacity completion (CCp), the GW to GWh conversion (Cf), the utilisation factor (Uf), and utilisation factor sensitivity (Ufs).

$$PCp = (CCp * Cf) * \left(Uf + step(Ufs, 2020)\right) \tag{17}$$

Production decommissioning (PDn) is given as:

$$\text{PDn} = \left(\frac{EnU}{AvPl}\right) \tag{18}$$

Where *EnU* is the actual energy utilised, which is also calculated as:

$$EnU = EnU_{ini} + \int \left[(CCp * Cf) * \left(Uf + step(Ufs, 2020)\right) - \left(\frac{EnU}{AvPl}\right)\right] dt \tag{19}$$

The power capacity backlog (PcB) is a function of the initial power capacity backlog (PcB_{ini}), the power capacity commencement rate:

$$PcB = PcB_{ini} + \int \left[\left(\frac{Max(Sla\,,\ Dar)}{Slt}\right) - \ Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right] dt \tag{20}$$

The power capacity construction (IPCC) is the sum of the initial power capacity construction (PcC_{ini}) at the start of simulation and the difference between the capacity commencement and capacity completion.

$$PcC = PcC_{ini} + \int \left[[Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right] - \left(\frac{PcC}{Ct}\right)\right] dt \tag{21}$$

Power capacity installed (PcI) accumulates the initial power capacity installed (PcI_{ini}), and the difference between capacity completion and capacity decommissioning.

$$PcI = PcI_{ini} + \int \left[\left(\frac{PcC}{Ct}\right) - \left(\frac{PcI}{AvPl}\right)\right] dt \tag{22}$$

Power capacity decommissioned (PcD) only integrates the initial power capacity decommissioned (PcD_{ini}) and the capacity decommissioning rate.

$$PcD = PcD_{ini} + \int \left(\frac{PcI}{AvPl}\right) dt \tag{23}$$

A key link between the access and supply sectors is the desired power capacity (DPC). This variable depends on the population growth, the average consumption per person, and the utilisation factor. The DPC is given by:

$$DPC = \left(\frac{\frac{AvCp * TP}{Uf}}{Cf} \right) + Ds \qquad (24)$$

Where *Uf* is the utilisation factor and *Cf* is the conversion factor. A complete overview of the electricity supply capacity sub-model is shown in Figure 4.4

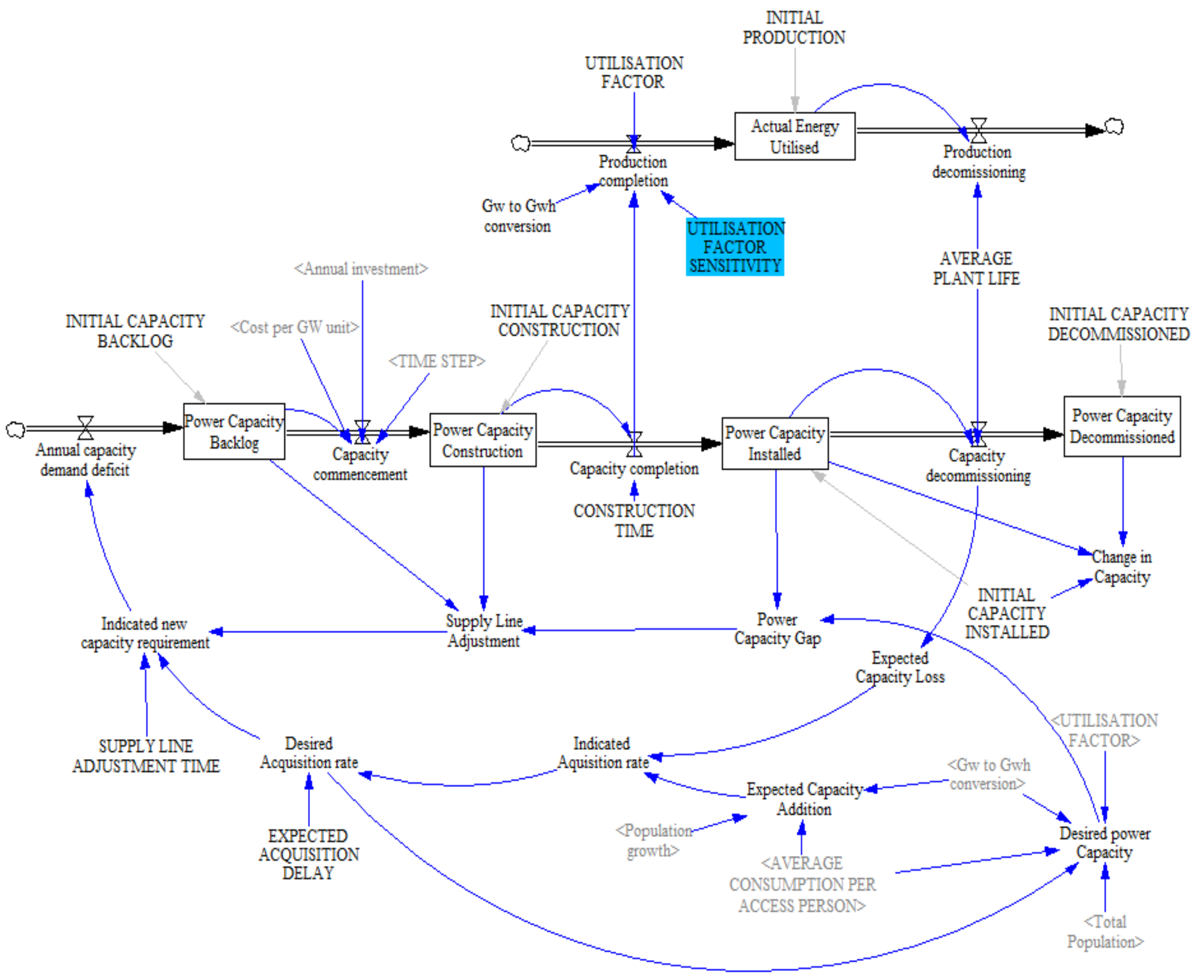


Figure 4.4: Electricity supply capacity sub-model

4.6.2 Model testing and validation

Model validation in system dynamics is an essential part of building confidence and reliability into the model. It is an exercise to establish that the model's structure and behaviour matches the knowledge of the actual system examined (Senge and Forrester, 1980), and boosts confidence when using the model for the purpose for which it was developed (Barlas, 1996). There are different ways for validating a model. Some key validation techniques include those for structural validity, a dimensional consistency check, parameter assessment, behaviour reproduction, and a sensitivity test.

4.6.2.1 Structural Validity

This is one of the key tests to establish that the model formulation is consistent with reality. It is a multidimensional process of problem identification and representation, logical formulation of the structure, as well as the illustration of the mathematical and causal relationships (Qudrat-Ullah and Seong, 2010). Structural validation ensures that the formulations in the model conform to conventional and logical wisdom. For example, it would be against such understanding if any of the population stocks attained negative values. In an effort to improve general understanding of the model, verification of its parameters, and validation, SDM-Doc (see: (Martinez-Moyano, 2012)) containing all the variables and parameters used, as well as their equations, is generated.

4.6.2.2 Dimensional Consistency

Another way to assess model validity is by checking that the units of all variables and parameters are indicated and consistent throughout the model. Since the model was developed using the Vensim software, which offers a functionality for checking dimensional (units and model) consistency (Eberlein and Peterson, 1992), this process was less cumbersome. The units of equations and the model were checked, and they indicated consistency.

4.6.2.3 Parameter Assessment

The data for certain key parameters was either not readily accessible, and/or different sources reported different figures for some parameters. As such, the resulting base-run was thus noticeably distinct from the reference mode. Some of these key parameters include the plant life, the initial average cost per GW unit, the average construction time, the initial capacity under construction, and the learning rate. Another key reason for calibrating these parameters is because this model aggregates different technologies which have different plant life, learning rate, construction time, average cost, and capacity under construction. To improve upon the model validity based on data, and obtain an aggregate value for the technologies involved, these parameters in the model were calibrated to ensure that values that are more accurate could be obtained for parameters with high uncertainty surrounding them. The calibration results are shown in Table 4.8.

Table 4.8: Model parameters calibration and results optimisation

Initial point of search	**Maximum payoff**
AVERAGE PLANT LIFE = 60 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 3 INITIAL CAPACITY CONSTRUCTION = 10 LEARNING RATE = 0.05 Simulations = 1 Pass = 0 Payoff = -86.0389	*AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 *INITIAL CAPACITY CONSTRUCTION = 12.0521 LEARNING RATE = 0.1 Simulations = 601 Pass = 3 Payoff = -15.1774
Confirmatory search	**Confirmation of Maximum payoff**
*AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 *INITIAL CAPACITY CONSTRUCTION = 12.0521 LEARNING RATE = 0.1 Simulations = 601 Pass = 3 Payoff = -15.1774	AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 INITIAL CAPACITY CONSTRUCTION = 12.0521 *LEARNING RATE = 0.1 Simulations = 71 Pass = 3 Payoff = -15.1774
Parameter confidence bound defined	**Parameter confidence bound found**
20 <= AVERAGE PLANT LIFE = 49.328 <= 80 2e+009 <= INITIAL COST PER GW UNIT = 2e+009 <= 5e+009 2 <= CONSTRUCTION TIME = 2.0015 <= 7 10 <= INITIAL CAPACITY CONSTRUCTION = 12.0521 <= 30 0.01 <= LEARNING RATE = 0.1 <= 0.1	46.3782 <= AVERAGE PLANT LIFE = 49.328 <= 52.6256 2e+009 *<= INITIAL COST PER GW UNIT = 2e+009 <= 2.04846e+009 2 *<= CONSTRUCTION TIME = 2.0015 <= 2.17994 10.606 <= INITIAL CAPACITY CONSTRUCTION = 12.0521 <= 13.4996 0.0192344 <= LEARNING RATE = 0.1 <= 0.1 *
The final payoff is -1.517738e+001	

4.6.2.4 Behaviour Reproduction

After conducting the parameter assessment through calibration optimisation, the calibrated base-run produced a behaviour that fitted better with the reference mode than the initial base-run. The calibration was conducted to build confidence in the parameter values that were surrounded by a high degree of uncertainty. Indeed, replication of the reference mode is not a guarantee that the model is correct, but only an indication that the model's validity is not questioned based on data. The comparison between the simulated results and historical data of key variables such as the power capacity installed and the population without electricity shows consistency between model behaviour and data.

4.6.2.5 Sensitivity Analysis

Another way to improve understanding of model structure and behaviour relationship is to conduct sensitivity analysis. It helps test the robustness of conclusions drawn in relation to parameters estimated (Sterman, 2000), especially those parameters with high uncertainty, but greater impact. Sensitivity also helps identify high leverage points for policy interventions. The results of the sensitivity tests are extensively discussed under the results and analysis section. Other related validation tests were carried out, including how the model responds to extreme tests of both parameters and simulation duration. The model produces results consistent with the dynamics and feedback processes design within.

4.6.3 Scenarios developed

The AFELA model examines four scenarios, namely the: the Baseline scenario, which represents the business as usual; Economies of scale scenario, which entails a decline in average unit cost through learning effect; Capacity utilisation factor scenario, which entails an improvement in the capacity utilisation factor; and Electricity access investment, which represents an increase in annual investment. These scenarios were assessed by conducting sensitivity analysis of three key parameters: the unit GW cost, the capacity utilisation factor, and the investment rate. This was to ascertain what must happen to achieve universal access to electricity in Africa by 2030, the target set by the UN Sustainable Development Goals. Whether a decline in the baseline scenario is enough, or a decline in cost per GW unit, or is an improvement in the efficiency of presently installed power plants to optimal capability, or is an increase in the annual investment rate. The simulation timeline extended to 2040, in part, to validate the model and ensure that the policy options that led to universal access by 2030 were robust beyond that timeline. It was also to understand how long it would take for universal access to be attained under the baseline scenario.

Key model parameters (see Table 4.9), identified as potential leverage points for policy actions to address the problem of lack of electricity access, and were varied independently to ascertain the impact on the behaviour of model variables. The baseline scenario shows the pattern of development of the variables if no policy interventions are implemented. The economies of scale scenario reduces the GW unit cost by half a billion dollars (US$). This conceptualisation is based on the likely outcome from employing economies of scale, research and development, and the learning effect.

Table 4.9: Scenario assessment parameters

Scenarios	**Parameters**	**GW unit Cost (US$)**	**Utilisation factor**	**Investment rate**
Baseline		2,000,000,000	0.48	0.01
Economies of scale		1,500,000,000	0.48	0.01
Capacity utilisation factor		2,000,000,000	0.80	0.01
Electricity access investment		2,000,000,000	0.48	0.03

The capacity utilisation scenario assumes that power plants generate at an optimal efficiency of 80%. This is grounded on an estimation of the mean efficiency of the different energy sources from which power is generated across Africa. The electricity access investment scenario looks at the effect an increase in investment rate poses on electricity access. The annual investment rate in this scenario is increased from one to three per cent of GDP.

4.6.3.1 The baseline scenario

This scenario considers how variables in the model will develop if nothing changes, or no policy intervention is implemented. This scenario assumes that all parameters will retain their base values and the future dynamics of the model is predetermined by such values. This is sometimes referred to as the 'business as usual case', suggesting that there is no change from the present initial conditions defined within the model. This scenario is important because it can help analysts decide whether the modelled problem requires intervention, or is destined to self-correct in the future.

4.6.3.2 Economies of scale scenario

This scenario considers the fact that average unit cost of production declines as an industry enjoys economies of scale. Through research and development, innovation, and the learning that occurs as a result of accumulated experience, the average real cost per GW unit of power is expected to decline over time. The scenario therefore assesses the implication of the learning effect on the unit cost of power over the simulation period. If there is high learning, the unit cost would decline, resulting in a rise in the number of people who gain access to electricity. On the other hand, a low learning effect indicates limited advantages accruing from the additions of capacity. This is especially common in cases where the technology has matured and the potential for further innovation to improve it is very limited.

4.6.3.3 Capacity utilisation factor scenario

The utilisation factor scenario is based on the understanding that no power plant operates at 100% efficiency. The actual fraction of energy generated compared to the potential energy based on the capacity installed is termed as the capacity utilisation factor (CUF). The CUF is thus the ratio between total energy a power plant generates vis-a-vis the maximum energy that it can posibly generate within a given period of operation. It is important to consider this scenario, because it is necessary to ascertain whether the lack of electricity access is due to infrastructural inadequacy (limited installed capacity), operational inefficiency (low utilisation factor), or both.

4.6.3.4 Electricity access investment scenario

This is the key policy policy parameter in the model. The overall thesis of the chapter relies on the hypothesis that an increase in the investment rate will result in more people gaining access to electricity. Under this scenario, the investment rate is varied, to observe the dynamics of the population without access to electricity over time.

4.7 AFELA MODEL RESULTS

The initial simulation results of the model did not accurately match the data key variables, such as the population with, and those without, electricity access, the power capacity installed, the energy utilised, and the total electricity access rate. In an effort to establish the validity based on data, the model was calibrated to improve the assumptions made of certain key parameters for which actual data was not obtained. These parameters included the average plant life, the cost per GW unit of power, the construction time, the initial capacity construction and the learning rate (see Table 4.8).

After conducting 601 simulations (see Table 4.9), all the calibrated parameters had recorded a change in value, except the cost per GW unit. The new values obtained are shown under the column *maximum payoff* in Table 4.8. There was also an improvement in the final payoff from -86.0389 to -15.1774, indicating that these new parameter values resulted in a better fit between the simulated model results and the actual data. The calibrated values of the base run model were then loaded and simulated under a different name, 'baseline'. A total of 71 (see Table 4.8) simulations were done under the baseline and the payoff remained at -15.1774, as expected, since the new values of the parameters were now initialised and run as the baseline. The simulation runs also offer confidence bounds for the parameters that were calibrated. The baseline model, therefore, becomes the final model used for assessing different scenarios and policy options through sensitivity analysis. The next section presents results and discussions from the AFELA model.

4.7.1 AFELA Baseline results

The AFELA baseline results replicate how the variables changed over time. The baseline result of the simulation is juxtaposed with historical data, to establish confidence in the model as a form of validation before using it as a policy tool. Figure 4.5 shows both the historical data and the baseline simulation results of the power capacity installed in Africa, as well as the energy used by all consumers for the period 2001 to 2015 and 2001 to 2040 respectively. The results show a reasonable fit between historical data and model results.

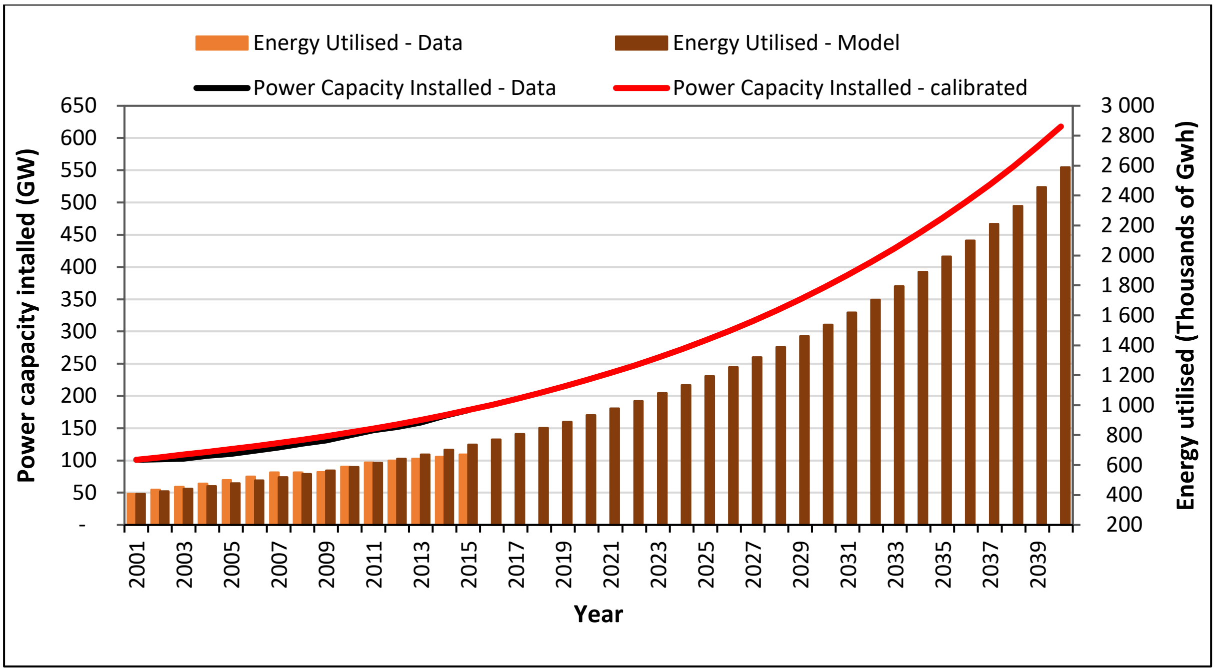


Figure 4.5: A comparison of data and baseline results of power capacity installed and energy utilised

The baseline results on the proportion of the African population with access to electricity in 2005 and 2010 was 39% and 43% respectively (see Figure 4.6), consistent with the findings of the IEA (2017). Figure 4.6 indicates that, under the baseline scenario, the number of people in Africa who would still live without electricity by 2030 will exceed half a billion people (approximately 597 million people), representing approximately 35% of the total population. This is also consistent with the forecasts of the Africa Progress Panel (2015) and IEA (2014), that a total of 600 and 635 million people, respectively, would not have electricity access by 2030. This calls for a concerted effort from stakeholders (governments and international agents) in the African electricity sector across local, national, and international levels, to set in motion policies that accelerate access from 65% under the 'business as usual case' to 100% by the year 2030.

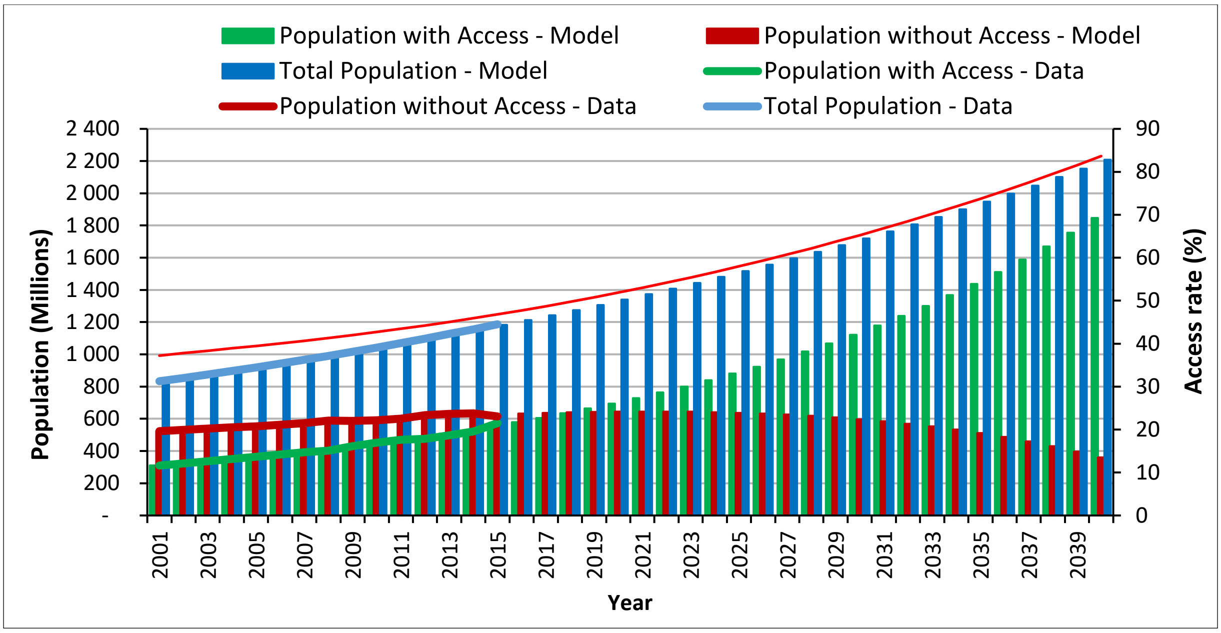


Figure 4.6: Africa's population with, and without electricity access, and of total population

4.7.2 Scenario analysis

The results of the four scenarios from 2019 and 2040 are presented in the preceding section.

4.7.2.1 Power capacity installed

Figure 4.7 shows the *total power capacity installed* results from the four scenarios.

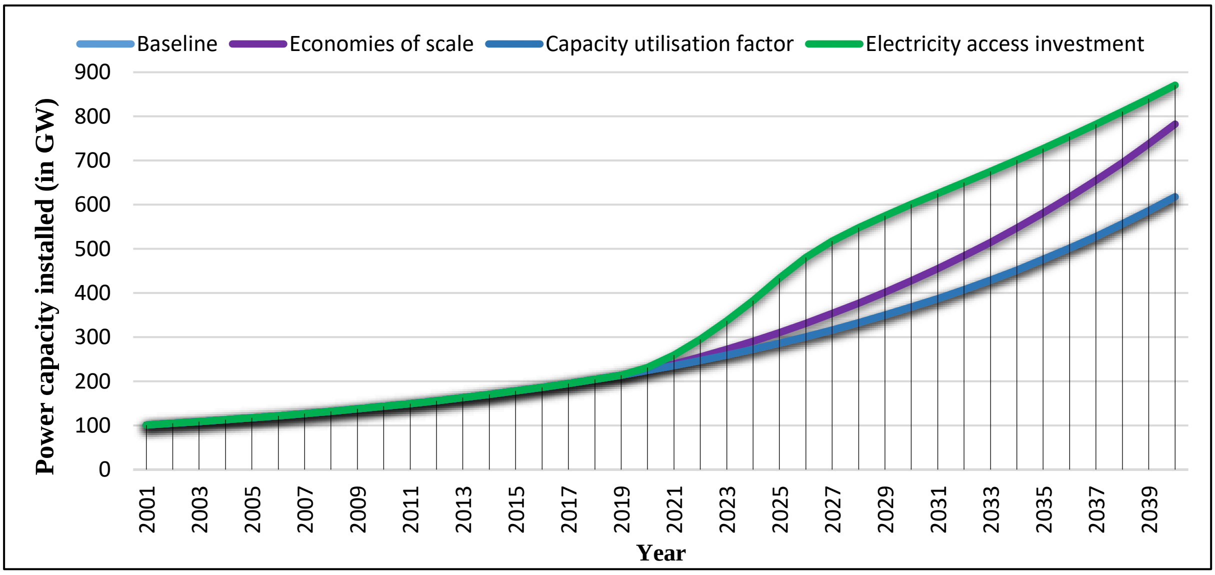


Figure 4.7: Power capacity installed under the different scenarios

The Electricity access investment scenario, which increases the annual investment rate from one to three per cent of GDP, has the highest impact, where the total capacity installed reaches 871 GW in 2040, compared to only 618 GW in the baseline scenario. The Economies of scale and Capacity Utilisation Factor scenarios reach 783 GW and 618 GW, respectively. The difference of 261 GW between the Baseline and the Electricity access investment scenario by 2040 highlights the extent to which power capacity can be expanded if annual investment were to increase by this margin. A potential decline in the GW unit cost under the Declined unit cost scenario would also lead to more capacity being installed, because the baseline annual investment could procure more GW units. There is, however, no change in the power capacity installed under the Baseline scenario and or the improved utilisation factor scenarios. The latter only boosts the efficiency of already installed capacity, without adding new power capacity units. In effect, it only affects the GWh and not the GW.

4.7.2.2 Energy utilised

There is a notable insight to be obtained from the results in Figure 4.7 and Figure 4.8. In Figure 4.7, the total power installed is greater (428 GW) under the Economies of scale scenario than the Capacity utilisation factor scenario (368 GW), by 2030. However, the total energy utilised (see Figure 4.8) is greater (3.9 million GWh) under the Capacity utilisation factor scenario than it would be under the Economies of scale scenario (3.3 million GWh) in the same year. This attest that while the power capacity installed influences the electricity access rate, the actual energy that is consumed is more critical in determining the number of people who have access to electricity.

Although the utilisation factor does not directly affect power capacity installed, it can be conceptualised that the rise in the amount of energy available through higher utilisation factor will eventually lead to a lower overall capacity being installed. Compared to the Baseline scenario, the Capacity utilisation factor and Electricity access investment scenarios lead to an extra one million GWh of energy being available in the African electricity market by 2040.

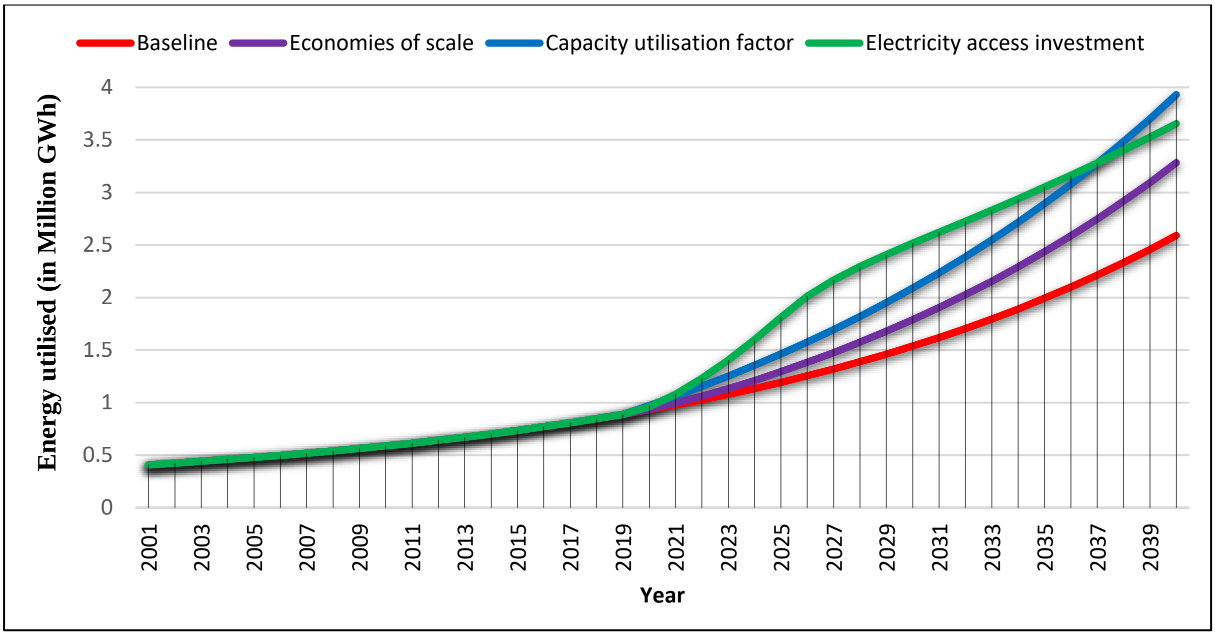


Figure 4.8: Energy utilised under the different scenarios

4.7.2.3 Total electricity access

The results (see Figure 4.9) reveal that, from the scenario start time of 2019, the access rate would be 51%. Under the Baseline scenario, approximately 84% of Africans will have access to electricity, while 16% remain without access.

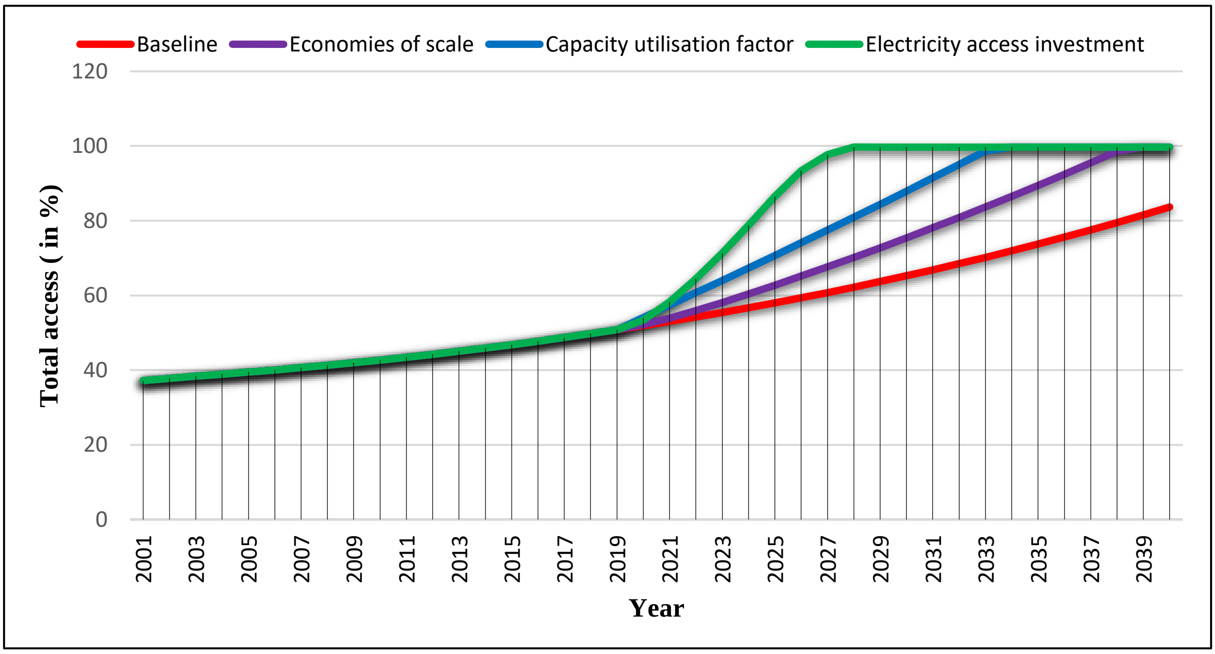


Figure 4.9: Total access under the different scenarios

The Electricity access investment scenario, however, will ensure that universal access is attained across the continent by 2028, a feat that would mean a realisation of the SDG7 in relation to electricity. Under the improved utilisation factor and declined GW unit cost scenarios, universal electricity access in Africa would not be achieved until 2033 and 2038, respectively.

4.7.2.4 Population without access

The goal relating to energy access in Africa is to get the stock of population without electricity access to zero. Under the Baseline scenario, about 600 million Africans would not have electricity access by 2030, and this would reduce to 360 million by 2040. This emphasises the need for stakeholders to act in a timely manner if the SDG7 is to be attained. Similarly, as shown in Figure 4.10 the Baseline, Economies of Scale, and Capacity Utilisation Factor scenarios would not lead to universal electricity access by 2030. The Electricity Access Investment scenario is the only among the four scenarios that would ensure universal access by 2030. It is apparent, therefore, that any proactive policy decision that pursues universal electricity access in Africa by 2030 would contain financial obligation that would require commitment to new investment into Africa’s power and electricity sectors.

Governments would battle with severe financial implications in an attempt to realise the investment needs under the electricity access investment scenario. As depicted in Figure 4.11 for instance, the annual investment would have to increase from US$26 billion in 2019 to US$114 in 2026 in order to achieve universal electricity access in 2028. Approximately US$ 500 billion dollars, equivalent to the investment backlog in 2019, would have to be cleared through the yearly investment during this period. This reality of the enormous scale of the financial resources required to pursue universal electricity access in Africa by 2030, supports the principal hypothesis of this study that private finance is essential to meet the investments required in Africa’s unmet electricity markets.

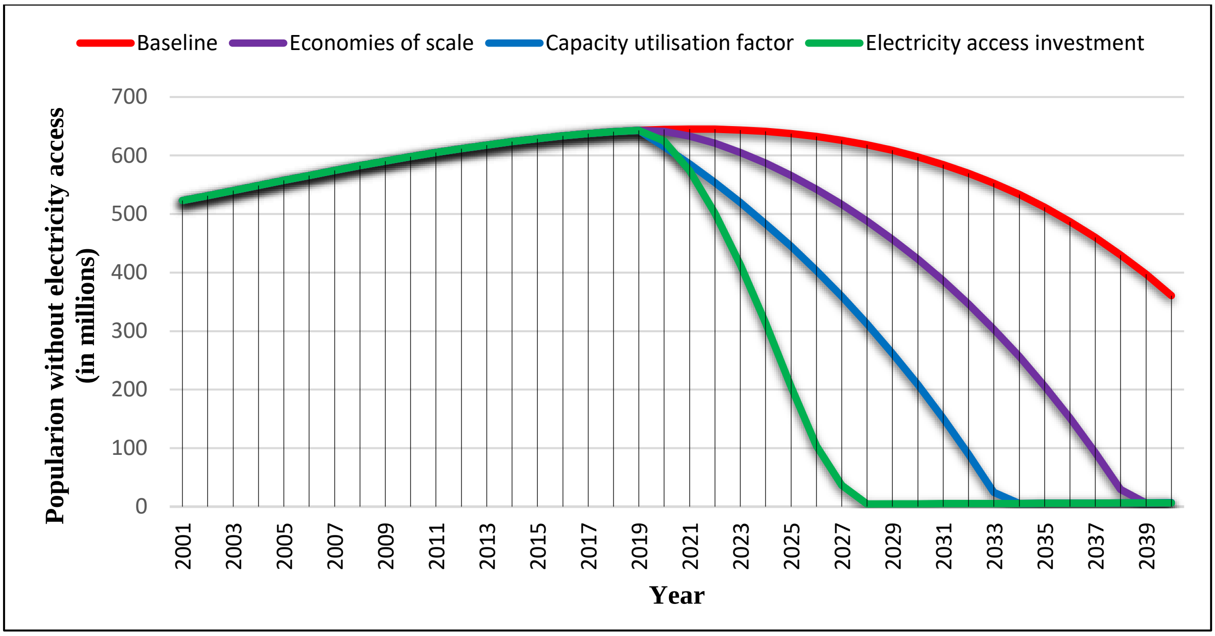


Figure 4.10: Population without electricity under the different scenarios

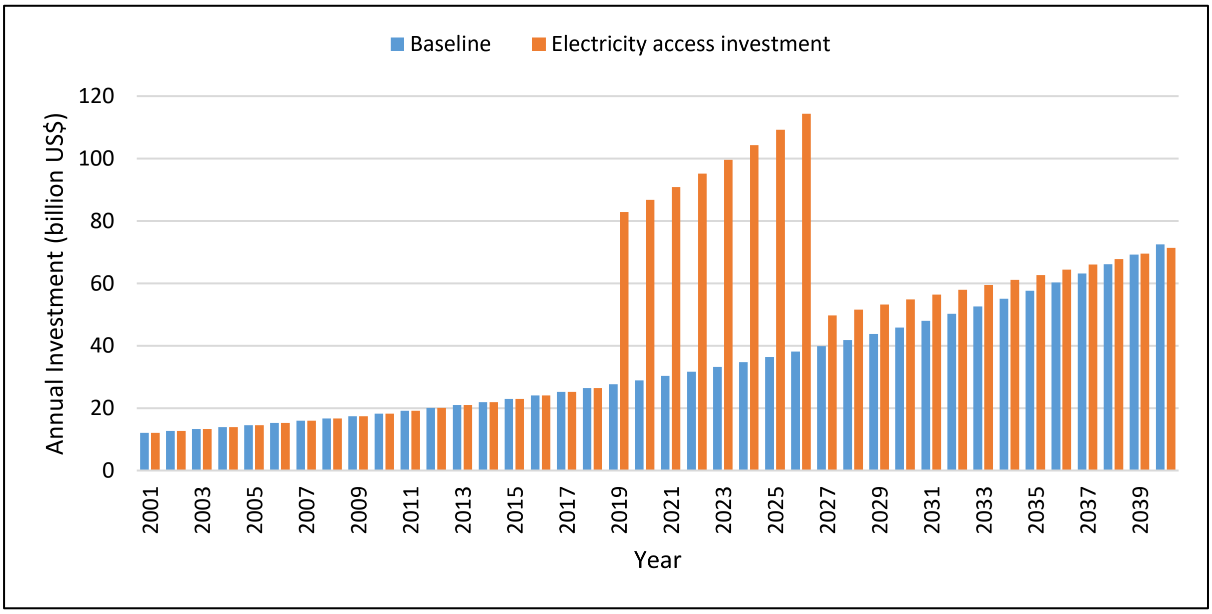


Figure 4.11: Annual investment under Baseline and Electricity Access 1nvestment Scenarios

Although the financial requirements appear out of reach, the incentive to incur lower capital expenditures in the future, in order to provide a service as critical as electricity, and the opportunity to utilise various funding sources within and beyond national and continental boundaries, makes this surmountable.

4.7.3 Sensitivity analysis

In order to ascertain how key variables in the model respond to changes of key parameters, a logical range of values is set for the three key variables that were used for the scenario assessment, in order to conduct a sensitivity analysis. Unlike scenarios, sensitivity permits a parameter value to vary between a lower and upper bounds through multiple simulations. The result then shows a range of patterns of an endogenous variable affected by such parameter. The parameters, as well as the range through which their values are varied, is illustrated in Table 4.10. An in-depth discussion of the results is in the preceding sub-sections.

Table 4.10: Parameters and value range for sensitivity analysis

Parameter	**Unit**	**Value**	**Range**
GW unit Cost	US$/GW	2,000,000,000	1,000,000,000 < = > 5,000,000,000
Utilisation factor	Dmnl	0.48	0.20 < = > 0.80
Investment rate	Dmnl/year	0.01	0.004 < = > 0.03

4.7.3.1 Sensitivity of GW Unit Cost

The value for GW unit cost is varied from a low of US$1 billion to a high of US$5 billion. Since one cannot tell with certaininty what the actual value would be in 2040, this range of sensitiviy offers insight on the outcome of a shock in this parameter within the given value range. Unlike the Economies of Scale scenario, which considers only a favourable shock where cost declines, this sensitivity exercise reflects on both favourable and unfavourable shocks. The results in Figure 4.12 suggest that, even when the GW unit cost declines by half, that alone cannot lead to universal electricity access in Africa. The total access does not reach 100% in 2030, since the population without electricity access reaches zero only in 2033. On the other hand, if the cost were to increase to US$5 billion, over one billion people would still not have electricity access in 2040 (see Figure 4.12) Focusing on the 50% confidence bound of these sensitivity results, universal access is not possible even by 2040.

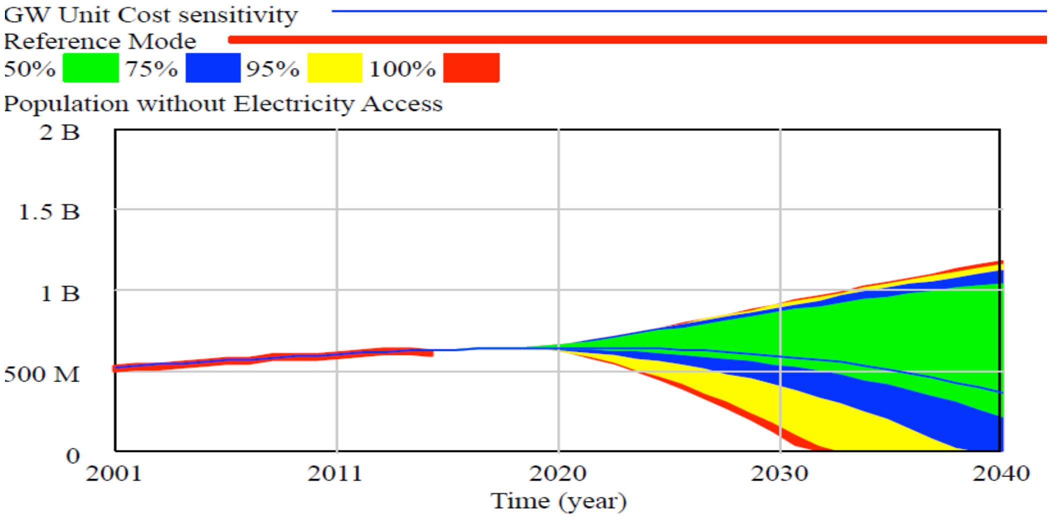


Figure 4.12: Sensitivity of GW unit cost on population without electricity access

4.7.3.2 Sensitivity of Utilisation Factor

This sensitivity considers the outcome of the number of the population without electricity if the current installed capacity is assumed to function at an average low of 20% efficiency, as is the case with some renewables, like solar photovoltaic, or at an average high of 80% efficiency as in the case of coal, gas thermal, and some hydro power. The results (see Figure 4.13) show a case of no universal access by 2030, even under 100% upper efficiency confidence bound.

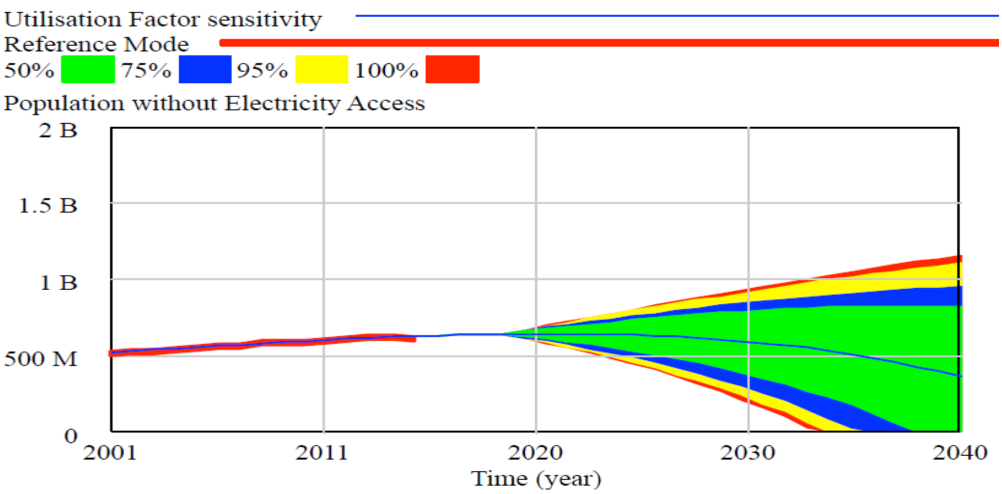


Figure 4.13: Sensitivity of utilisation factor on population without electricity access

An improvement in the utilisation factor of current power capacity alone by cutting the transmission and distribution losses, with the assumption that it will lead to an average performance efficiency of 80%, would still not be enough to achieve universal access by 2030.

4.7.3.3 Sensitivity of Investment Rate

Based on the proposition of this study, which suggests that an increase in finance flow to the power sector is a necessity, it is imperative to test the sensitivity of the investment rate to ascertain the impact of varying annual investments on the rate of electricity access in Africa. The investment rate or the fraction of African GDP invested towards electricity access, ranges from a minimum of 0.4% to 3% of GDP between 2019 and 2040. The sensitivity results in Figure 4.14 indicate that, at 100%, or 50% upper confidence bound, a universal access to electricity is achievable by 2028 or 2030 respectively. This implies that, Africa can reach total electricity access by 2030, if it invests approximately 3% of its GDP between 2019 and 2030 to the electricity sector. However, if investment falls from the current 1% to 0.04% of GDP during this period, the population without access could rise to 907 million and 1.2 billion people by 2030 and 2040 respectively.

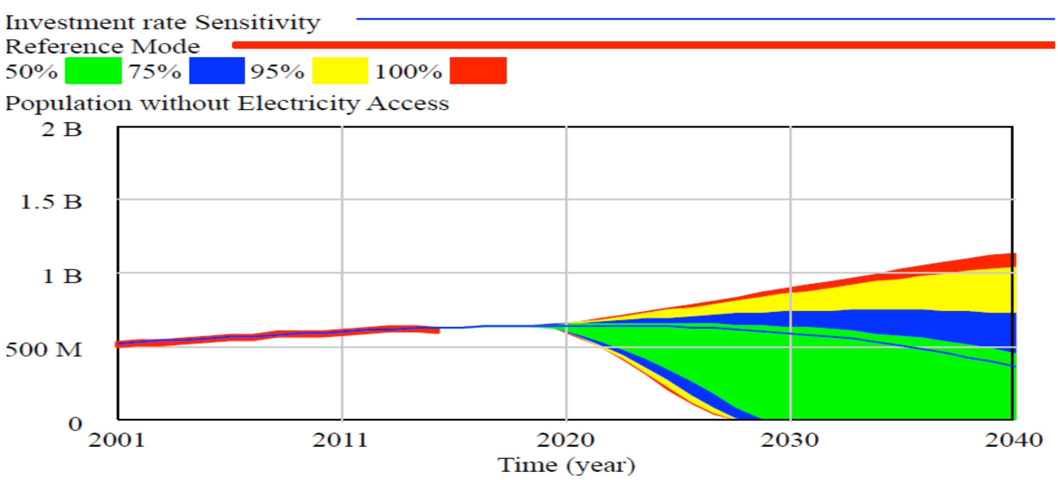


Figure 4.14: Sensitivity of investment rate on population without electricity access

The need for private sector investment in the Africa electricity market is affirmed, and it requires a change in market conditions, including liberalising markets that restrict private entity entry through regulatory reforms, and offering tax incentives to private firms that build and/or operate power plants. The success of the various power pools in the European electricity market populated by private sector operators is evidence that involvement of private entities in the African power market could boost the region's power generation capacity. In fact, such market policies could be the stimulus for expanding the renewable energy share in the total energy mix and increasing power availability.

4.8 CONCLUSIONS

National governments, and multilateral and bilateral aids, are crucial sources of funds for power infrastructure in Africa. These funding sources are however inadequate, less reliable, and in the long run, not sustainable for addressing the financial challenges associated with the required access to electricity. Private finance is a viable alternative that can be explored to bridge the finance gap, as it offers an opportunity to expand the financial robustness of the energy sector amid national budget constraints and inconsistent multilateral and bilateral fund flows.

The study considered four scenarios, namely: the Baseline scenario, Economies of scale scenario, Capacity utilisation factor scenario, and Electricity access investment scenario, to determine which, under the constraints of the model, offers the fastest means to universal electricity access in Africa. The study finds neither the current learning effect on cost decline, nor the optimal utilisation of present capacity enough to achieve universal access. An increment of the annual investment in the power sector is the most viable roadmap to universal electricity access. It is therefore imperative to induce investment from the private sector, given the limited funds from multilateral and bilateral aids, and the constrained budgets of national governments that are imbued with the mandate of providing electricity.

The path to universal electricity access in Africa is characterised by a litany of challenges. This study affirms that limited finance for power infrastructure is one of them. An answer to the question of why this challenge persists may be found in the nature of the market conditions and regulatory structures of Africa's electricity sector. In addition, given the abundance of renewable energy resources in relation to the challenges that pertain to conventional energy power plants in Africa, investing in renewable energy could accelerate the attainment of universal electricity access status. Indeed, there are limitations (e.g. lower utilisation factor) to pursuing renewable energy sources for electricity generation, rather than conventional energy sources. The pursuit of renewables for electricity could avail funding opportunities, including the Climate Investment Fund, the Global Environment Facility, and the Clean Technology

Fund, to reduce the financing gap and consequently promote universal electricity access in Africa.

The study contends that a liberalised market that promotes competition, coupled with an incentive scheme, would lead to an increased private sector participation and flow of financial resources to the power sector and, consequently, would promote universal electricity access. Going forward, the study recommends; policy reforms that strengthen the institutions within the electricity sector, allow private investors to participate in the sector, and offer guarantees and safety nets to hedge the risks of private investors. This would lay the foundation for improving innovation and performance, and increase the funding available to the electricity sector.

Chapter 5 examines the electricity sector in Ghana, which is customised from the AFELA model, to understand universal electricity access at a country level.

CHAPTER FOUR REFERENCES

ABDUL-SALAM, Y. & PHIMISTER, E. 2016. The politico-economics of electricity planning in developing countries: A case study of Ghana. *Energy Policy,* 88**,** 299-309.

ACKAH, I., ADU, F. & TAKYI, R. O. 2014. On The Demand Dynamics of Electricity in Ghana: Do Exogenous Non-Economic Variables Count? *International Journal of Energy Economics and Policy,* 4**,** 149-153.

ADOM, P. K. & BEKOE, W. 2013. Modelling electricity demand in Ghana revisited: The role of policy regime changes. *Energy Policy,* 61**,** 42-50.

AFDB. 2013. *The High Cost of Electricity Generation in Africa* [Online]. Available: https://www.afdb.org/en/blogs/afdb-championing-inclusive-growth-across-africa/post/the-high-cost-of-electricity-generation-in-africa-11496/ [Accessed 13th April 2017].

AFRICA PROGRESS PANEL 2015. Power People Planet: Seizing Africa's energy and climate opportunities. Africa Progress Report: Africa Progress Panel.

AGECC, U. 2010. Energy for a sustainable future: summary report and recommendations. *UN (United Nations)/The Secretary-General's Advisory Group on Energy and Climate Change. New York, USA.*

AHMAD, S., MAT TAHAR, R., MUHAMMAD-SUKKI, F., MUNIR, A. B. & ABDUL RAHIM, R. 2016. Application of system dynamics approach in electricity sector modelling: A review. *Renewable and Sustainable Energy Reviews,* 56**,** 29-37.

ALISHAHI, E., MOGHADDAM, M. P. & SHEIKH-EL-ESLAMI, M. 2012. A system dynamics approach for investigating impacts of incentive mechanisms on wind power investment. *Renewable energy,* 37**,** 310-317.

ANAND, S., VRAT, P. & DAHIYA, R. 2006. Application of a system dynamics approach for assessment and mitigation of CO 2 emissions from the cement industry. *Journal of environmental management,* 79**,** 383-398.

ASSILI, M., DB, M. H. J. & GHAZI, R. 2008. An improved mechanism for capacity payment based on system dynamics modeling for investment planning in competitive electricity environment. *Energy Policy,* 36**,** 3703-3713.

BACON, R. 1995. Lessons from power sector reform in England and Wales. *Public Policy for the Private Sector***,** 13-16.

BARFOROUSHI, T., MOGHADDAM, M. P., JAVIDI, M. H. & SHEIKH-EL-ESLAMI, M. K. 2010. Evaluation of regulatory impacts on dynamic behavior of investments in electricity markets: a new hybrid DP/GAME framework. *IEEE Transactions on Power Systems,* 25**,** 1978-1986.

BARLAS, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System dynamics review,* 12**,** 183-210.

BATINGE, B. Sustainable Energy Future: A System Dynamics approach to solving the Electricity shortfall in Ghana. Paper presented at the 33rd International Conference of the System Dynamics Society., 2015 Cambridge, Massachusetts USA. System Dynamics Review.

BATINGE, B., MUSANGO, J. K. & BRENT, A. C. 2017. Leapfrogging to renewable energy: The opportunity for unmet electricity markets. *The South African Journal of Industrial Engineering,* 28**,** 32-49.

BERGARA, M. E., HENISZ, W. J. & SPILLER, P. T. 1998. Political institutions and electric utility investment: A cross-nation analysis. *California management review,* 40**,** 18-35.

BOOM, A. 2003. Investments in electricity generating capacity under different market structures and with endogenously fixed demand. Berlin: SSOAR.

BOUILLE, D., DUBROVSKY, H. & MAURER, C. 2001. Reform of the electric power sector in developing countries: case study of Argentina. *Ieebf, Wri*.

BROWN, A. C., STERN, J., TENENBAUM, B. W. & GENCER, D. 2006. *Handbook for evaluating infrastructure regulatory systems,* Washington, World Bank Publications.

BUNN, D. W., DYNER, I. & LARSEN, E. R. 1997. Modelling latent market power across gas and electricity markets. *System Dynamics Review,* 13**,** 271-288.

BUNN, D. W., LARSEN, E. R. & VLAHOS, K. 1993. Complementary modelling approaches for analysing several effects of privatization on electricity investment. *Journal of the Operational Research Society,* 44**,** 957-971.

CASTELLANO, A., KENDALL, A., NIKOMAROV, M. & SWEMMER, T. 2015. Brighter Africa: The growth potential of the sub-Saharan electricity sector. Mckinsey.

CASTRO-RODRIGUEZ, F., MARÍN, P. L. & SIOTIS, G. 2009. Capacity choices in liberalised electricity markets. *Energy Policy,* 37**,** 2574-2581.

CHI, K. C., NUTTALL, W. J. & REINER, D. M. 2009. Dynamics of the UK natural gas industry: system dynamics modelling and long-term energy policy analysis. *Technological Forecasting and Social Change,* 76**,** 339-357.

CLARK, A., DAVIS, M., EBERHARD, A., GRATWICK, K. & WAMUKONYA, N. 2005. Power sector reform in Africa: assessing the impact on poor people. *Energy Sector Management Assistance Programme, and World Bank.* Cape Town: ESMAP/World Bank.

CONNOLLY, D., LUND, H., MATHIESEN, B. V. & LEAHY, M. 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy,* 87**,** 1059-1082.

CROUSILLAT, E., HAMILTON, R. & ANTMANN, P. 2010. Addressing the electricity access gap. *Background Paper for the World Bank Group Energy Sector Strategy*. Washington: World Bank.

DELMON, J. 2009. *Private sector investment in infrastructure: Project finance, PPP projects and risks,* Kluwer Law International.

DEPARTMENT-OF-ECONOMIC-AND-SOCIAL-AFFAIRS, D. 2006. *Energy Statistics Yearbook 2004,* UN.

DUARTE, M., NAGARAJAN, S. & BRIXIOVA, Z. 2010. Financing of sustainable energy solutions. *AfBD Committee of Ten Policy Brief, Published by AfBD-African Development Bank, Ivory Cost*.

DYNER, I. & LARSEN, E. R. 2001. From planning to strategy in the electricity industry. *Energy policy,* 29**,** 1145-1154.

EBERHARD, A., GRATWICK, K., MORELLA, E. & ANTMANN, P. 2016. *Independent power projects in Sub-Saharan Africa: Lessons from five key countries*, World Bank Publications.

EBERLEIN, R. L. & PETERSON, D. W. 1992. Understanding models with Vensim™. *European journal of operational research,* 59**,** 216-219.

EDJEKUMHENE, I., AMADU, M. B. & BREW-HAMMOND, A. 2001. Power sector reform in Ghana: The untold story. *KITE, Ghana*.

FENG, Y. Y., CHEN, S. Q. & ZHANG, L. X. 2013. System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecological Modelling,* 252**,** 44-52.

FORD, A. 1997. System dynamics and the electric power industry. *System Dynamics Review,* 13**,** 57-85.

FOSTER, V. & BRICEÑO-GARMENDIA, C. 2010. Africa's infrastructure: a time for transformation. *World Bank Publications*.

FRITZ, W. Renewable energy feed in tariffs, REBID, SASGI and the smart grid. Industrial and Commercial Use of Energy Conference (ICUE), 2012 Proceedings of the 9th, 2012. IEEE, 1-5.

GALAL, A. & SHIRLEY, M. 1995. Bureaucrats in Business: The Economics and Politics of Government Ownership World Bank Policy Research Report. *Washington, DC: World Bank*.

GOLDEN, M. & MIN, B. 2012. Theft and loss of electricity in an Indian State. *Journal of the International Growth Centre*.

GRIMSEY, D. & LEWIS, M. 2007. *Public private partnerships: The worldwide revolution in infrastructure provision and project finance*, Edward Elgar Publishing.

ICA 2011. Regional Power Status in African Power Pools. Infrastructure Consortium of Africa.

IEA 2002. World Energy Outlook 2002. Paris: OECD/IEA.

IEA 2011. *World Energy Outlook 2011*, Paris, OECD/IEA.

IEA 2015. World Energy Outlook 2015. Paris: OECD/IEA.

IEA 2016a. Boosting the Power Sector in Sub-Saharan Africa - China's Involvement. *Partner Country Series*. Paris: OECD/IEA.

IEA 2016b. World Energy Outlook 2016. Paris: OECD/IEA.

IEA 2017. World Energy Outlook 2017: From Poverty to Prosperity. *Special Report*. Paris: OECD/IEA.

IEA, A. E. O. 2014. A focus on the energy prospects in sub-Saharan Africa, World Energy Outlook Special Report. *International Energy Agency Publication*. Paris: OECD/IEA.

IPCC 2014. Climate Change 2014 Synthesis Report.

IRENA 2015. Africa 2030: Roadmap for a Renewable Energy Future. IRENA, Abu Dhabi.: www.irena.org/remap.

KABERUKA, D. 2011. Development and aid in Africa: What have we learned from the past 50 years? *Development Co-operation Report 2011 50th Anniversary Edition***,** 57.

KARAN, M. B. & KAZDAĞLI, H. 2011. The development of energy markets in Europe. *Financial Aspects in Energy.* Springer.

KPMG 2015. Power in Africa. *Sector report.* KPMG.

KUBLI, M. & ULLI-BEER, S. 2016. Decentralisation dynamics in energy systems: A generic simulation of network effects. *Energy Research & Social Science,* 13**,** 71-83.

LAMECH, R. & SAEED, K. 2003. What international investors look for when investing in developing countries. *Energy and Mining Sector Board Discussion Paper*.

LEFEVRE, T. & TODOC, J. L. IPPs in APEC economies: issues and trends. Clean and Efficient Use of Fossil Energy for Power Generation Conference, Bangkok, Thailand, 2000.

LI, B. & DORIAN, J. P. 1995. Change in China's power sector. *Energy policy,* 23**,** 619-626.

LIPP, J. 2007. Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. *Energy policy,* 35**,** 5481-5495.

LITTLECHILD, S. 2000. Privatization, competition and regulation in the British electricity industry, with implications for developing countries.

MANDELLI, S., BARBIERI, J., MATTAROLO, L. & COLOMBO, E. 2014. Sustainable energy in Africa: A comprehensive data and policies review. *Renewable and Sustainable Energy Reviews,* 37**,** 656-686.

MARTINEZ-MOYANO, I. J. 2012. Documentation for model transparency. *System Dynamics Review,* 28**,** 199-208.

MUSANGO, J. K. & BRENT, A. C. 2011. A conceptual framework for energy technology sustainability assessment. *Energy for Sustainable Development,* 15**,** 84-91.

MUZENDA, D. 2009. Increasing private investment in African energy infrastructure. *for the Ministerial and Expert Roundtable of the NEPAD-OECD Africa Investment Initiative on,* 1**,** 112.

NAGAYAMA, H. 2009. Electric power sector reform liberalization models and electric power prices in developing countries: An empirical analysis using international panel data. *Energy Economics,* 31**,** 463-472.

NAILL, R. F. 1977. *Managing the energy transition: a system dynamics search for alternatives to oil and gas.[use of COAL2 model]*.

NEUHOFF, K. & DE VRIES, L. 2004. Insufficient incentives for investment in electricity generations. *Utilities Policy,* 12**,** 253-267.

OECD, O. F. E. C.-O. D.-. 2016. *African Economic Outlook 2016: Sustainable Cities and Structural Transformation*, OECD.

QUDRAT-ULLAH, H. & SEONG, B. S. 2010. How to do structural validity of a system dynamics type simulation model: the case of an energy policy model. *Energy policy,* 38**,** 2216-2224.

ROSNES, O. & SHKARATAN, M. 2011. *Africa's power infrastructure: investment, integration, efficiency*, World Bank Publications.

SAUNDERS, R. J. 1993. The world Bank’s role in the electric power sector. *A World Bank Policy Paper, Washington DC*.

SCOTT, A. 2015. Building Electricity Supplies in Africa for Growth and Universal Access. *Working Paper, The New Climate Economy*.

SENGE, P. M. & FORRESTER, J. W. 1980. Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences,* 14**,** 209-228.

SHIN, J., SHIN, W.-S. & LEE, C. 2013. An energy security management model using quality function deployment and system dynamics. *Energy Policy,* 54**,** 72-86.

SOVACOOL, B. K. 2013. A qualitative factor analysis of renewable energy and Sustainable Energy for All (SE4ALL) in the Asia-Pacific. *Energy Policy,* 59**,** 393-403.

STERMAN, J. D. 2000. *Business dynamics: systems thinking and modeling for a complex world*, Irwin/McGraw-Hill Boston.

STRIDBAEK, U. 2006. Lessons from Liberalised Electricity Markets. *IEA publication*.

TRIMBLE, C. P., KOJIMA, M., PEREZ ARROYO, I. & MOHAMMADZADEH, F. 2016. Financial viability of electricity sectors in Sub-Saharan Africa: quasi-fiscal deficits and hidden costs.

TURKSON, J. & WOHLGEMUTH, N. 2001. Power sector reform and distributed generation in sub-Saharan Africa. *Energy Policy,* 29**,** 135-145.

UN 2015. World Population Prospects: The 2015 Revision *Department of Economic and Social Affairs - Population Division.* New York: UN.

UNSD 2017. Electricity, net installed capacity of electric power plants. *In:* UN (ed.) *Energy Statatistics Yearbook.* UN data, A world of information.

WAMUKONYA, N. 2003. Power sector reform in developing countries: mismatched agendas. *Energy Policy,* 31**,** 1273-1289.

WHO 2014. Burden of disease from household air pollution for 2012. Geneva: World Health Organization.

WOO, C.-K., KING, M., TISHLER, A. & CHOW, L. 2006. Costs of electricity deregulation. *Energy,* 31**,** 747-768.

WORLD-BANK 2016. Enterprise Surveys Indicator Descriptions. *World Bank Enterprise Survey, http://www.enterprisesurveys.org.*

WU, J.-H., HUANG, Y.-L. & LIU, C.-C. 2011. Effect of floating pricing policy: an application of system dynamics on oil market after liberalization. *Energy Policy*, 39**,** 4235-4252.

ZHANG, Y.-F., PARKER, D. & KIRKPATRICK, C. 2008. Electricity sector reform in developing countries: an econometric assessment of the effects of privatization, competition and regulation. *Journal of Regulatory Economics*, 33**,** 159-178.

5 CHAPTER FIVE: TRANSITION PATHWAYS TO ACHIEVE UNIVERSAL ELECTRICITY ACCESS AND RENEWABLE ENERGY GOALS IN GHANA[4]

5.1 CHAPTER OVERVIEW

Chapter Five pursues the fourth objective of the study: to examine the extent of Ghana's progress towards achieving universal electricity access and increased renewable energy. The chapter presents an overview of Ghana's electricity sector, and uses a system dynamics methodology to build a model of Ghana's electricity access, referred to in this study as the GELA model. The results show that Ghana will not meet its universal electricity access and renewable energy goals by 2020. Both goals are, however, attainable within the SDG timeframe of 2030.

Abstract

Ghana's electricity market remains unmet, and its target of 2020 for both universal electricity access and renewable energy appears to be out of reach at the current pace and trend. This is attributable to the low level of investment in the power sector and the concentration of investment on conventional energy particularly gas thermal power, at the expense of renewable energy alternatives. Using system dynamics, this paper developed the Ghana Electricity Access Model (GELA) to investigate the investment trend in the power sector, electricity access, and the share of renewable energy in the electricity sector energy mix in Ghana. The results show that Ghana would not achieve its dual energy targets by the 2020 timeline. The investment distribution in the power sector should to be reapportioned to ensure that the goals are attained closer to the timeline. It is recommended that policy actions centre on incentivising independent power producers to invest in the electric power sector. A substantial proportion of such investment should also be directed towards solar energy, in order to increase the renewables share of total energy, and thus achieve the dual energy goal by 2025. For this to

[4] BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Pathways for attaining universal electricity access and renewable energy goals in Ghana. *Renewable & Sustainable Energy Reviews*

succeed, stakeholders, particularly government, should pursue infrastructural and regulatory reforms to boost third parties' confidence and guarantee them a payback for participating in the effort to deliver electricity services to the populace.

Keywords: *Ghana; Electricity; Investment; Renewable energy; Universal access.*

5.2 INTRODUCTION

Electricity access is increasingly critical in recent times, not only to businesses, but also to households, as society in general transitions towards the dominance of technology. In Africa, electricity is often found to be most inadequate of the variables that are essential for the productivity of industrial firms (UNECA, 2017). Firms in Africa have identified power outages as the most pressing obstacle to doing business (World-Bank, 2016). About 13 per cent of firms' productive hours, and six per cent of sales cost, is attributed to power outages (Iarossi, 2009). Currently, a growing number of people in Africa still do not have access to electricity, a reality that impedes the realisation of the United Nation's Sustainable Development Goal pertaining to universal access to modern energy. The African electricity market is best described as unmet (Batinge, Musango and Brent, 2017), although the scale of electricity access poverty varies among countries.

Ghana, like most other countries in Africa, is characterised by unmet electricity markets. In 2016, electricity accounted for only 14% of the total energy consumed in Ghana, while biomass and petroleum products constituted 39% and 47% respectively (GEC, 2017). Most Ghanaians reply on solid fuels as a major source of energy, especially in the household settings. These solid fuels, usually from biomass, are largely used for performing energy-intensive services such as cooking. In Ghana, 76% of household use solid fuels for cooking while the rest rely on Liquefied Petroleum Gas (LPG), kerosene, electricity, and other energy sources. The combustion of solid fuels, however, comes with adverse effects such as air pollution. According to the Global Alliance for Clean Cookstoves, household air pollution resulting from solid fuel consumption account for 1,500 child deaths and 14,500 total deaths per year in Ghana (GACC, 2016). This makes the need to attain the energy goals defined in Ghana's strategic national energy plan in 2006 more compelling. In 2006, Ghana set two key energy goals; universal electricity access by 2020 and 10% renewable energy (excluding large hydro and wood fuels) in its total electricity generation mix by 2020 (GEC, 2006), a decade earlier than the United Nations' goal. At the time, electricity access was 57%, while the renewables share made up only about 0.1 per cent of the total generation mix, excluding large hydro.

In 1989, the National Electrification Scheme was introduced, in order, among other goals, to accelerate access to electricity in Ghana (GEC, SE4All and UN, 2012). A significant proportion of Ghana's unmet electricity market is made up of people in rural communities who did not fall within the NES criterion of focusing on connecting communities with over 500 people to the national grid. The need for the inclusion of renewable energy in Ghana's energy mix, especially for the purposes of pursuing universal electricity access in the medium to long-term, seems inevitable. Given that the energy consumption of these rural settlements is often minimal and may not justify the capital cost of extending the already strained grid, the paradigms of energy leapfrogging by Batinge et al. (2017) is useful for deciphering the ideal way to meet rural energy needs. The increasing population growth, coupled with the low level of electricity access in rural parts of the country, necessitates the expansion of energy infrastructure, the diversification of supply capacity, and the improvement of supply reliability (Eshun and Amoako-Tuffour, 2016), as well as the exploitation of renewable energy sources (Gyamfi, Modjinou and Djordjevic, 2015), to compensate for the rising demand.

This study aims to assess Ghana's progress with regard to its dual energy goals of universal electricity access and 10% renewable energy in the overall energy mix by 2020. The study also seeks to ascertain whether these energy goals are conflicting, that is, does the pursuit of the 10% renewable energy goal undermine the attainment of the universal electricity access by 2020? This objective is investigated, using a system dynamics model dubbed; Ghana Electricity Access Model (GELA), a simulation model developed specifically for assessing Ghana's electricity access dynamics. An integrated energy mix, that takes cognisance of the dual national target of both the promotion of renewable energy and universal electricity access, is of paramount interest in this study.

5.3 GHANA'S ELECTRICITY SECTOR OVERVIEW

There are four main state-owned enterprises involved in Ghana's electricity supply. The Volta River Authority (VRA) is mainly focused on electricity generation. After electricity has been generated, the Ghana Grid Company (GRIDCo) takes charge of transmitting it through the grids to the distributors. Two organisations; the Electricity Company of Ghana (ECG) and the

Northern Electricity Department Company (NEDCo) distribute the power to the final consumers.

The Volta River Authority is the main public power supplier in Ghana. Established in 1961 under the Volta River Development Act, (Act46), it is mandated to generate, transmit, and distribute electricity. In 2005, the Act was amended, as part of Ghana Government Power Sector Reforms. The amendment of the VRA Act both restricts VRA's operations to power generation, and draws Independent Power Producers (IPPs) into the Energy Market. VRA subsequently shed all of its transmission activities to GRIDCo Ghana, and a large part of its distribution responsibilities to the Electricity Company of Ghana (ECG) in 1997. The Northern Electricity Department (NED), a subsidiary of VRA established in 1987 to distribute electricity was subsequently transformed into the Northern Electricity Distribution Company (NEDCo).

Ghana Grid Company (GRIDCo Ghana) is currently solely responsible for transmission of electricity from the generators to the distributors. It was created in 2005 in accordance with the Volta River Development Act (Act 692) and the 1997 Energy Commission Act (Act 541) to decouple the activities of the Volta River Authority, by establishing an independent National Interconnected Transmission System. The Volta River Authority's transmission functions, as well as the core staff of transmissions, were transferred to GRIDCo Ghana. Incorporated as a private limited liability company in December 2006, GRIDCo Ghana commenced operations in August 2008. The key functions of GRIDCo Ghana include planning transmission systems, the provision of transmission services, and metering and billing of bulk customers.

The Electricity Company of Ghana (ECG) is a state owned limited liability company, which was incorporated in 1997, under the 1963 Companies Code (Act 179). Established as the Electricity Department in 1947, it was tasked with power distribution for the entire country until 1962, when it became the Electricity Division. Presently, ECG distributes electricity to the southern half of Ghana including the Greater Accra, Eastern, Central, Western, Ashanti, and Volta regions.

The Northern Electricity Distribution Company (NEDCo) distributes electricity mainly to the Northern part of Ghana. The company's operations span about 64% of Ghana geographically, covering the Brong-Ahafo, Northern, Upper East and Upper West Regions, as well as parts of the Ashanti, Volta, and Western Regions. The customer density in NEDCo's coverage area is, however, low. The structure of Ghana's electricity sector is depicted in Figure 5.1. The customer groups can be classified broadly into residential, commercial, and industrial customers.

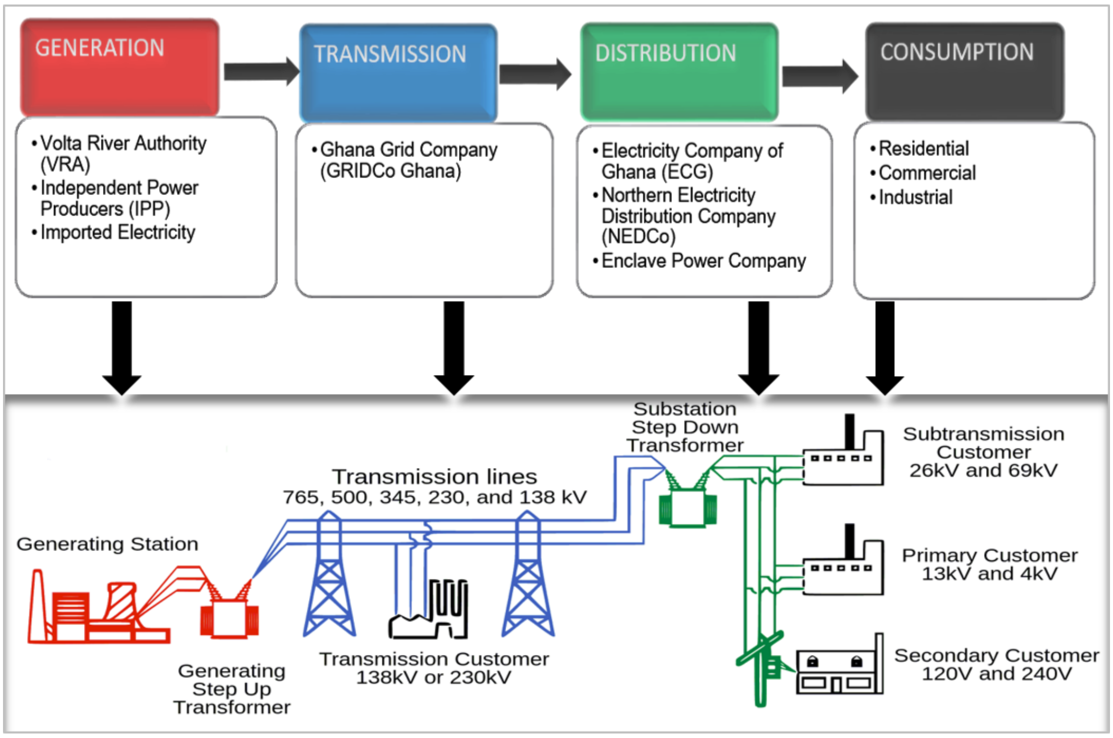


Figure 5.1: Ghana's electricity sector framework

5.3.1 Ghana's electricity supply overview

In Ghana, electricity is generated from three main energy sources: hydropower, gas/diesel thermal (any reference to thermal hereafter means gas/diesel thermal), and solar. Hydro power dominated Ghana's energy mix for electricity from the mid-1960s until the past decade, during which the increasing electricity demand resulted in a rapid growth of the thermal capacity. Commercial scale solar installations started only about five years ago when the VRA completed a 2 MW solar photovoltaic (PV) grid-connected plant in Navrongo. A brief profile of the current and potential power sources in Ghana is presented next.

5.3.1.1 Hydro

Hydroelectric power has been Ghana's leading power source since the completion of the Akosombo dam in 1965. When the power demand soared in in the early 1980s, another hydropower plant, the Kpong hydroelectric plant, was constructed and commissioned in 1982 to cater for the rising demand. Hydropower generated approximately 100% of the country's power until 1998, when the first thermal power plant was commissioned. Since 2010, Ghana's hydropower capacity has again increased, with the completion of the 400 MW Bui hydro plant in 2013. According to the Ministry of Energy, there are still twenty-one viable small and medium sized hydropower sources in Ghana with capacities from 4 KW to 95 MW, summing to approximately 840 MW (Seth and Mawufemo, 2012).

The challenges of hydro power in Ghana relates to the periodic fluctuations in the dam water level owing mainly to unpredictable rainfall pattern and rate of water inflow (Eshun and Amoako-Tuffour, 2016). The recent seemingly rapid changes in climatic conditions could worsen this challenge. In the lenses of thermal power proponents, this reality, and the generally limited potential of the remaining hydro power sources, buttresses the argument for the recent expansion in thermal power.

5.3.1.2 Thermal

Thermal power is presently the leading installed electric power source for electricity generation in Ghana. It has overtaken hydro, which until 2009 was the major source of electricity in the country. However, due to the low utilisation factor of thermal power, its total electricity generation only surpassed that of hydro in 2016. Currently, there are about thirteen major power plants with capacities exceeding 100 MW, eight of which are owned by independent power producers, and five under the ownership of State Enterprises. Despite the significant growth in capacity, the thermal sub-sector in Ghana also faces pressing challenges. Most of these challenges relate to the availability of fuel to operate the plants, and issues of plant breakdowns and maintenance. For example, of the 123 million standard cubic feet per day (mmscfd) of gas contracted from Nigeria in 2014 to fuel the thermal plants, the supply averaged only between 30 to 50 mmscfd (Eshun and Amoako-Tuffour, 2016). The supply shortfall rendered some thermal plants dormant, and compelled others to switch to the more costly crude oil.

Ghana depends on Nigeria for a significant quantity of natural gas for its thermal plants. The primary goal of the Nigerian government, however, is to meet its domestic gas demand. Gas shippers in Nigeria are therefore compelled to meet local quotas before export; hence, a reliable gas supply to Ghana is not assured. Ghana's dependency on gas from Nigeria through the West

African Gas Pipeline (WAGP) exposes it to the geopolitics risks of the Delta region, and unpredictable catastrophes relating to the pipeline (IEA, 2014). In 2011, a ship anchor severed the WAGP, which runs through Benin and Togo in the Gulf of Guinea, plunging about half of Ghana into darkness and creating a lengthy load shedding. An end to the gas supply challenges does not appear to be in sight soon, as Nigeria plans to increase its power capacity from 11,000 MW, of which 8,600 MW (81%) is thermal based.

5.3.1.3 Solar

Ghana, like many countries in Africa, possesses significant solar power potential suitable for grid and off-grid power. The solar energy potential is estimated at 35 Exajoules (EJ), equivalent to 100 times the present energy consumption in Ghana. A study dubbed Ghana Solar Export Potential Study (SEPS) by (UNEP, 2015) estimates that Ghana's solar PV potential is 106.2 GW, equivalent to 167, 200 GWh. Solar irradiation in the country is also estimated in the range of 4 to 6 KWh/m2 daily (Gyamfi et al., 2015; Nazeeruddin, Baranoff and Grätzel, 2011), which is sufficient for power supply. While Ghana's solar irradiation cannot claim superiority over that ofneighbouring countries, its stable political environment, reliable institutions, and broad transmission networks means it can attract investors to develop infrastructure for power generation (UNEP, 2016). In 2015, Blue Energy was scheduled to commence construction of the biggest solar energy plant in Africa called the Nzema project, in Ghana. The 155 MW plant, which is currently under construction, would electrify over 100, 000 households, and increase the national generation capacity and government's renewable targets by 6% and 20%, respectively. Although Ghana's solar industry has progressed in recent times, there remain financial, technological, and policy obstacles (Atsu, Agyemang and Tsike, 2016) that impede widespread 'take-off' of solar across the country. The passage of the Renewable Energy Act (Act-832, 2011) in 2011 is expected to attract private investment into solar, as it offers various incentives, including the bulk electricity consumers' purchase obligation, Feed-in tariffs, tax exemptions, and fund renewable energy.

5.3.1.4 Wind

There is considerable wind energy potential along the coastal belt of Ghana. The Ghana Energy Commission estimates that up to 2,000 MW of energy could be harnessed from the 9 to 9.9 m/s wind speed recorded, and has issued nine licences and two sitting permits for wind power totalling 951 MW (GEC et al., 2012). The records of wind speed so far vary between 3.33 m/s to 6.08 m/s, and the speed for which wind is economically viable ranges between 7.1 and 9.0 m/s (GEC, 2006; Kemausuor, Obeng, Brew-Hammond and Duker, 2011). Despite the prospects of wind power in Ghana, there is presently still no significant wind power development or energy generation.

5.3.1.5 Biomass

Biomass is a major energy source for Ghanaians. In some rural communities, it is almost the only source of energy. Biomass covers approximately 87% of the surface land mass in Ghana. Biomass fuels in Ghana can be categorised into wood fuels, charcoal, and plant residues. Bioenergy is a viable source for expanding electricity access in Ghana, however, the private sector, including households and individuals, are those involved in biomass harvesting. The way biomass is harvested in Ghana today is done with little regard for the environment, hence increasing the rate of depletion and destructive climatic effects, especially on agricultural activities. The heavy dependence on biomass by rural folk also means that women and children, who mainly gather biomass, spend a significant number of hours in that process, which exposes them to health and safety risks. There is large arable land mass in Ghana available for cultivating plants that are suitable for bio-energy production (Gyamfi et al., 2015). Kemausuor, Nygaard and Mackenzie (2015) analysed different scenarios of bioenergy prospects in Ghana's total electricity production and concluded that the contribution of biomass to total electricity would decline from 5.8% in 2015 to 4% in 2030 in a high bioenergy scenario because of a displacement by biogas and an improvement in cookstoves and charcoal carbonisation technologies.

5.3.1.6 Coal

Ghana does not possess any coal resources presently. In 2015, however, the Volta River Authority in collaboration with Shenzhen Energy released an Environmental and Social Impact Assessment (ESIA) scoping report divulging plans to develop a 2 * 350 MW Supercritical Coal Fired Power Plant at Ekumfi in the Central Region of Ghana (VRA, 2015). This coal-fired power generation, according to the report, was necessary to meet Ghana's energy demand growth with peak forecasts of 3652 MW, 4960 MW and 7000 MW in 2020, 2025 and 2030 respectively. The feasibility study finds coal-fired power generation in Ghana viable and sustainable by coal imports from South Africa. The first coal-fired power plant (phase I 2×350 MW) is expected to come on stream in 2020, but no concrete infrastructural arrangement is presently visible.

5.3.1.7 Nuclear

The Ghana Atomic Energy Commission (GAEC) holds the mandate to explore and advance nuclear energy opportunities in Ghana. There is currently no nuclear energy plant in Ghana. The Ghana Energy Commission remains optimistic that nuclear energy would become part of total energy mix in the near future, because of the progress GAEC has made.

The rest of this study will focus on the power sources (hydro, thermal, and solar) in Ghana for which there are presently significant installed capacity. The main ones are shown in Table 5.1 below.

Table 5.1: Power generation in Ghana as of December 2017

VRA Installed Generation Capacity				
Plant Name	Plant type	Energy source	Installed Capacity (MW)	Dependable Capacity (MW)
Akosombo	Hydro	Water	1,020	900
Kpong	Hydro	Water	160	140
TAPCO – T1	Thermal	Gas/LCO	330	300
TAPCO – T2	Thermal	Gas/LCO	330	320
Mines Reserve Plant (MRP)	Thermal	Gas	80	0
Tema Thermal 1 Power Plant (TT1PP)	Thermal	Gas/LCO	110	100
Tema Thermal 2 Power Plant (TT2PP)	Thermal	Gas	49.5	45
Tema Thermal 2 Power Plant – Expansion (TT2PP-X)	Thermal	Gas	38	32
Kpone Thermal Power Plant (KTPP)	Thermal	Gas/DFO	220	200
VRA Navrongo Solar Plant	Solar	Sunlight	2.5	-
Sub-Total			***2,340***	***2,037***
Installed Capacity of Independent Power Producers (IPPs) and other Plants				
Bui	Hydro	Water	400	340
Kar Power Barge 1	Thermal	HFO	235	225
Kar Power Barge 2	Thermal	HFO	470	450
Sunon Asogli Phase 1	Thermal	Gas	200	180
Sunon Asogli Phase 2 Stage 1	Thermal	LCO/Gas	180	160
Sunon Asogli Phase 2 Stage 2	Thermal	Gas/LCO	180	160

Cenit Power Plant	Thermal	LCO	110	100
Ameri Power Plant	Thermal	Gas	250	230
BXC Solar	Solar	Sunlight	20	-
AKSA	Thermal	HFO	289	270
Sub-Total			***2,334***	***2,115***
Grand Total			**4,674**	**4,152**
Power Source Composition:				
Total Hydro			***1,580***	***1,380***
Total Thermal			***3,071.5***	***2772***
Total Solar			***22.5***	***-***

LCO is Light Crude Oil; DFO is Distillate Fuel Oil, and HFO for Heavy Fuel Oil

Source: (GEC, 2017)

5.3.2 Ghana's electricity access overview

Ghana is one of eight countries (Gabon, Mauritius, Reunion, Seychelles, Swaziland, South Africa, Cape Verde) in sub-Saharan Africa to record an electricity access rate of over 80% (IEA, 2017). Electricity access as at 2016 stood at 84%, despite a continuous growth in demand of approximately 10% per annum (Eshun and Amoako-Tuffour, 2016). This is a remarkable improvement from an access rate of 20%, and grid coverage of less than a third of the country in 1989. However, access does not imply availability, because of the rampant load shedding locally referred to as *Dumsor*. There are also unplanned power outages attributed to transformer overloads, grid quality, and issues with generation. Ghana embarked on a vigorous electricity access drive through the National Electrification Scheme, which was introduced in 1989, to ensure that all communities with a population above 500 people are connected to the national grid system by 2020. Energy and electricity access has since taken centre-stage in Ghana's political discourse, particularly in the past two decades. This has resulted in significant strides, connecting most communities of over 500 people in the country to the grid. Electricity access increased from 45% in 2000 to 84% in 2016 (IEA, 2017). Recently, peak demand has also increased from 1506 MW in 2010 to 2087 MW in 2016 (GEC, 2017). While electricity access challenges persist, the pursuit of the NES goals, and the political capital associated with the provision of electricity in Ghana, has intensified the collective efforts towards achieving universal access. Ghana appears to be on course to attain universal electricity access status by 2030, however, the growing demand and low reliability of its power sector, which is due to operational challenges, hints at a problem that requires a long-term remedy rather than a short term-fix.

5.4 METHOD

This study adopts a system dynamics modelling approach, a methodology that is not peculiar in the energy and the electric power sector. It has been applied in energy market dynamics (Naill, 1977), energy development and energy structure testing (Chi, Nuttall and Reiner, 2009; Connolly, Lund, Mathiesen and Leahy, 2010) energy and CO2 emissions (Anand, Vrat and Dahiya, 2006; Feng, Chen and Zhang, 2013), energy security, particularly from supply and demand in at national level (Shin, Shin and Lee, 2013; Wu, Huang and Liu, 2011), and electricity sector modelling (Ahmad, Mat Tahar, Muhammad-Sukki, Munir and Abdul Rahim, 2016). Andrew Ford (Ford, 1997) also presents a list of studies on the electric power industry where system dynamics modelling is used as the methodology. In Africa, system dynamics application in the energy and electricity sector is low. At the national level, most works that have applied systems dynamics modelling to African countries are found in South Africa where the methodology is used to model the technology sustainability assessment of biodiesel (Musango, Brent, Amigun, Pretorius and Müller, 2011) and green economy transitions (Musango, Brent and Bassi, 2014). System dynamics was also used by Batinge (2015) to assess pathways for a sustainable energy future in Ghana.

The data for the study was obtained from both primary and secondary sources. The primary data was obtained through unstructured interviews/interactions with staff members of the Ghana Energy Commission and the Volta River Authority. The goal of the interview process was mainly to confirm data and information obtained from secondary sources, outside the publications of the interviewees. The process was also intended to solicit insights pertaining long-term energy planning in Ghana. The interview exercise, in addition to visits to the largest hydroelectric power station and two large thermal power stations, afforded a better understanding of the operations of Ghana’s power sector and electricity generation. Equipped with the knowledge of the sector’s operations, a system dynamics model of Ghana’s Electricity Access was developed, using the Vensim simulation software.

5.5 GHANA ELECTRICITY ACCESS (GELA) MODEL

The Ghana Electricity Access model contains three modules, namely: (i) electricity access module, (ii) electricity investment module (iii) electricity supply module; consisting of hydro, thermal, and solar sub-models.

The simulation period for the model is from 2006 to 2040, while the base simulation period is from 2006 to 2016. The reason for choosing 2006 as the base year is because it is the year Ghana's Strategic National Energy Plan started (GEC, 2006). Also, Ghana rebased its GDP in 2010, using 2006 as the base year. This led to an upward revision of the GDP by more than 60% (Jerven and Duncan, 2012). Since power sector investment in the model is anchored on GDP, 2006 becomes an appropriate base year. The historical data for this period is then used to validate the model. Once a significant degree of confidence had been established in calibrations, the model was then used to assess future scenarios until 2030. A timestep of 0.0625 was used to enhance accuracy, and the results are saved annually. The Euler integration method was chosen in the model setting, for its simplicity and speedy computations.

5.5.1 GELA model feedback loops

The power sector was the focus of the study; hence, key feedback loops within the sector's different sub-models were identified, and are illustrated in Figure 5.2, Figure 5.3, Figure 5.4, and Figure 5.5. The 'electricity supply gain and loss loops' of the hydro, solar, and thermal sub-sectors indicate the additional energy generated and lost due to new power plant capacity, completions and decommissioning.

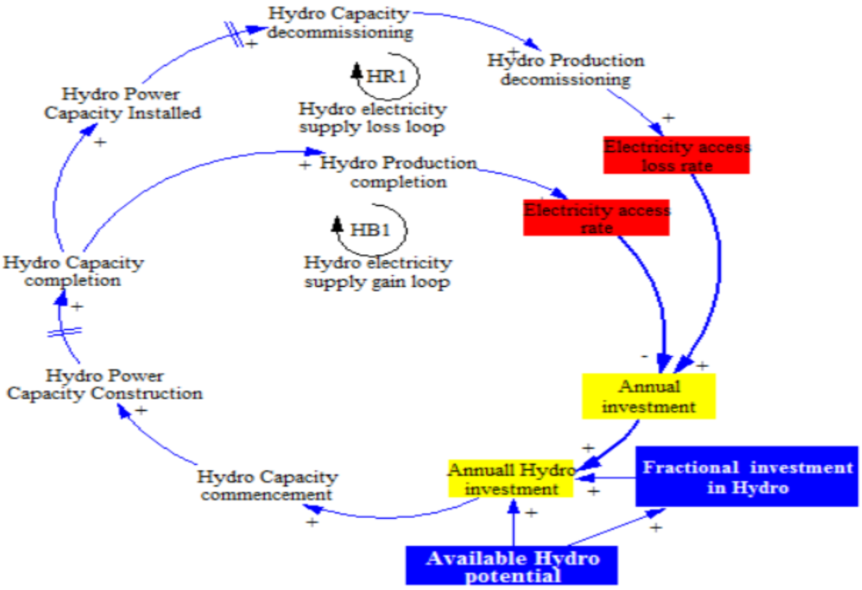


Figure 5.2: Hydro sub-sector feedback loops

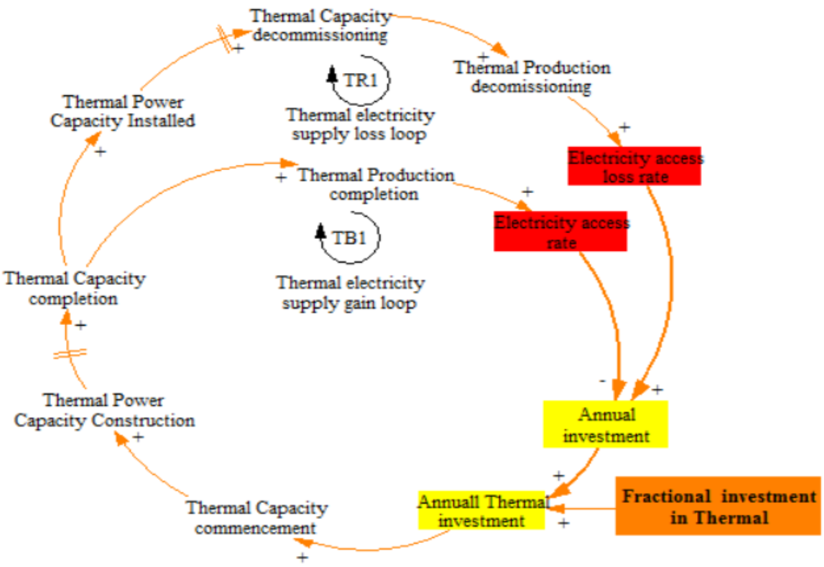


Figure 5.3: Thermal sub-sector feedback loops

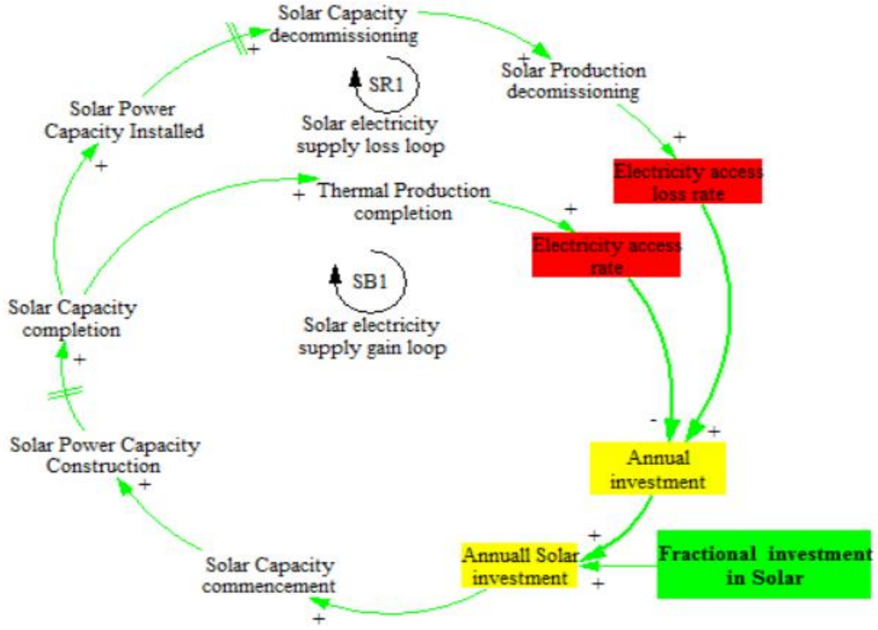


Figure 5.4: Solar sub-sector feedback loops

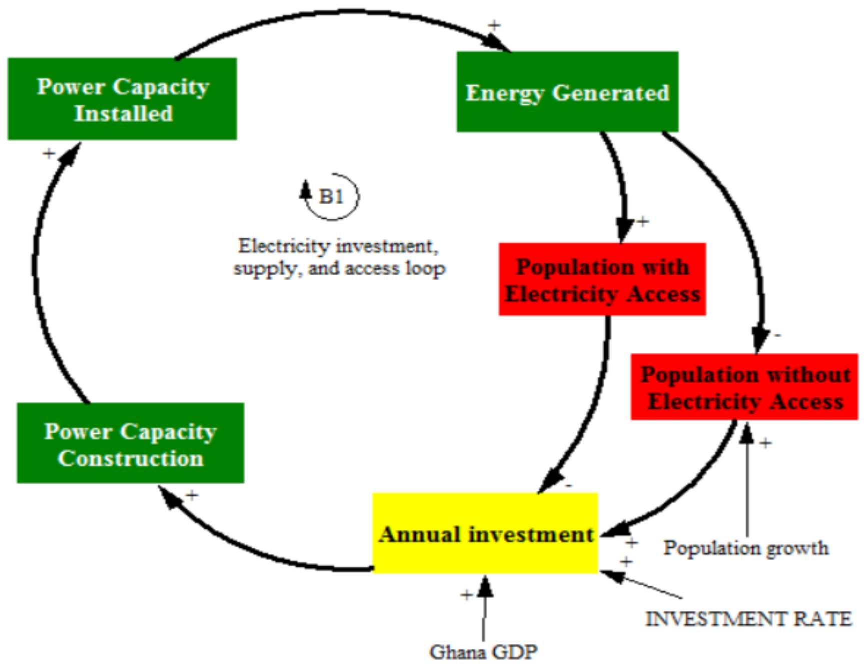


Figure 5.5: Key power sector feedback loops

5.5.2 GELA model structure

The GELA model consists of three modules: the electricity access module, the electricity investment module, and the electricity supply module. Details of the GELA model structure, layout and boundary are discussed below.

5.5.2.1 Electricity access module

This module shows the two key population categories: people with electricity access and people without electricity access. The module structure is similar to the Bass diffusion model (Bass, 1969), where the population without electricity denotes the 'potential adopters', the population with electricity denotes the 'adopters', and the electricity access rate represents the 'adoption rate'. The electricity access loss rate in this context represents people who discard the product and become potential customers again. Unlike the Bass diffusion model, another flow; the population growth rate, is added because the 'potential adopters' has a natural growth equivalent to net population growth. The population without electricity access (*PwA*), is the sum of the initial population without electricity access (PwA_{int}) and an accumulation of the net of three flows; the electricity access rate *(EAr),* population growth rate (*PGr*), and electricity access loss rate (*EALr*). The *PwA* is computed as:

$$PwA = PwA_{int} + \int [PGr + EALr - EAr]\, dt \qquad (25)$$

The population with electricity access (*PnA*) is the sum of the initial population with electricity access (PnA_{int}) and the net of electricity access rate and electricity access loss rate. The *PnA* is given as:

$$PnA = PnA_{int} + \int [EAr - EALr]\, dt \qquad (26)$$

A snapshot of the layout of the electricity access model is shown in Figure 5.6 depicting key endogenous and exogenous variables.

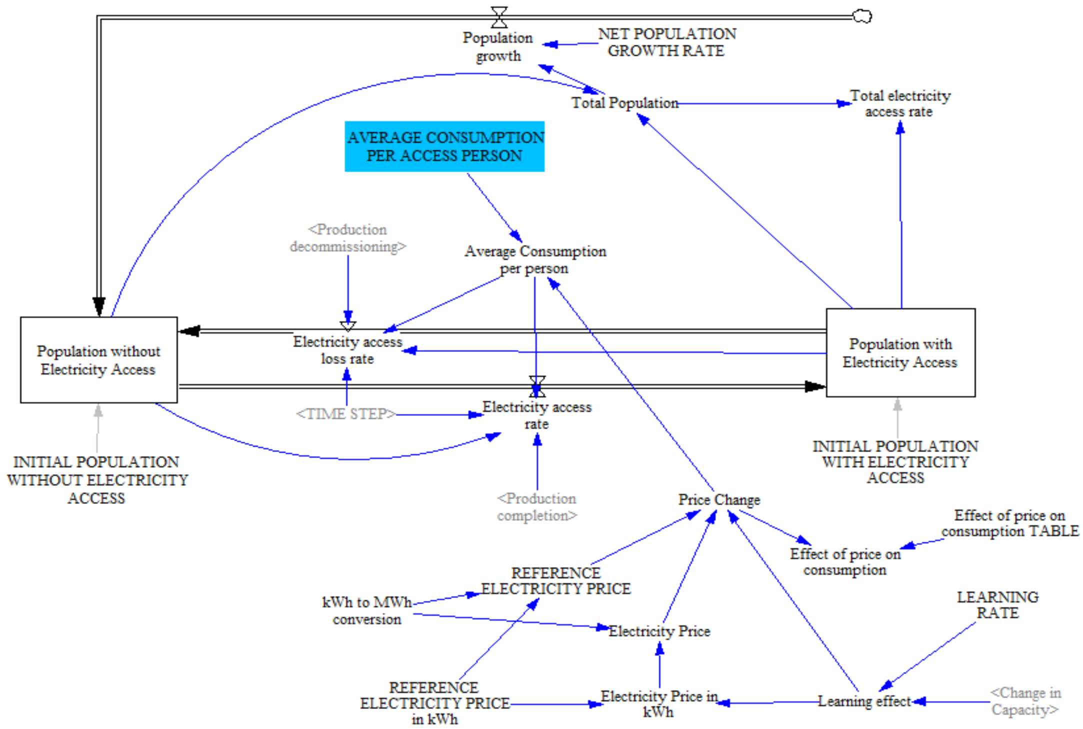


Figure 5.6: Electricity access model

5.5.2.2 Electricity investment module

The annual investment into power infrastructure in Ghana is extrapolated as a fraction of the Gross Domestic Product (*GdP*). As the *GdP* grows/changes annually, so does the budgeted investment for the power sector. The *GdP* is computed as:

$$GdP = GdP_{init} + \int [GdPg]\, dt \qquad (27)$$

where GdP_{init} is the initial *GdP*, and *GdPg* is the annual GDP growth. Details of how the *GdP*, as used to compute the annual investment, is depicted in the investment sub-model as shown in Figure 5.7. The annual investment (*AIr*) is calculated as the minimum between the indicated investment (*IIr*), which is based on the power capacity demand gap, and the budgeted investment (*BIr*), which is the annual new electric power capacity budget as a fraction of GDP.

$$AIr = Min\,[(IIr), (BIr)] \qquad (28)$$

The fraction of investment in solar (*Si*) is the difference of total investment, which is equivalent to one, and the sum of hydro investment fraction (*Hi*) and thermal investment faction (*Ti*). The solar investment rate is thereby given as:

$$S_i = \left[\left(\frac{[1-(Hi+Ti)]}{1}\right)\right] \tag{29}$$

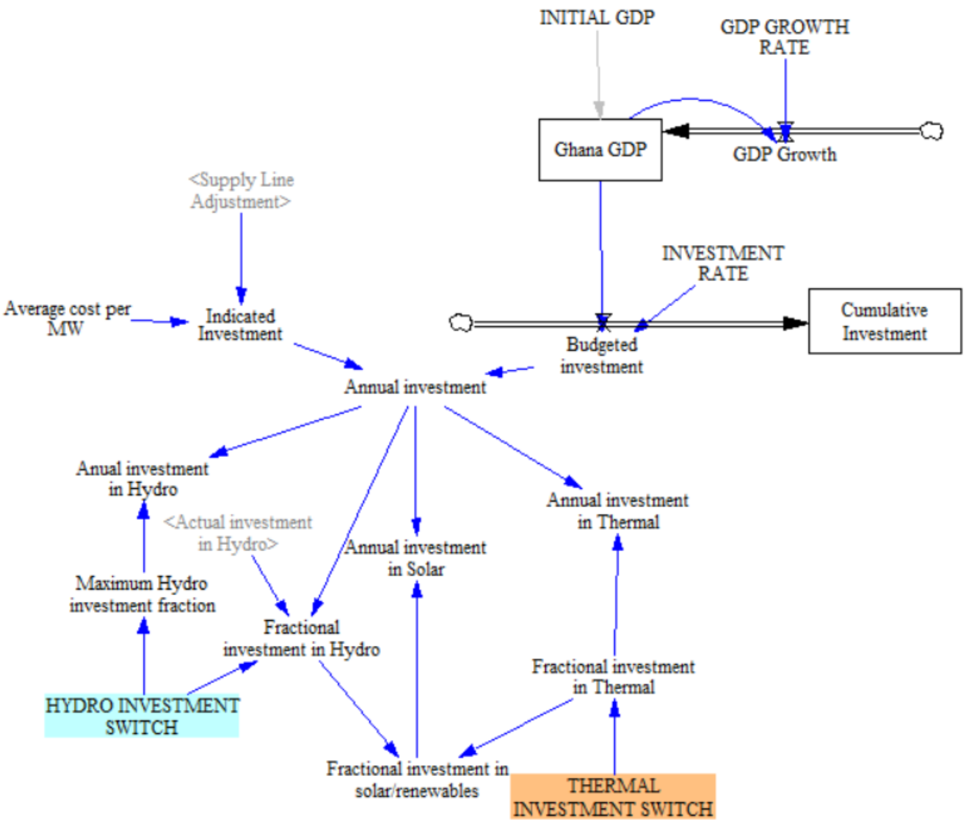


Figure 5.7: Electricity investment model

5.5.2.3 *Electricity supply module*

The electricity supply module consists of three key sub-models, namely the hydropower sub-model, the thermal (gas/diesel) power sub-model, and the solar sub-model. These three sub-models represent the key electric power sources in Ghana. Potential power sources, such as wind, nuclear, bioenergy, and coal, are not considered because there are no significant capacities of these sources currently installed or in operation. The capacity growth of the hydro, thermal, and solar stocks depends on the annual investment made available for each. The annual investment is anchored on the GDP. There are also two key variables, which policy interventions try to influence. These are the total electricity access, and the share of solar in the total energy mix. The equations of the main stocks of the power sector module are described next. Power capacity installed (*PcI*) accumulates the initial power capacity installed (PcI_{ini}), and the difference between capacity completion (*CCp*) and capacity decommissioning (*PCd*). The power capacity is therefore computed as:

$$PcI = PcI_{ini} + \int [CCp - PCd]dt \quad (30)$$

The power capacity installed is also the sum of hydro, thermal, and solar power capacities calculated respectively as:

$$HcI = HcI_{ini} + \int [HCc - HCd]dt \quad (31)$$

$$TcI = TcI_{ini} + \int [TCc - TCd]dt \quad (32)$$

$$ScI = ScI_{ini} + \int [SCc - SCd]dt \quad (33)$$

where:

HcI is the hydro capacity installed; HcI_{ini} is the initial hydro capacity installed; *HCc* is the hydro capacity completion; *HCd* is the hydro capacity decommissioning; *TcI* is the thermal capacity installed; TcI_{ini} is the initial thermal capacity installed; *TCc* is the thermal capacity completion; *TCd* is the thermal capacity decommissioning; *ScI* is the solar capacity installed; ScI_{ini} is the initial solar capacity installed; *SCc* is the solar capacity completion; *SCd* is the solar capacity decommissioning.

The desired power capacity (*DPC*) is an important connection between the electricity access and supply modules. It is a function of the total population (*TP*), average electricity consumed per person (*AvCP*), the utilisation factor (*Uf*), and the conversion factor (*Cf*) which is the change from MW to MWh, and the desired acquisition rate (*DAr*) which captures the delayed capacity demand growth emanating from population growth and expected capacity loss due to annual power capacity decommissioning. The *DPC* is given by:

$$DPC = \left(\frac{AvCP * TP}{Uf} * \frac{1}{\mathrm{Cf}}\right) + DAr \tag{34}$$

A complete overview of the electricity supply module is shown *Figure 5.8*.

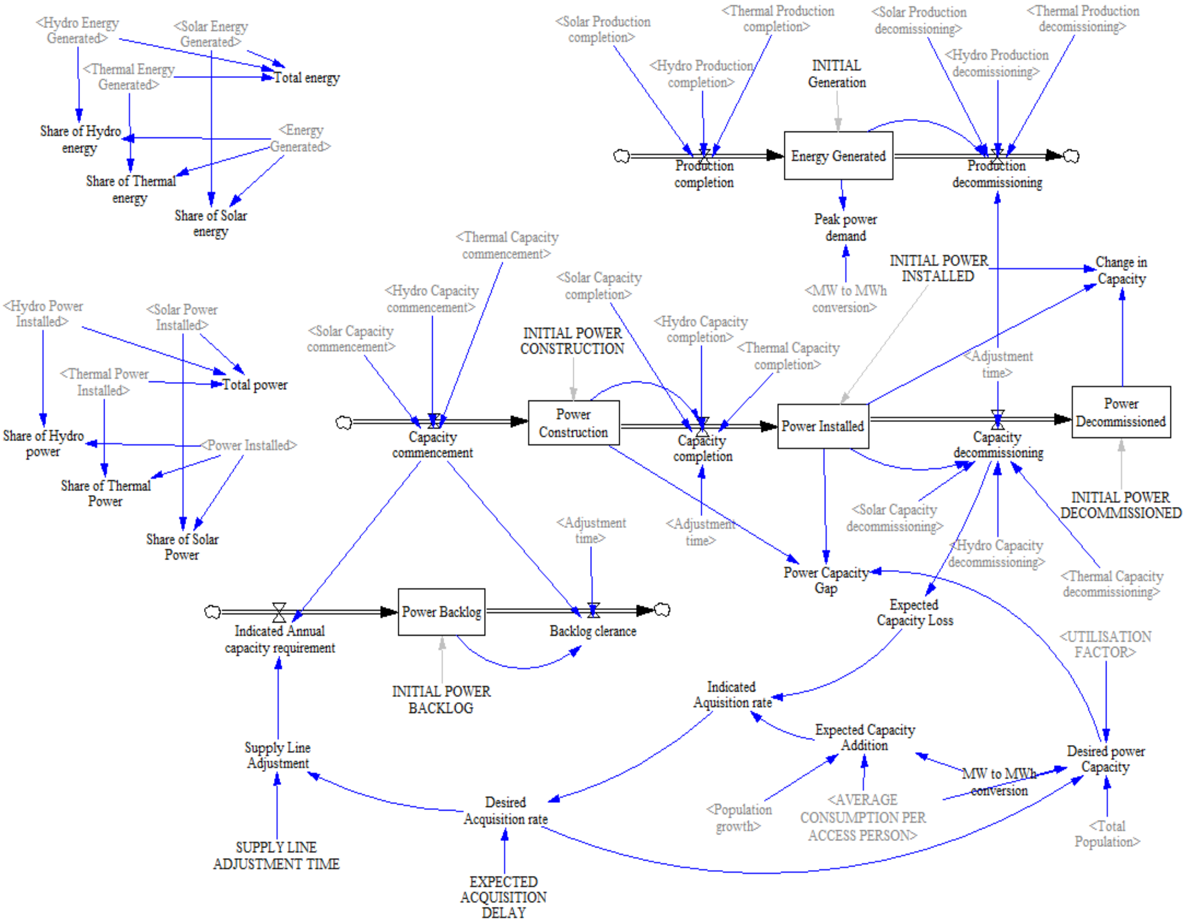


Figure 5.8: Electricity supply model

5.5.3 Model validation

Model testing and validation is highly encouraged in system dynamics modelling. This is to ensure that models adequately represent the structure of the problem they represent (Senge and Forrester, 1980). There are different ways to validate system dynamics models: structural validation (Qudrat-Ullah and Seong, 2010), dimensional consistency (Eberlein and Peterson, 1992) of the units of the model equations, behaviour reproduction that corresponds to the historical or reference mode, sensitivity analysis (Sterman, 2000), and parameter assessment among others. All these validation tests were applied to the GELA model. The preliminary simulation results of the GELA model differed from the data for certain key variables, such as the population with, and without electricity access, the power capacity installed, the energy generated, and the total electricity access rate. In order to address this issue, an in-depth parameter assessment test was carried out through calibration to improve the assumptions made of key parameters such as the investment rate, as a fraction of GDP invested in the power sector. The result of the calibration is presented in Table 5.2.

Table 5.2: Parameter calibration and optimisation of base run results

Initial calibration results	
Initial point of search.	**Maximum payoff found at:**
INVESTMENT RATE = 0.014. Simulations = 1. Pass = 0. Payoff = -207.093. ---------------------------------.	*INVESTMENT RATE = 0.0178173. Simulations = 17. Pass = 3. Payoff = -73.3454. ---------------------------------.
Confirmation of optimised results	
Initial point of search.	**Maximum payoff found at:**
INVESTMENT RATE = 0.0178173. Simulations = 1. Pass = 0. Payoff = -73.3455. ---------------------------------.	*INVESTMENT RATE = 0.0178146. Simulations = 11. Pass = 3. Payoff = -73.3454. ---------------------------------.
:COMSYS After 17 simulations :COMSYS Best payoff is -73.3454 :COMSYS Normally terminated optimization :OPTIMIZER=Powell :SENSITIVITY=Off :MULTIPLE_START=Off :RANDOM_NUMER=Default :OUTPUT_LEVEL=On :TRACE=Off :MAX_ITERATIONS=1000 :RESTART_MAX=0 :PASS_LIMIT=2 :FRACTIONAL_TOLERANCE=0.0003 :TOLERANCE_MULTIPLIER=21 :ABSOLUTE_TOLERANCE=1 :SCALE_ABSOLUTE=1 :VECTOR_POINTS=25 0.01 <= INVESTMENT RATE = 0.0178173 <= 0.02	:COMSYS After 11 simulations :COMSYS Best payoff is -73.3454 :COMSYS Normally terminated optimization :OPTIMIZER=Powell :SENSITIVITY=Payoff Value=4 :MULTIPLE_START=Off :RANDOM_NUMER=Default :OUTPUT_LEVEL=On :TRACE=Off :MAX_ITERATIONS=1000 :RESTART_MAX=0 :PASS_LIMIT=2 :FRACTIONAL_TOLERANCE=0.0003 :TOLERANCE_MULTIPLIER=21 :ABSOLUTE_TOLERANCE=1 :SCALE_ABSOLUTE=1 :VECTOR_POINTS=25 0.01 <= INVESTMENT RATE = 0.0178146 <= 0.02
:COM The base payoff is -73.3454 :COM A * Means a bound was reached, i.e. payoff not at criterion. :SENSITIVITY = PAYOFF_VALUE = 4 0.0171222 <= INVESTMENT RATE = 0.0178146 <= 0.0186467	

From Table 5.2, the investment rate of 1.4% was calibrated within the lower and upper boundaries of 1% to 2%. After 17 simulations, it was revealed that at an investment rate of 1.78% the payoff improved from -207 to -73, which suggests a better match between the model and the data. The investment rate in the model was then changed from 1.4% to 1.78%. A total of 11 simulations were executed again, with the investment rate of 1.78%, and the payoff remained -73. This affirmed that under the given model boundary, 1.78% was the best estimate for Ghana's budgeted investment rate as a fraction of its GDP.

5.5.4 Scenarios assessed

Different scenarios were assessed to ascertain the outcome of changing key parameters that could be leverage points for decision-making. These scenarios are named: the Baseline Scenarios (Baseline), High Access Low Renewables Scenario (HALRS), Medium Access Medium Renewables Scenario (MAMRS), Low Access High Renewables Scenario (LAHRS), and High Renewables Scenario (HRS). The investment distributions among hydropower, gas thermal and solar are elaborated in Table 5.3.

Table 5.3: Parameters for scenario assessment

Scenarios **Investment distribution**	**Hydro investment fraction**	**Thermal investment fraction**	**Solar investment fraction**
Baseline	25%	65%	10%
High Access Low Renewables	25%	50%	25%
Medium Access Medium Renewables	25%	40%	35%
Low Access High Renewables	25%	35%	40%
High Renewables	25%	0%	75%

All scenarios, with the exception of the High Renewables scenario, assumed that hydro investment would remain at 25% of annual investment until the maximum hydro potential in the country is reached. The key dynamics across the different scenarios is centred on the apportionment between gas/diesel thermal and solar power. The outcome of re-allocating the annual electric power budget in Ghana among the different power sources in operation is presented and discussed next.

5.5.4.1 Baseline Scenario (Baseline)

The baseline (business as usual) scenario depicts how the power sector would develop under the present trend of investment and population dynamics. The outcome of this scenario is compared to other alternative scenarios that could emerge through policy action to access the potential for expediting electricity access and expanding the renewable energy capacity in the energy mix. Under this scenario, the investment distribution for the various power sources in 2019 was 10%, 25%, and 65% for solar, hydro, and gas thermal power plants, respectively. However, this changes to 35%, 0% and 65% in 2026, once all the hydro potential has been developed in 2026.

5.5.4.2 High Access Low Renewables Scenario (HALRS)

The share of solar investment under this scenario increases by 15% between 2019 and 2026, and increases further by a further 25% in 2026, when its potential capacity is exhausted. The thermal share declines by 15% from 2019 to 2030. Hydro continues to be allocated 25% of the annual investment from 2019 until 2026, when the hydro fraction of investment is redirected towards solar. The investment distribution for the various power sources changes from 25%, 25%, and 50% for solar, hydro, and gas thermal power plants in 2019, to 50%, 0% and 50% in 2026, after all the hydro potential is developed in 2026.

5.5.4.3 Medium Access Medium Renewables Scenario (MAMRS)

Similar to the previous scenario, the hydro investment remains at 25% of annual investment until its capacity limit is reached in 2026, and its investment share is diverted to solar. The initial solar fraction from the policy start point is 35% in 2019, an increment of 25% from that of the Baseline Scenario between 2019 and 2026. The investment distribution starts as 35%, 25%, and 40% for solar, hydro, and gas thermal power plants in 2019, to 60%, 0% and 40% in 2026, after developing the remaining hydro potential.

5.5.4.4 Low Access High Renewables Scenario (LAHRS)

Under this scenario, thermal investment is also slightly reduced and solar investment increases by the same fraction as thermal reduction. Also, the present investment that goes into hydro continues until all potential sites are developed, after which the solar investment increases again by the fraction that hitherto was invested in hydro. The investment apportionment changes from 40%, 25%, and 35% for solar/renewables, hydro, and gas/diesel thermal power plants, to 65%, 0% and 35% after developing the remaining the hydro potential.

5.5.4.5 High Renewables Scenario (HRS)

This scenario evaluates what happens if all investment were to be directed towards renewables/solar. It assumes that the remaining small hydro sites are not developed, and no further investment is made in gas thermal power. The investment allocation under this scenario starts as 25%, 0%, and 75% for solar, hydro, and gas/diesel thermal power plants, and ends as 0%, 0%, and 100% respectively, once the potential hydro capacity is exhausted.

5.6 GELA MODEL BASELINE RESULTS

The GELA model baseline (business as usual) results are briefly discussed with focus on the three sectors: investment, power and energy, supply and population or electricity access. The investment sector discusses the annual investments in power capacity expansion, the power and energy shows the trend of the different power sources and the total power capacity and energy generation, and the population sector captures how many people and what fraction of the entire population would have electricity access over time.

5.6.1 Investment sector development

The amount of investment made in Ghana’s power sector is anchored to the GDP of the country. Since an increase in GDP growth leads to a rise in the demand for energy, a linear relation is assumed. The total investment made available for the power sector from the national budget is herein referred to as the budgeted investment. Since investment is subject to the power capacity gap, the budgeted investment is compared with the investment required to cover the capacity gap that is the indicated investment. The minimum between the budgeted and indicated investment is the annual investment made in the power sector. These investments are shown in Figure 5.9 below.

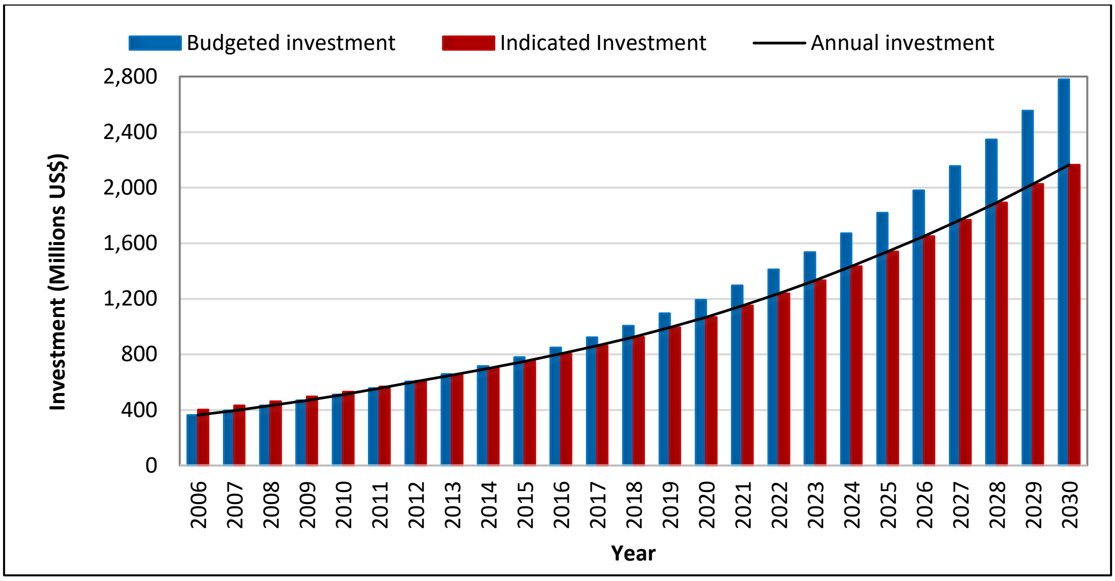


Figure 5.9: Budgeted, indicated, and annual investment in power capacity, Baseline Scenario

It is clear from Figure 5.9 that between 2006 and 2013, the annual investment was equivalent to the budgeted investment, and thereafter, from 2014, to the indicated investment. This implies that, from 2014, Ghana's annual power sector investment was adequate to offset the annual capacity backlog issue in the medium to long-term. Ghana's power sector investment has doubled in the past decade, from US$400 million in 2007 to US$800 million in 2016.

5.6.2 Power and energy sector development

Electric power investment in Ghana is focused on three key energy sources: hydropower, gas thermal, and solar. Although there is potential for other electric power sources, such as bioenergy and wind, there are yet to be any visible power plants. The past decade witnessed a period of steady increase in the size of thermal power capacity (see Figure 5.10).

As at 2016, thermal capacity in Ghana exceeded hydro, which hitherto had been the dominant power source in the country. However, hydro still accounts for over half of the electricity consumed in Ghana. This is because it has a higher utilisation factor, averaging about 44% in Ghana, than thermal, which has utilisation factor of about 32% as at 2016. The low efficiency of thermal in Ghana is partly attributed to the intermittency of the availability of fuel for operating the plants. Solar power and energy is also expected to increase in the coming years, while hydro is almost at its limit (see Figure 5.10)

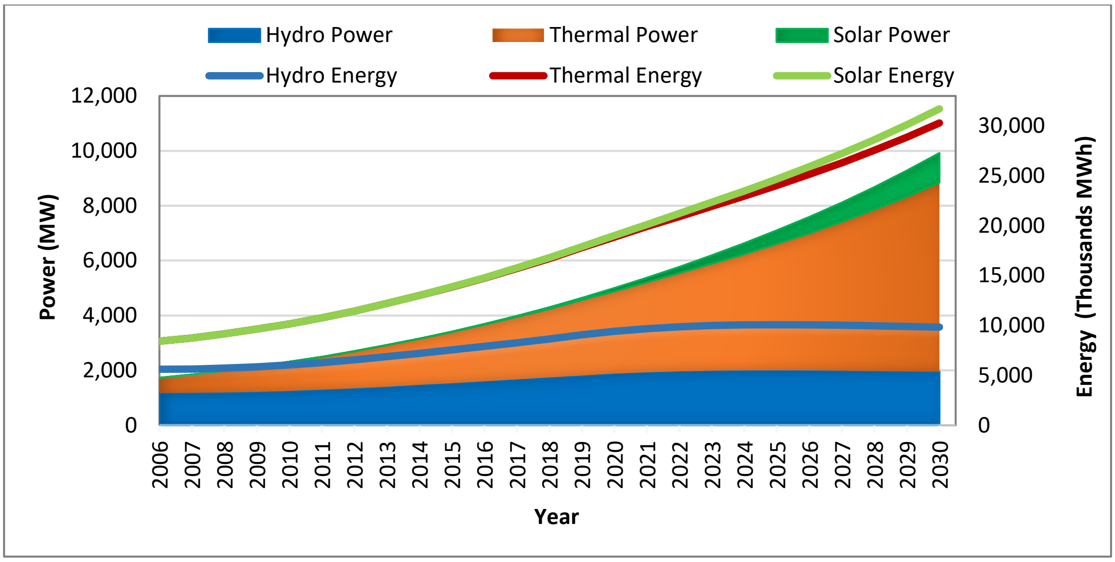


Figure 5.10: Power capacity and energy generation from the different sources, Baseline Scenario

5.6.3 Population sector development

This sector presents the two groups of population: people with and people without, access to electricity, which sum up to the total population of Ghana (see Figure 5.11).

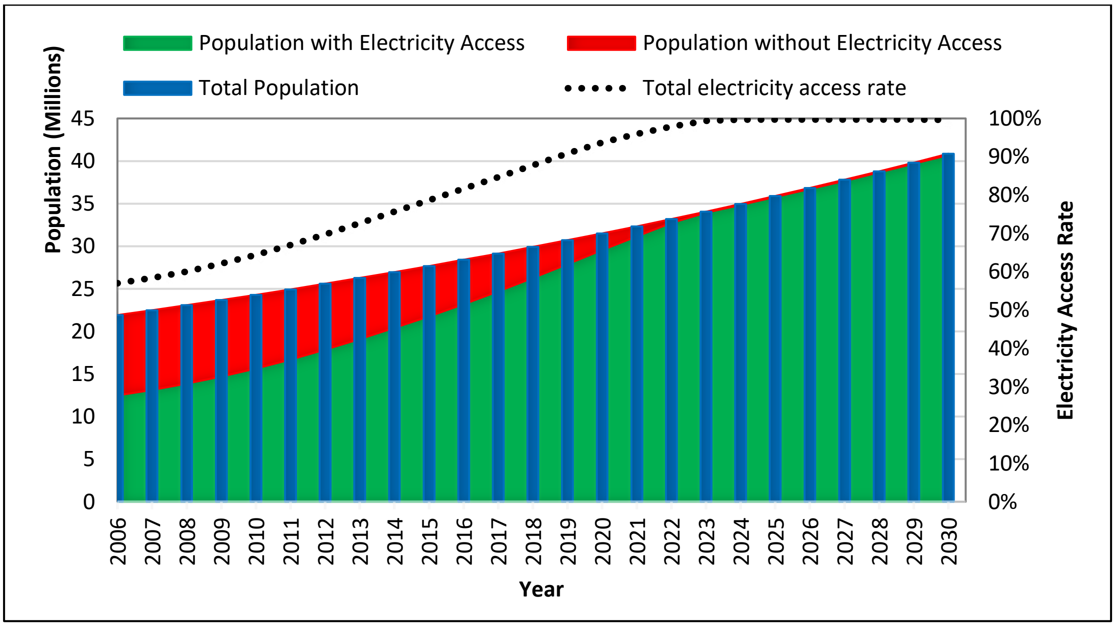


Figure 5.11: Population categories and total electricity access rate, Baseline Scenario

The population with electricity access is expressed as a fraction of the total population to deduce the total electricity access rate over time. This helps determine which year Ghana can expect to attain universal access to electricity under the business as usual scenario, in which no policy interventions are introduced. From the results in Figure 5.11 below, Ghana will achieve universal electricity access in 2023; three years after the strategic national energy plan goal elapses.

5.6.4 GELA scenarios and discussion

The scenarios differ mainly because of variations in the distribution of investment among the different power types. Two variables are key to the achievement of the study objective. They are the total electricity access rate and the share of renewable power capacity. The result of these variables' values from the different scenarios assessed is presented in Table 5.4.

Table 5.4: Total electricity access rate and renewable energy share under the different scenarios

	INVESTMENT DISTRIBUTION			***Total electricity access rate from different scenarios (%)***													
SCENARIOS	**Hydro investment fraction**	**Thermal investment fraction**	**Solar investment fraction**	2006	2016	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	***25***	***65***	***10***	57	82	91	94	96	99	100	100	100	100	100	100	100	100
HALRS	***25***	***50***	***25***	57	82	91	94	96	98	99	100	100	100	100	100	100	100
MAMRS	***25***	***40***	***35***	57	82	91	94	96	97	98	99	100	100	100	100	100	100
LAHRS	***25***	***35***	***40***	57	82	91	94	96	97	98	99	99	100	100	100	100	100
HRS	***25***	***0***	***75***	57	82	91	93	95	95	95	94	93	91	90	88	86	85
				Share of Solar in total power mix (%)													
Baseline	***25***	***65***	***10***	0	1	2	2	3	4	5	6	7	8	9	9	10	11
HALRS	***25***	***50***	***25***	0	1	2	2	4	5	7	8	10	11	12	14	15	16
MAMRS	***25***	***40***	***35***	0	1	2	2	4	6	8	10	12	13	15	17	18	20
LAHRS	***25***	***35***	***40***	0	1	2	3	4	6	8	10	12	15	16	18	20	22
HRS	***25***	***0***	***75***	0	1	2	3	5	9	12	16	20	23	27	30	34	37

5.6.4.1 Total electricity access rate

It is clear from the results in all scenarios (see Table 5.4) that Ghana does not meet its universal electricity access (100%) goal by the 2020 timeline. The highest access rate attainable by 2020 is 94%, which occurs under all scenarios except the high renewables scenario. Ghana, under the baseline or business as usual scenario, will achieve universal access to electricity is 2023, which is also the earliest time to reach that milestone. This implies that, as far as access to universal access is concerned, and if investment allocation becomes the only decision variable, Ghana is better off on its present investment path under the Baseline Scenario where renewables receive 10% of the annual investment.

Under HALRS, universal electricity access is delayed by a year because of the lower utilisation factor and higher unit cost of solar. When renewables is allocated 35% of annual investment in MAMRS and 40% in LAHRS, universal access to electricity is attained in 2025 and 2026 respectively. An interesting insight from the results is that, if all annual power budgets are invested in only solar, the access rate grows until it reaches 95% in 2023, and then declines slightly until 2030. This is because of the lower utilisation factor of solar. Because renewables are also slightly more expensive than gas thermal and large hydropower, the total renewable capacity installed in MW is lower and, coupled with the lower utilisation, people who hitherto have had access to electricity, begin to experience power insufficiencies.

5.6.4.2 Share of Solar in total power mix

The results shows that Ghana will not meet its 10 % renewable energy goal by 2020 as contained in the strategic national energy plan. Under the baseline scenario, the share of renewables, in the form of solar, will amount to only 2% of total power capacity (see Table 5.4). It is observed that Ghana achieves the 10% renewables goal only in 2029 under the baseline scenario. Some interventions are, therefore, necessary to achieve this goal. The investment allocation among the different power sources needs to be reapportioned to favour the growth of renewables. The renewables goal can be attained earlier than the baseline scenario, but that would require an increase in the fraction of the total investment allocated for renewables. An increase in the percentage of annual power budget invested in renewables, from the baseline10% to 25% in HALRS, 35% in MAMRS, and 40% in LAHRS achieves a 10% renewables share by 2025, 2024, and 2024 respectively (see Table 5.4).

The earliest time a 10% renewables can be achieved in Ghana is 2023, under the model boundaries and parameters. This require all (100%) investment (HRS) is directed towards solar energy from 75% renewables investment after hydro capacity is fully exhausted. A 12% renewables share is realised under this scenario by 2023. It would not, however, be feasible as universal electricity access would be compromised due to the low utilisation factor of renewables, and their relatively high cost, hence a low total capacity in MW units would be installed as a result.

5.6.4.3 Hydro sub-sector development

Hydropower is a finite resource, and as such, only a limited amount of hydro can be developed in Ghana. According to Seth and Mawufemo (2012), Ghana has a total of 2,420 MW hydro potential. The present installed hydro capacity stands at 1,580 MW from the three plants; Akosombo, Bui, and Kpong. This means the remaining undeveloped hydro potential is about 840 MW. The GELA model assumes the present annual investment in hydropower will continue under all scenarios until the hydro potential is all developed. The capital/capacity budget for hydro will then be diverted to solar automatically.

The results in Figure 5.12 show that the hydro capacity under all the scenarios remains the same, the maximum hydro capacity is also constant throughout the simulation period, and the remaining undeveloped capacity depletes to zero as the total potential developed approaches the maximum capacity. Hydro capacity decommissioning rises linearly and gradually as the hydro plants age.

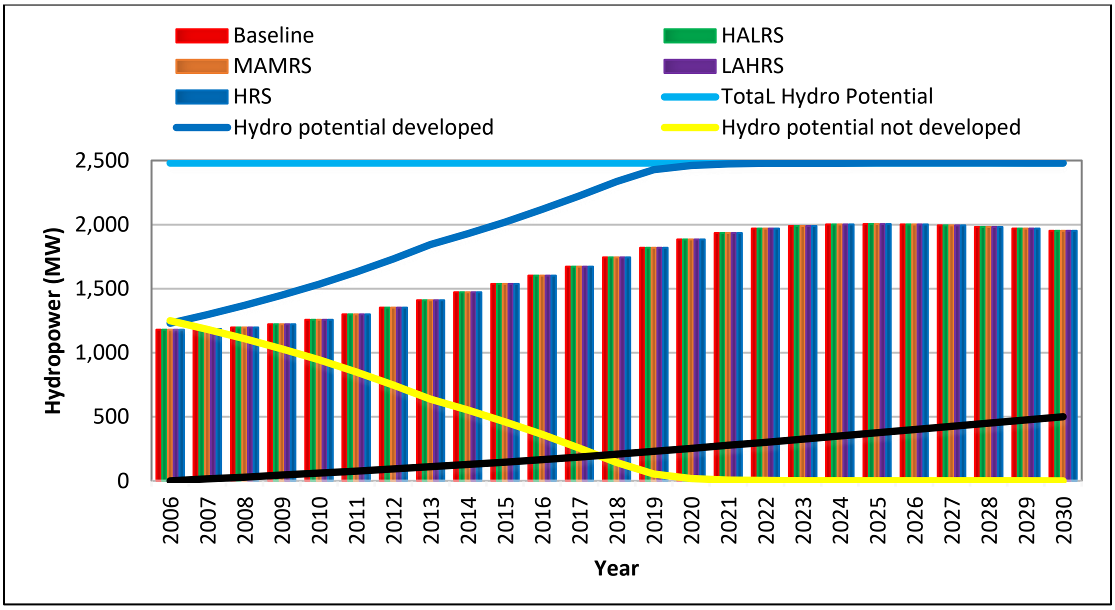


Figure 5.12: Hydro potential and capacity installation

5.6.4.4 Thermal sub-sector development

In the past decade, thermal power in Ghana recorded the largest capacity growth overall. In 2006, total installed capacity was 550 MW generating approximately 2,810,000 MWh of energy. The thermal capacity installed quadrupled to 2,066 MW from 2006 to 2016, generating 6,848,882 MWh of electricity in 2016 (Figure 5.13).

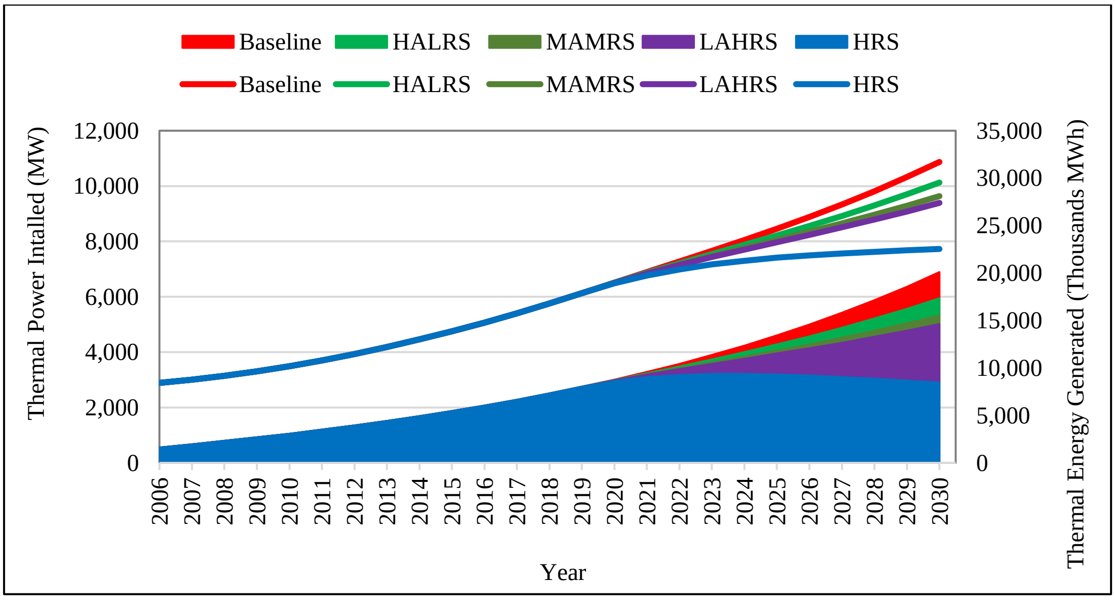


Figure 5.13: Thermal power installation and energy generation

By the year 2020, Ghana's total installed thermal capacity reaches 3,005 MW and increases thereafter to 4,602 MW and 6,891MW in 2025 and 2030 respectively, under the Baseline Scenario. Similarly the thermal energy generation increases from 9,452,277 MWh in 2020 to 13,951,354, which is equivalent to the total electricity consumption in 2018, and 20,469,052 MWh in 2025 and 2030 respectively (see Figure 5.13).

The thermal power capacity and energy generation values were at their lowest under the HRS Scenario. The HRS ceases future investments in thermal, thereby resulting in a decline in total thermal capacity and total energy generation (see Figure 5.13) due to capacity decommissioning. Under the HRS, thermal capacity installed for 2020, 2025, and 2030 were 2,956 MW, 3,192 MW, and 2,898 MW; and energy generations of 9,311,320 MWh, 9,875,799 MWh, and 8,924,282 MWh, respectively, during the same period. Also under HRS, the goal of universal electricity access would remain unmet (see Figure 5.13). The HALRS, MAMRS, and LAHRS scenarios would all result in less thermal capacities and energy generation than the Baseline Scenario, but more than the HRS.

5.6.4.5 Solar sub-sector development

Solar energy investment in Ghana has been growing steadily since 2013. The pursuit of renewable energy targets in the SNEP (GEC, 2006), and the commitment of the Ghana Energy Ministry to increase renewable energy proportion (Ministry-Energy, 2010), are driving forces for the growing investment in solar power. The simulation result of the GELA model show that solar capacity installed reaches 494 MW and 1,077 MW in 2025 and 2030 respectively (see Figure 5.14). On the other hand, if 100% of the annual power investment is diverted to solar (HRS Scenario), capacity installation will rise from 1,264 MW in 2025 to 2,886 MW in 2030, representing, a 20% to 37% share of renewables in the total energy mix.

The energy generated from solar will also increase from 648,200 MWh in 2025 to 1,415,103 MWh in 2030 under the Baseline Scenario, and from 1,660,827 MWh to 3,792,463 MWh (Figure 5.14) for the same period under the HRS Scenario. The undesirable consequence of the delayed universal electricity access means that this scenario is not ideal. Under both the Baseline and HRS Scenarios, the dual energy policy targets will not be met at the same time, or even within a five-year period, apart. The HALRS, MAMRS and LAHRS Scenarios are closer to ideal investment pathways.

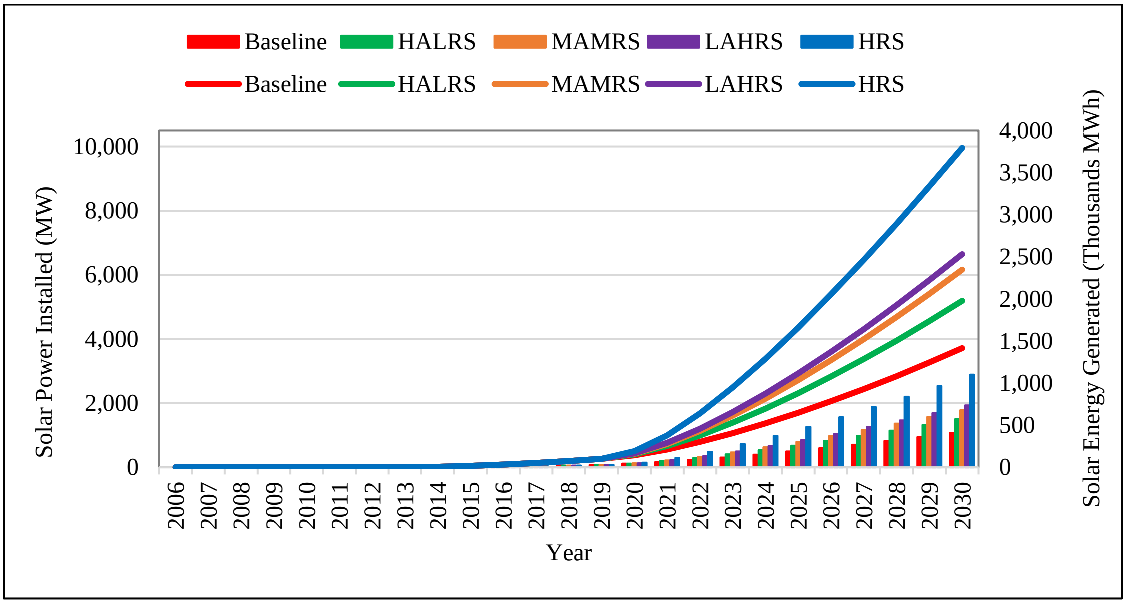


Figure 5.14: Solar power installation and energy generation

5.6.4.6 Total power and energy development

Ghana has witnessed a significant growth in its total power capacity and energy generation in the last decade. The power capacity installed has increased from 1,731 MW in 2006 to 3,418 MW in 2016 (see Figure 5.15).

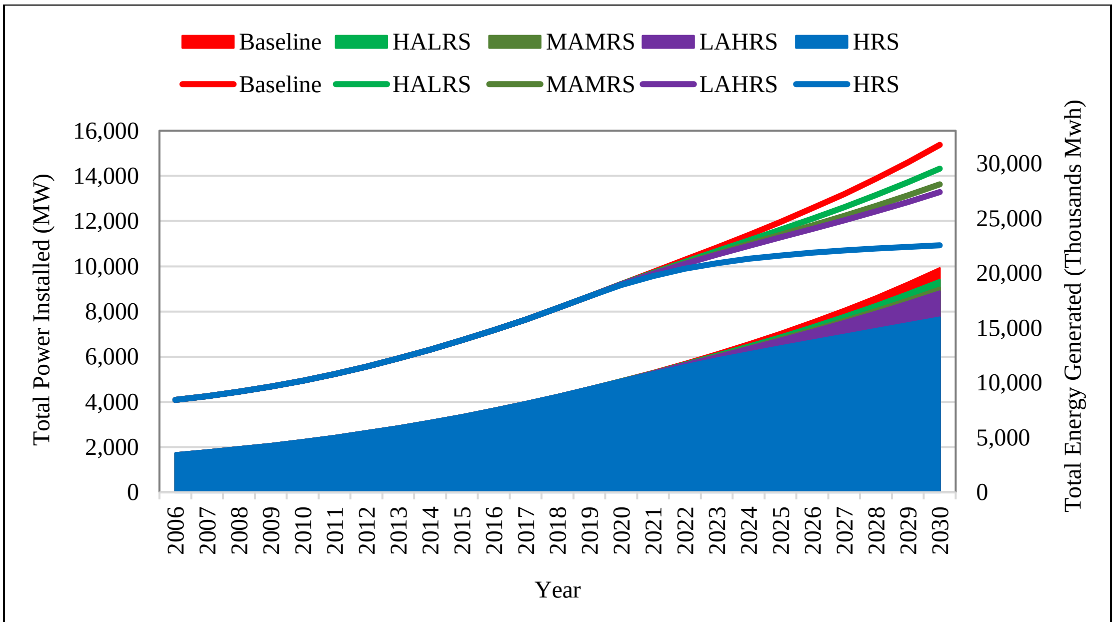


Figure 5.15: Total power installation and energy generation

During the same period, the energy generated also increased from 8,429,000 MWh to approximately 14,790,939. This represents an increase in power capacity and energy generation of 49% and 43% respectively. The disparities in power and energy growth is partly explained by the low capacity utilisation factor of some of the new power plants, fuel shortages for operating some thermal plants, and the low water levels of major hydro dams, owing to irregular rainfall. The power capacity installation under the baseline scenario is expected to reach 5,000 MW in 2020, 7,100 MW in 2025, and 9,920 MW in 2030. Energy generation for the same period will be 19,009,930 MWh, 24,676,474 MWh, and 31,708,922 MWh respectively, under the baseline scenario.

From Figure 5.15, it is clear that the baseline scenario produces the highest total power capacity installed and energy generated. This is because, under the baseline scenario, thermal, which is cheaper and has a higher utilisation factor than solar, records the highest investment share (65% of annual investment) when compared to the other scenarios. The results under the HRS for 2020, 2025, and 2030 indicate 4,986 MW, 6,461 MW, and 7,735 MW of power installed and 18,915,418 MWh, 21,613,546 MWh, and 22,541,508 MWh of energy generated respectively. This is significantly lower than the Baseline scenario, and underscores a key challenge of solar energy; its efficiency. The Baseline and HRS are the lower and upper bounds of the results (see Figure 5.15). The results from HALRS, MAMRS, and LAHRS scenarios all fall within the extreme bounds.

5.7 CONCLUSIONS

Ghana will certainly not achieve universal electricity access by 2020 under the existing investment pattern, or any other apportionment of the annual investment among the various power sources. This would still be the case, even with an increase in the annual investment. This is because of the delay time in plant construction even, for solar which requires a shorter time to install. The results shows that 2025 is the earliest time that Ghana can meet its dual energy goal of universal electricity access and to have 10% renewables in the total energy mix would require 50% of annual investment to be directed towards solar energy.

Ghana’s investment allocation among the three different power sources that is nearest to the desired goal is the High Access Low Renewables Scenario (HALRS), which attains universal electricity access in 2024 and 10% renewables in 2025. Alternatively, Medium Access Medium

Renewables Scenario (MAMRS) attains universal electricity access in 2025 and meet the renewables goal in 2024. The Baseline Scenario (Baseline) and Low Access High Renewables Scenario (LAHRS) are less desirable, as they delay the renewable energy target and universal electricity access until 2029 and 2026, respectively. The High Renewables Scenario (HRS) is not a viable option, as universal electricity access is not yet to be attained in 2030.

CHAPTER FIVE REFERENCES

ACT-832 2011. Renewable Energy Act. *Parliament of the Republic of Ghana.* Ghana.

AHMAD, S., MAT TAHAR, R., MUHAMMAD-SUKKI, F., MUNIR, A. B. & ABDUL RAHIM, R. 2016. Application of system dynamics approach in electricity sector modelling: A review. *Renewable and Sustainable Energy Reviews,* 56**,** 29-37.

ANAND, S., VRAT, P. & DAHIYA, R. 2006. Application of a system dynamics approach for assessment and mitigation of CO 2 emissions from the cement industry. *Journal of environmental management,* 79**,** 383-398.

ATSU, D., AGYEMANG, E. O. & TSIKE, S. A. 2016. Solar electricity development and policy support in Ghana. *Renewable and Sustainable Energy Reviews,* 53**,** 792-800.

BASS, F. M. 1969. A new product growth for model consumer durables. *Management science,* 15**,** 215-227.

BATINGE, B. Sustainable Energy Future: A System Dynamics approach to solving the Electricity shortfall in Ghana. Paper presented at the 33rd International Conference of the System Dynamics Society., 2015 Cambridge, Massachusetts USA. System Dynamics Review.

BATINGE, B., MUSANGO, J. K. & BRENT, A. C. 2017. Leapfrogging to renewable energy: The opportunity for unmet electricity markets. *The South African Journal of Industrial Engineering,* 28**,** 32-49.

CHI, K. C., NUTTALL, W. J. & REINER, D. M. 2009. Dynamics of the UK natural gas industry: system dynamics modelling and long-term energy policy analysis. *Technological Forecasting and Social Change,* 76**,** 339-357.

CONNOLLY, D., LUND, H., MATHIESEN, B. V. & LEAHY, M. 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy,* 87**,** 1059-1082.

EBERLEIN, R. L. & PETERSON, D. W. 1992. Understanding models with Vensim™. *European journal of operational research,* 59**,** 216-219.

ESHUN, M. E. & AMOAKO-TUFFOUR, J. 2016. A review of the trends in Ghana's power sector. *Energy, Sustainability and Society,* 6**,** 1-9.

FENG, Y. Y., CHEN, S. Q. & ZHANG, L. X. 2013. System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecological Modelling,* 252**,** 44-52.

FORD, A. 1997. System dynamics and the electric power industry. *System Dynamics Review,* 13**,** 57-85.

GACC. 2016. *Country profiles: Ghana* [Online]. Available: http://cleancookstoves.org/country-profiles/18-ghana.html [Accessed 25 May 2018].

GEC 2006. Strategic National Energy Plan 2006 – 2020. *Main Report.*

GEC 2017. National Energy Statistics. Accra: Ghana Energy Commission.

GEC, SE4ALL & UN 2012. Sustainable Energy For All - Ghana Action Plan.

GYAMFI, S., MODJINOU, M. & DJORDJEVIC, S. 2015. Improving electricity supply security in Ghana—The potential of renewable energy. *Renewable and sustainable energy reviews,* 43**,** 1035-1045.

IAROSSI, G. 2009. Benchmarking Africa's costs and competitiveness. *The Africa Competitiveness Report 2009*.

IEA 2017. World Energy Outlook 2017: From Poverty to Prosperity. *Special Report.* Paris: OECD/IEA.

IEA, A. E. O. 2014. A focus on the energy prospects in sub-Saharan Africa, World Energy Outlook Special Report. *International Energy Agency Publication.* Paris: OECD/IEA.

JERVEN, M. & DUNCAN, M. E. 2012. Revising GDP estimates in sub-Saharan Africa: lessons from Ghana. *African Statistical Journal,* 15**,** 13-24.

KEMAUSUOR, F., NYGAARD, I. & MACKENZIE, G. 2015. Prospects for bioenergy use in Ghana using Long-range Energy Alternatives Planning model. *Energy,* 93**,** 672-682.

KEMAUSUOR, F., OBENG, G. Y., BREW-HAMMOND, A. & DUKER, A. 2011. A review of trends, policies and plans for increasing energy access in Ghana. *Renewable and sustainable energy reviews,* 15**,** 5143-5154.

MINISTRY-ENERGY 2010. National Energy Policy.

MUSANGO, J. K., BRENT, A. C., AMIGUN, B., PRETORIUS, L. & MÜLLER, H. 2011. Technology sustainability assessment of biodiesel development in South Africa: a system dynamics approach. *Energy,* 36**,** 6922-6940.

MUSANGO, J. K., BRENT, A. C. & BASSI, A. M. 2014. Modelling the transition towards a green economy in South Africa. *Technological forecasting and social change,* 87**,** 257-273.

NAILL, R. F. 1977. *Managing the energy transition: a system dynamics search for alternatives to oil and gas.[use of COAL2 model]*.

NAZEERUDDIN, M. K., BARANOFF, E. A. & GRÄTZEL, M. 2011. Dye-sensitized solar cells: a brief overview. . *Solar energy,,* 85**,** 1172-1178.

QUDRAT-ULLAH, H. & SEONG, B. S. 2010. How to do structural validity of a system dynamics type simulation model: the case of an energy policy model. *Energy policy,* 38**,** 2216-2224.

SENGE, P. M. & FORRESTER, J. W. 1980. Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences,* 14**,** 209-228.

SETH, M. & MAWUFEMO, M. 2012. Opportunities in The Ghana Renewable Energy Act 2011, Act 832. Ministry of Energy.

SHIN, J., SHIN, W.-S. & LEE, C. 2013. An energy security management model using quality function deployment and system dynamics. *Energy Policy,* 54**,** 72-86.

STERMAN, J. D. 2000. *Business dynamics: systems thinking and modeling for a complex world*, Irwin/McGraw-Hill Boston.

UNECA 2017. Economic Report on Africa 2017: Urbanization and Industrialization for Africa's Transformation. Addis Ababa, Ethiopia.

UNEP 2015. Ghana Solar Export Potential Study. *Green Economy and Trade.* Geneva: United Nations Environment Programme.

UNEP 2016. GE-TOP Ghana Strategy Proposal – Realizing solar PV projects in a cross-border power supply context. *Green Economy and Trade.* Geneva: United Nations Environment Programme.

VRA 2015. 2x350 MW SUPERCRITICAL COAL-FIRED POWER PLANT. *Environmental and Social Impact Assessment - Scoping Report.*

WORLD-BANK 2016. Enterprise Surveys Indicator Descriptions. *World Bank Enterprise Survey, http://www.enterprisesurveys.org.*

WU, J.-H., HUANG, Y.-L. & LIU, C.-C. 2011. Effect of floating pricing policy: an application of system dynamics on oil market after liberalization. *Energy Policy,* 39**,** 4235-4252.

6 CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The overall research objective was to explore how energy transition, particularly leapfrogging to renewable energy, can accelerate universal electricity access in Africa. This chapter synthesises the investigations and discussions in the previous chapters and presents the contributions of the study, a summary of the findings, the theoretical and practical implications of the findings, the limitations, and recommendations for future research.

6.2 STUDY CONTRIBUTIONS

This study contributes towards the literature on transition frameworks, specifically energy transitions, in the context of developing countries. An important theoretical contribution of the study is that it has developed a contextual energy transition framework for unmet electricity markets. The framework is representative of, and suitable for, energy transition in unmet electricity markets (see Figure 6.1*)*.

The framework is based on gaps identified in the literature on existing transition frameworks, and the unique characteristics of the electricity market in Africa. The study identified six key dimensions that make this transition framework particularly suitable for the unmet electricity market in the context of a developing country. These are: (i) fulfilled, versus unmet, power market; (ii) large, versus small, scale; (iii) fossil, versus renewable, energy; (iv) time aspect: slow versus fast transition; (v) diminishing return versus niche opportunities, and (vi) single, versus multi-dimensional, pressures. The study's argument is that contextual awareness in designing policy frameworks for energy transition is essential to achieve sustainable energy for all, particularly in unmet electricity markets.

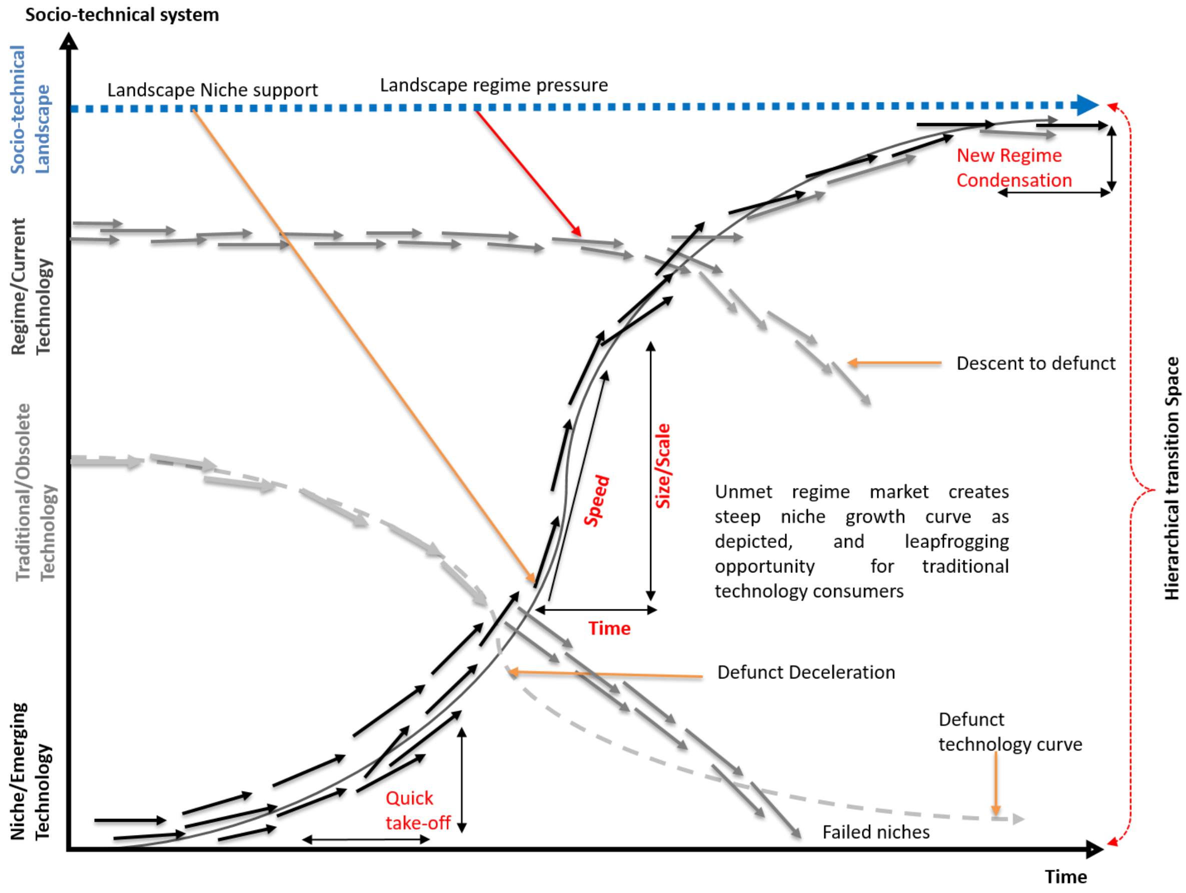


Figure 6.1: Transition framework for unmet electricity markets

The study also provides a conceptual contribution. It has established that unmet electricity markets, characterised by significant traditional energy, can leapfrog the conventional energy, to renewable energy to accelerate electricity access. Three potential leapfrogging paradigms were conceptualised, namely: *Revolutionary, Scattered, and Coned* pathways (see Figure 6.2). These paradigms were defined by the pace and magnitude of transition that can be observed, and depend on the intensity of the identified drivers in a specific unmet electricity market.

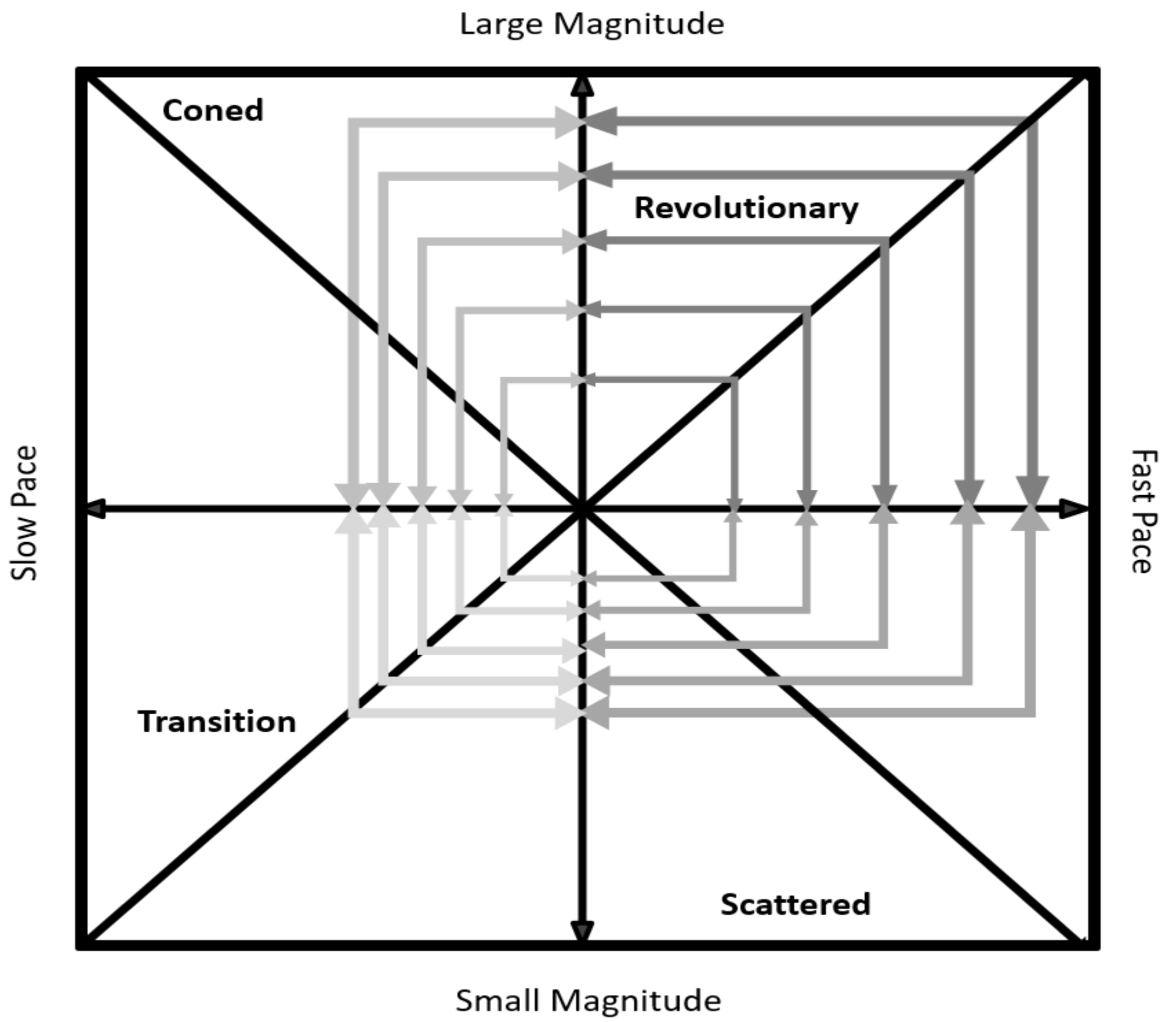


Figure 6.2: Conceptualised leapfrogging trajectories

Revolutionary leapfrogging is seen where the transition from one technology, and the adoption of a novel one, occurs at a fast pace and large scale, because of the capabilities of the adopter, and the positive characteristics of the new technology compared to the current technology. Scattered leapfrogging refers to transition with a small magnitude of change because of an existing large-scale infrastructure, to which small additions of new technology are made at a faster pace. Coned leapfrogging is a form of transition that involves changing an existing large-scale infrastructure, leading to a large magnitude of change at a slow pace, which involves a longer period for the adoption of the new technology to be completed.

The study submits that the transition in unmet electricity markets should be rapid, because of the urgency of need and the unique services it offers, which challenges the conceptualisations of existing transition frameworks that describe transition as a slow and gradual linear progression.

This study further makes a methodological contribution, based on the systematic literature review. This method unearthed extensive information on transitions, and aided in the development of a robust transition framework for the African energy market. The use of system dynamics modelling to develop the AFELA model elucidated the dynamics and fundamental structure of the electricity access problem. It also serves as a template for energy sector modelling. The GELA model represents how the AFELA model template can be refined and detailed for a more in-depth empirical application to a specific country. In addition, the qualitative and quantitative techniques used to collect data to design and populate the models, enhance the validity of the models. The model design process, which included stakeholder interaction, also demonstrates how problems can be better conceptualised in a dynamic environment.

The AFELA and GELA models also contribute to the empirical studies on electricity access across Africa, and specifically in Ghana. The models provide a more appropriate definition of electricity access per person. They address a fundamental limitation in the existing conceptualisation of the electricity consumption per access person, which uses the average per capita of electricity. Given that only a fraction of the total population has access to electricity; using average per capita, which expresses access over the entire population, understates the actual average electricity consumption per person with access. The average electricity consumed per person with access is thus expressed as a function of the effect of price on consumption, and the initial average consumption per person with access. This study calculated the average electricity consumption per person with access by dividing the access population at start time by the energy used at the start time. This results in a better estimation of the average electricity consumption per person with access, per capita over time. With an initial value of approximately 1,130 kWh, this figure is still far below the global average of 2,730 kWh. This formulation diminishes the error that arises from using population as the basis for estimating electricity needs, improving the accuracy of modelling for the future probability.

6.3 SUMMARY OF FINDINGS

The study made a number of discoveries from the investigation of the problem. First, it discovered that Africa, because of the size of its unmet energy market, might not face the inertia resulting from the lock-ins that developed countries have encountered pertaining to transitions in socio-technical infrastructures. While socio-cultural and political lock-ins in Africa could still impinge on energy transitions in its unmet electricity markets, the diffusion of electricity-dependent technologies, such as that of mobile phones in rural African communities, undermines the rigidity that these lock-ins supposedly exert. Socio-cultural and political factors must, however, be considered in implementing this transition framework.

Secondly, by virtue of its large unmet electricity market, the urgency for universal energy access, and the availability of renewable energy resources, Africa has the opportunity to leapfrog the fossil-intensive energy regime, to a renewable energy regime without going through the stage of reliance on conventional fossil energy. This is important, not only to meet the universal electricity access targets, but also to preserve the environment.

Thirdly, there is significant funding deficit in Africa for meeting its energy infrastructural needs. Results from the AFELA model indicate that, universal electricity access will not be achieved by 2030 under the current trend of investment. About 597 million (35%) and 360 million (16%) Africans were still projected to lack access to electricity by 2030 and 2040 respectively, if annual investment continues on the present trajectory. The results showed that the Electricity Access Investment Scenario, which entails an increase in the annual investment in the power sector by at least three times the present annual investment, is the most viable option to ensure universal electricity access in Africa by 2030. It is therefore imperative to induce investment from the private sector, given the limited funds from multilateral and bilateral aid agencies, and the constrained budgets of the national governments that are imbued with the mandate of providing electricity. Improving the operations of the power sector is also necessary; to ensure that generation plants function at a level above average, to boost their utilisation efficiency and the overall availability of electricity.

Lastly, it was found from the simulation results of the GELA model that Ghana is bound to miss its targets of universal electricity access and 10% renewables in its total electricity sector energy mix (excluding large hydropower) by 2020. Under the present investment pathway, Ghana attains its universal electricity access and 10% renewable energy goals only in 2023 and 2029 respectively.

6.4 THEORETICAL AND PRACTICAL IMPLICATIONS OF THE STUDY

The transition framework developed in the study offers a better archetypal and more robust layout of the peculiarities of Africa's energy market than has been hitherto available. Policy-makers can therefore adopt and adapt this framework for assessing transitions in unmet electricity markets. The African electricity market is largely suitable for the three leapfrogging paradigms. There exists, therefore, an opportunity to leapfrog Africa's unmet electricity markets, such as those of traditional energy consumers who still do not have any or adequate access to electricity, to renewable energy.

The role of the key feedback loops is to present a long-term view of the key dynamics in the power secctor. For example, the supply capacity feedback loop illustrates how the long-run dynamics of the power sector should be viewed as a reinforcing feedback and not a counteracting feedback. In the long-run, decommissiong occurs, resulting in an increase in the capacity backlog, which everntually leads to more capaciy commencements, more power installed, and more capacity getting decommissioned. When the power sector dynamics is viewed only in the short-run, a balancing feedback loop is visualised as more capacity installed leads to less capacity backlog. Power sector investment decisions should therefore take long'term view rather than short-term understanding to ensure early attainment of universal energy access.

It is incumbent upon state regulatory authorities fully understand the enormous sum of the financial resources required for achieving universal access to electricity in Africa by 2030. Meeting this financial obligation would require multi-stakeholder participation from both public and private actors. In order to attract private sector investment into energy, reforms must be made to guarantee the private sector of sufficient returns on their investment.

It is clear that Ghana will miss its dual energy goal of universal electricity access and 10% renewables share in the energy mix by 2020. The allocation of the energy budget among the different power generation options should be restructured in favour of renewable energy, to grant any chance of achieving this dual goal by 2025. An investment restructuring among the key power sources is thus essential to the attaining of the energy goals.

Although this study was conducted with a focus on one sub-objective at a time, there is clear coherence and insights to, as well as logical consistency with, the overall study objective. The empirical quantitative analysis and findings of the third and fourth objectives follows on from the transition framework and the leapfrogging paradigms in unmet electricity markets demonstrated in objectives one and two. For example, the traditional technology curve in the transition framework for unmet electricity markets illustrates the lack of electricity access in Africa, which is mirrored in the investment gap identified in objective three. Similarly, the leapfrogging paradigms in Chapter Three show how the traditional energy consumers in Ghana, who are mainly in rural areas, can be leapfrogged to renewable energy, in order to meet their energy needs, attain universal electricity access, and increase the share of renewable energy in the total energy mix.

This implies that policy-makers can understand the development of the different energy types using the transition framework, and analyse how leapfrogging can be executed in unmet electricity markets using that framework. They can also attract private sector investment to address the funding challenge, promote the market conditions necessary for such investments, and use the empirical insights from Ghana to assess how both universal electricity access and increased renewable energy share can be attained.

6.5 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Although the transition framework for unmet electricity markets has detailed and captured the landscape pressure on the regime, and support for the niche, it shares limitations with previous frameworks concerning how the landscape effects can be quantified in an empirical case. Quantification of the landscape effects requires in-depth empirical analysis, which is beyond the scope of this study. Future transition research should, investigate the landscape effect on transition. Further studies should also investigate the policy frameworks, to facilitate the transitions envisaged in this framework.

The leapfrogging paradigms that the study advances may overlap, and not manifest as concisely in an empirical case as described. For example, it is possible for what may start as a revolutionary leapfrogging to end up as a coned or scattered leapfrogging, and vice versa, depending on factors such as availability of resources, political environment, and social acceptability, amongst other things. There may also exist social, cultural, and political factors that impinge upon leapfrogging efforts. Further research is recommended on the contextual boundaries of these paradigms, as well as the potential social, cultural, and political factors that may act as inertia on leapfrogging.

The AFELA and GELA models are based on the system dynamics modelling approach. The models did not provide detailed feedbacks linking the energy sector to other key economic sectors such as agriculture, education and manufacturing. The models also made estimates for certain parameters for which actual data was not found. Though the estimation error in both models is reduced through calibration, slight differences may still exist between the actual and model data. Future research should consider these models as templates and endeavour to include other economic sectors, and also populate the models with more accurate data to improve the overall validity of the results.

The study modelled electricity access using individuals, not households. Given that grid-connected electricity is largely calculated on a household basis, a limitation of the study is the implied assumption that all individuals in those households connected to the grid have electricity access. The exception of this assumption are those households that fall outside the definition of 'electricity access' in this study: a consistent uninterrupted electricity supply for five days in a week. Future research should employ explicit computation techniques to accurately distinguish grid connection from electricity access, and capture the population that does not have the defined electricity access.

APPENDICES

APPENDIX A: PUBLICATIONS

A1. Peer reviewed Journals

BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., 2017. Leapfrogging to renewable energy: the opportunity for unmet electricity markets. *The South African Journal of Industrial Engineering*, *28*(4), pp.32-49.

A2. Conference Proceedings

BATINGE B., MUSANGO J., BRENT A. C. 2018. Imperatives for Private Sector Financing in Unmet Electricity Markets in Africa. Accepted for presentation at *AFRE International Conference on Innovations in Engineering Sciences, Smart Materials, Bioinformatics, Manufacturing & Industrial Technologies*. September 25 – 26, 2018. Accra, Ghana.

BATINGE B., MUSANGO J., BRENT A. C. 2017. Implications of urbanization in Sub-Saharan African cities on sustainable energy access. *First Symposium of International Network – Michelin cities, November 29 – December 1 2017.* Clermont-Ferrand, France

BATINGE B., MUSANGO K. J., AND BRENT A. C. 2017. Boosting electricity access in Africa through private sector financing. Presented at the 35th International Conference of the System Dynamics Society, July 16-20, 2017, Cambridge, Massachusetts USA.

BATINGE, B. 2015. Sustainable Energy Future -A System Dynamics approach to solving the Electricity shortfall in Ghana. *Conference Proceedings: 33nd International Conference of the System Dynamics Society*, *July 19-23, 2015*, Cambridge, Massachusetts USA

A3. Manuscripts submitted to peer reviewed Journals

BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Sustainable Energy Transition Framework for Unmet Electricity Markets. *Energy Policy*

BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Assessing the funding gap of Africa's Unmet Electricity Markets. *Energy for Sustainable Development*

BATINGE, B., MUSANGO, J.K. AND BRENT, A.C., (in review). Pathways for attaining universal electricity access and renewable energy goals in Ghana. *Renewable & Sustainable Energy Reviews*

A4. Selected abstracts of peer reviewed publications

South African Journal of Industrial Engineering December 2017 Vol 28(4), pp 32-49

LEAPFROGGING TO RENEWABLE ENERGY: THE OPPORTUNITY FOR UNMET ELECTRICITY MARKETS

B. Batinge[1*], J.K. Musango[1] & A.C. Brent[2,3]

ARTICLE INFO

Article details
Submitted by authors 6 Jul 2016
Accepted for publication 20 Sep 2017
Available online 13 Dec 2017

Contact details
* Corresponding author
benjaminb50@gmail.com

Author affiliations
1 School of Public Leadership, Urban Modelling and Metabolism Assessment (uMAMA), Centre for Complex Systems in Transition (CST), Stellenbosch University, South Africa

2 Department of Industrial Engineering, Centre for Renewable and Sustainable Energy Studies (CRSES), Urban Modelling and Metabolism Assessment (uMAMA), Stellenbosch University, South Africa

3 Sustainable Energy Systems, Engineering and Computer Science, Victoria University of Wellington, New Zealand

ABSTRACT

Electricity plays a crucial role in the socio-economic development of any country. Developing countries, however, unlike their developed counterparts, do not have electricity markets that are fully satisfied, nor are they 'laden' with large-scale infrastructure that could create inertia about making the transition. The objective of this paper is to identify the potential trajectories for unmet electricity markets in sub-Saharan Africa to leapfrog to renewable energy as they strive to accelerate access to electricity. The following key drivers of renewable energy leapfrogging in unmet electricity markets were identified from the review: the need to achieve sustainability targets; the availability of renewable energy resources on a sufficient scale; growing investment in renewable energy; maturing niche renewable technologies; a weakening renewable energy cost hypothesis; and a growing population and increasing urbanisation. The paper further conceptualised three potential transition paradigms: *revolutionary*, *scattered*, and *coned* pathways. These paradigms were defined by the pace and magnitude of the transition that can be observed, and depend on the intensity of the identified drivers in a specific unmet electricity market. The paper argues that the largely unmet electricity market in sub-Saharan Africa provides an opportunity to leapfrog the fossil-intensive energy regime to adopt a renewable energy regime.

APPENDIX B: INTERVIEW REQUEST LETTER

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

Dear Sir/Madam,

Request to Participate in Research

My name is Benjamin Batinge, a doctoral candidate at the Stellenbosch University. I am writing my dissertation on the topic: "*Expediting transitions in unmet electricity markets: the case of leapfrogging renewable energy in Africa*". The research is conducted under the supervisory of Dr. Josephine Musango of the School of Public Leadership and Centre for Renewable Energy (South Africa), and Prof. Alan Brent of the Industrial Engineering Department of the University. The study purpose is to explore the energy transition in an unmet electricity market in Africa and how leapfrogging to renewable energy can accelerate universal electricity access, using Ghana as a case study.

The results of the study will contribute to a research paper, and the overall dissertation. I am contacting you for participation because of your immense experience and knowledge of Ghana's Energy sector and Electricity system. The research process, should you choose to grant me the opportunity, will involve scheduling of an unstructured interview session in December 2016 or January 2017 to discuss the nature and operations as well as challenges and opportunities of the energy sector. An essential theme would be assessment of renewable energy up-scaling potential in locations currently not connected to the national grid.

The purpose of the interview is to enable me design accurate System Dynamics Model of Ghana's Electricity System that can inform policy trajectories and implications through simulation process using the Vensim simulation software. You will have the privilege of assessing the model should you desire to do so before it becomes part of any academic publication or final submission.

Any information that is obtained in connection with this study, which can be identified with you, will remain confidential and will be disclosed only with your permission. Confidentiality will be maintained by means of the coding procedures. The study also adheres to the strict code of conduct and ethical research process of Stellenbosch University. You will be at liberty to opt-out in the process of an interview, or choose to decline from answering questions that you deem sensitive to you or the organisation you represent.

If you have any questions or concerns about the research, please feel free to contact me: Benjamin Batinge (*benjaminb50@gmail.com - +27 788 3113 82*), or superviisors: Dr. Josephine Musango (*jmusango@sun.ac.za*), and Prof. Alan Brent (*acb@sun.ac.za*). Should you wish to reach the University for reasons relating to this research/request, you can also do so through Ms Maléne Fouché (*mfouche@sun.ac.za; +2721 808 4622*) at the Division for Research Development. I am counting on your kind consideration and participation to enable me complete this research. I look forward to hearing from you. Thank you very much.

Benjamin Batinge
Economic and Management Sciences Faculty
University of Stellenbosch, South Africa
Mobile: +27788311372

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

SPL
SCHOOL OF PUBLIC LEADERSHIP

CENTRE FOR RENEWABLE & SUSTAINABLE ENERGY STUDIES

SUSTAINABILITY INSTITUTE

APPENDIX C: INTERVIEW QUESTIONS

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

EXAMINING GHANA'S ENERGY SECTOR IN THE CONTEXT OF AN UNMET ELECTRICITY MARKET

Interview Questions

Power Sector Overview

1. What is the size of Ghana's electricity demand sector presently?
2. Who is currently the main electricity consumer in the country?
3. How significant is the impact of population growth to the electricity access challenge in Ghana?
4. To what extent do the present electricity tariffs reflect the power market conditions in the country?
5. What is the proportion of the electricity cost is subsidised by the government?
6. Do the electricity tariffs differ for the different consumers in Ghana?
7. Operating at full capacity, how adequate is the present installed power in relation to catering for the country's electricity needs?
8. How is investment made in the energy sector, particularly the electricity systems? Simply just a fraction of GDP allotted for energy yearly, or periodical investment times exceeding one year?
9. Recent investments in the power sector appears to be directed to thermal power, why is this the case?
10. Transmission and Distribution losses are commonly identified with the power sector. What accounts for these losses?
11. What can be done and/or has been done to reduce these losses?
12. Ghana's hydropower infrastructure has been underperforming in recent years, what causes this problem?
13. What are the key challenges of Ghana's thermal power sector?

Power Sector Potential

1. Previous geographic survey identified some potential mini-hydro sites across the country, what are the plans regarding these sites?
2. Globally, the advocacy for renewable energy integration seems to be growing. How realistic is the potential for renewable technologies such as solar photovoltaic and CSP in Ghana?
3. What is the feasibility of introducing wind power in Ghana's power sector energy mix?
4. How feasible is it to provide electricity through renewable energy, to communities that are not yet connected to the national electricity grid in Ghana, for example through distributed or stand-alone plants for instance?
5. Given the challenges relating to thermal power in the country, what are the future investments plans regarding thermal projects?
6. What is the feasibility of coal power in Ghana, and is there or has there even been considerations to introduce coal power in the country's energy mix?
7. There is a renewable energy policy in the Strategic National Energy Plan (SNEP). How far or close is the sector towards achieving the renewable energy target?
8. What opportunities or challenges would regulatory changes that ensure active private sector participation in Ghana's power sector avail/pose?
9. Different international development agencies (e.g. International Climate Fund, Power Africa) give grants for energy infrastructural projects, how significant is this contribution to alleviating the power sector challenges in Ghana?
10. Energy end-user efficiency is often proclaimed as a means to reducing electricity demand. What end-user efficiency measures are currently in place to reduce electricity consumption?
11. Given the prevailing policy frameworks and the nature of the power market in Ghana, what trend of electricity demand and supply gap (decreasing/increasing/stable) would you project, and why?
12. What opportunities are available for improving the country's power systems infrastructure?

Benjamin Batinge
Economic and Management Sciences Faculty
University of Stellenbosch, South Africa
Mobile: +27788311372

SPL SCHOOL OF PUBLIC LEADERSHIP
CENTRE FOR RENEWABLE & SUSTAINABLE ENERGY STUDIES
SUSTAINABILITY INSTITUTE

APPENDIX D: RESEARCH ETHICS COMMITTEE APPROVAL

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

Approval Notice
New Application

29-Nov-2016
Batinge, Benjamin B

Proposal #: SU-HSD-003501
Title: **Expediting transitions in unmet electricity markets: the case of leapfrogging renewable energy in Africa**

Dear Mr Benjamin Batinge,

Your **New Application** received on **03-Nov-2016**, was reviewed
Please note the following information about your approved research proposal:

Proposal Approval Period: **24-Nov-2016 -23-Nov-2019**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

Please remember to use your **proposal number** (SU-HSD-003501) on any documents or correspondence with the REC concerning your research proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The Committee will then consider the continuation of the project for a further year (if necessary).

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for an external audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.

We wish you the best as you conduct your research.

If you have any questions or need further help, please contact the REC office at 218089183.

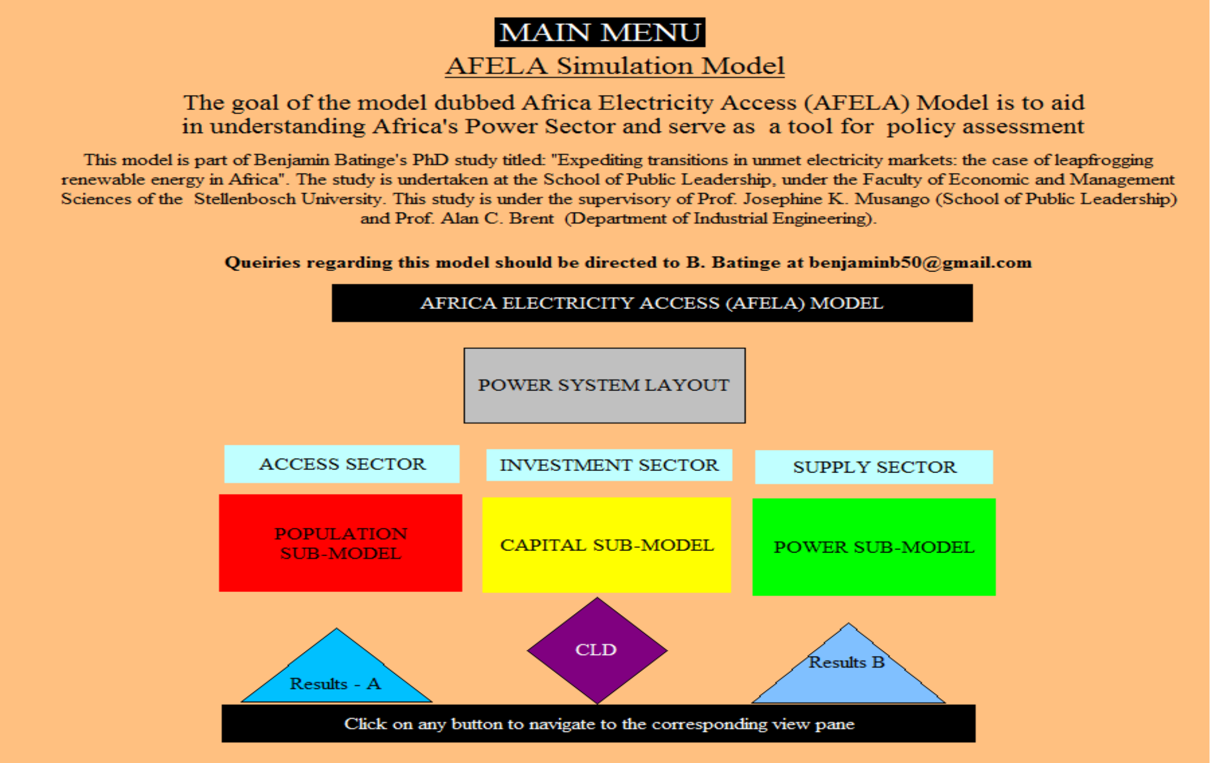
Included Documents:

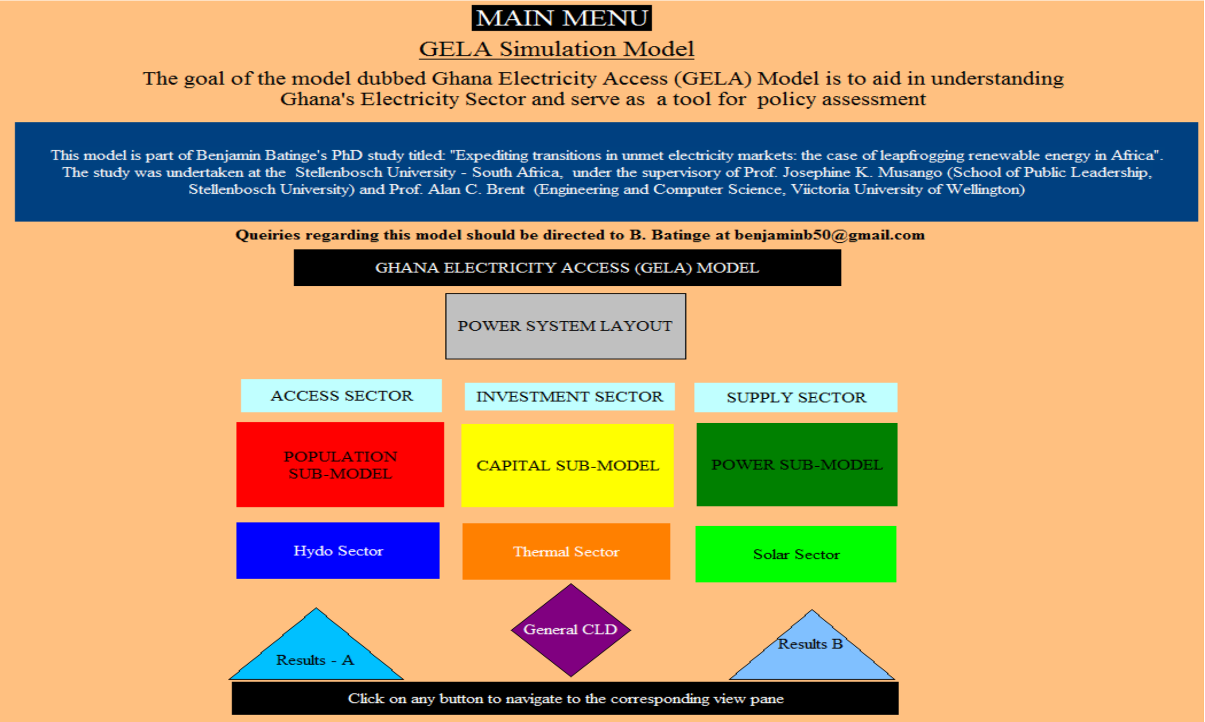
DESC Report
REC: Humanities New Application

Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)

APPENDIX E: INTERFACE AND EQUATIONS OF AFELA AND GELA MODELS





Documentation of AFELA Model

View the 72 variables sorted by type, module, group, variable name, module/group/name, Level Structure, or in a view summary.

Model Assessment Results

Model Information	Number
Total Number of Variables	72
Total Number of State Variables (Level+Smooth+Delay Variables)	10 (13.9%)
Total Number of Stocks (Stocks in Level+Smooth+Delay Variables) †	10 (13.9%)
Total Number of Macros	0
Variables with Source Information	0
Variables with Dimensionless Units	13 (18.1%)
Variables without Predefined Min or Max Values	63 (87.5%)
Function Sensitivity Parameters	0
Data Lookup Tables	0
Time Unit	year
Initial Time	2001
Final Time	2040
Reported Time Interval	1
Time Step	0.0625
Model Is Fully Formulated	Yes
Modeler-Defined Groups	**- No -**
VPM File Available	**- No -**

Warnings	Number
Undocumented Equations	5 (6.9%)
Equations with Embedded Data (0 and 1 constants ignored)	10 (13.9%)
Equations With Unit Errors or Warnings	Unavailable
Variables Not in Any View	0
Incompletely Defined Subscripted Variables	0
Nonmonotonic Lookup Functions	0
Cascading (Chained) Lookup Functions	0
Non-Zero End Sloped Lookup Functions	1 (1.4%)
Equations with "IF THEN ELSE" Functions	0
Equations with "MIN" or "MAX" Functions	8 (11.1%)
Equations with "STEP", "PULSE", or Related Functions	3 (4.2%)

Potential Omissions	Number
Unused Variables	0
Supplementary Variables	2
Supplementary Variables Being Used	0
Complex Variable Formulations (Richardson's Rule = 3)	7
Complex Stock Formulations	0

Types:					
	L : Level (10 / **10**) *	**SM** : Smooth (0 / **0**) *	**DE** : Delay (0 / **0**) * †	**LI** : Level Initial (9)	**I** : Initial (5)
	C : Constant (25)	**F** : Flow (12)	**A** : Auxiliary (31)	**Sub**: Subscripts (0)	**D** : Data (0)
	G : Game (0)	**T** : Lookup (1 / **1**) ††			

* (state variables / **total stocks**)
† Total stocks do not include fixed delay variables. †† (lookup variables / **lookup tables**).

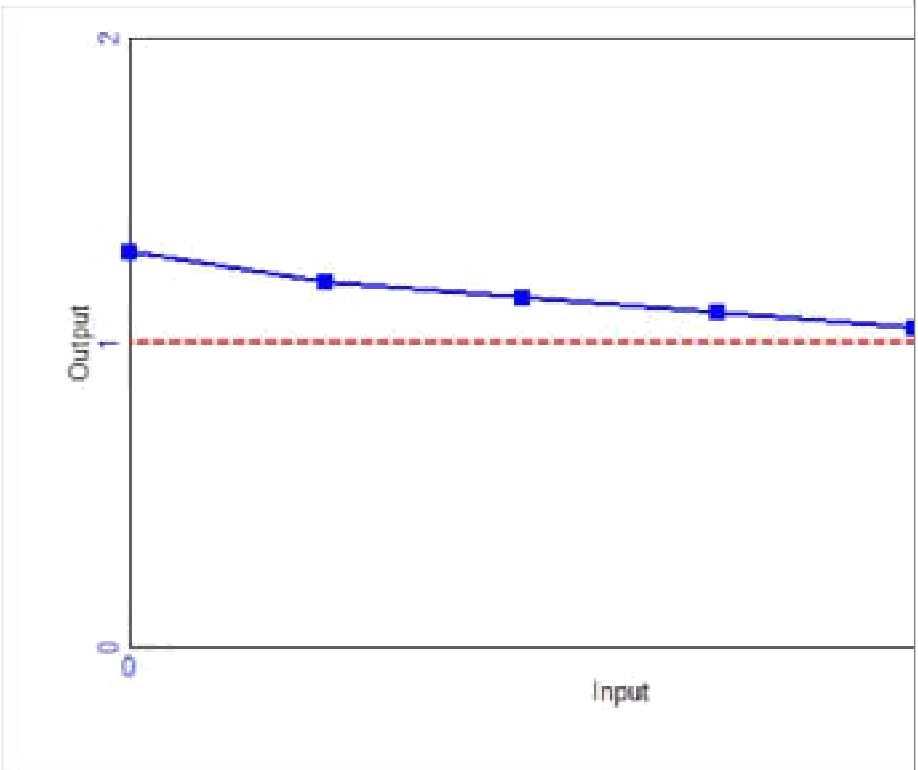
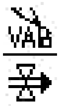
Groups:			
	AFELA Model (68) (Default)	**Control** (4) Simulation Control Parameters	

Modules:		
	Default (72)	

Views:					
	INTERFACE (0)	**POWER SYSTEM LAYOUT** (0)	**Demand/Population sector** (26)	**Capital/Investment sector** (25)	**Supply/Power sector** (46)
	Results - A (0)	**Results B** (0)	**CLD** (1)		

TOP	**INTERFACE** (0 variables)		
Module	Group	Type	Variable Name and Description
TOP	**POWER SYSTEM LAYOUT** (0 variables)		
Module	Group	Type	Variable Name and Description
TOP	**Demand/Population sector** (26 variables)		
Module	Group	Type	Variable Name and Description
Default	AFELA Model (Default)	#1 L	**Actual Energy Utilised** (Gwh) $= \int$ Production completion-Production decommissioning dt + [INITIAL PRODUCTION] **Description:** *This is the total amount of energy consumed each year. It does not include transmission losses.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Production decommissioning - This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.
Default	AFELA Model (Default)	#5 C	**AVERAGE CONSUMPTION PER ACCESS PERSON** (Gwh/People [0,0.0025]) = 0.00131 **Description:** *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* **Present in 2 views:** x Demand/Population sector

			x Supply/Power sector **Used by:** x Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	AFELA Model (Default)	#6 A	**Average Consumption per person** (Gwh/People) = Effect of price on consumption*AVERAGE CONSUMPTION PER ACCESS PERSON **Description:** *This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand.* **Present in 1 view:** x Demand/Population sector **Used by:** x Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	AFELA Model (Default)	#17 A	**Effect of price on consumption** (Dmnl) = Effect of price on consumption TABLE(Price Change) **Description:** *It calculates how average consumption will respond to price changes.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand.
Default	AFELA Model (Default)	#18 L	**Effect of price on consumption TABLE** (Dmnl) = [(0,0)-(1,2)],(0,1.3),(0.2,1.2),(0.4,1.15),(0.6,1.1),(0.8,1.05),(1,1) **Description:** *It represents the electricity price and consumption relationship.* **Present in 1 view:**

			x Demand/Population sector **Used by:** x Effect of price on consumption - It calculates how average consumption will respond to price changes. 
Default	AFELA Model (Default)	#19 F,A 	**Electricity access loss rate** (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) **Description:** *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Population with Electricity Access - This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#20 F,A	**Electricity access rate** (People/year) = MAX(MIN((Production completion/Average Consumption per person),

			(Population without Electricity Access/TIME STEP)), 0) **Description:** *This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.* **Present in 1 view:** x Demand/Population sector **Used by:** x Population with Electricity Access - This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#21 A	**Electricity Price** (US$/Gwh) = Electricity Price in kWh/kWh to GWh conversion **Description:** *This is the actual electricity price which accounts for the effect of learning - it declines over time.* **Present in 1 view:** x Demand/Population sector **Used by:** x Price Change - It is the percentage change in price multiplied by the learning effect.
Default	AFELA Model (Default)	#22 A	**Electricity Price in kWh** (US$/kWh) = REFERENCE ELECTRICITY PRICE in kWh*Learning effect **Present in 1 view:** x Demand/Population sector **Used by:** x Electricity Price - This is the actual electricity price which accounts for the effect of learning - it declines over time.
Default	AFELA Model (Default)	#42 LI,I	**INITIAL POPULATION WITH ELECTRICITY ACCESS** (People) = INITIAL(3.1e+008) **Description:** *This refers to the population with access in the base year.* **Present in 1 view:** x Demand/Population sector **Used by:** x Population with Electricity Access - This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss.

Default	AFELA Model (Default)	#43 LI,I	**INITIAL POPULATION WITHOUT ELECTRICITY ACCESS** (People) = INITIAL(5.2332e+008) **Description:** *This refers to the population without access in the base year.* **Present in 1 view:** x Demand/Population sector **Used by:** x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#48 C	**kWh to GWh conversion** (Gwh/kWh) = 1e+006 **Present in 1 view:** x Demand/Population sector **Used by:** x Electricity Price - This is the actual electricity price which accounts for the effect of learning - it declines over time. x REFERENCE ELECTRICITY PRICE - This refers to the average price of electricity at the start time.(Estimated based on Trimbel et al. 2016 electricity cost in African countries)
Default	AFELA Model (Default)	#49 A	**Learning effect** (Dmnl) = Change in Capacity^(LN(1-LEARNING RATE)/LN(2)) **Description:** *It is the overall learning accumulated through the change in capacity over time, and the rate of learning that occur with each unit addition.* **Present in 2 views:** x Demand/Population sector x Capital/Investment sector **Used by:** x Cost per GW unit - This is the actual GW unit cost at any given point in time of the simulation. x Electricity Price in kWh x Price Change - It is the percentage change in price multiplied by the learning effect.
Default	AFELA Model (Default)	#51 C	**NET POPULATION GROWTH RATE** (Dmnl/year) = 0.025 **Description:** *The net population growth aggregates factors including deaths, births, and migration on the total population. The data for this parameter is obtained from worldometers (http://www.worldometers.info/world-population/africa-population/), which compute population growth in real time.* **Present in 1 view:** x Demand/Population sector **Used by:**

- Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.

Default AFELA Model (Default)	#52 F,A	**Population growth** (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) **Description:** *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* **Present in 4 views:** - Demand/Population sector - Capital/Investment sector - Supply/Power sector - CLD **Used by:** - Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. - Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default AFELA Model (Default)	#53 L	**Population with Electricity Access** (People) = ∫Electricity access rate-Electricity access loss rate *dt* + [INITIAL POPULATION WITH ELECTRICITY ACCESS] **Description:** *This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss.* **Present in 1 view:** - Demand/Population sector **Used by:** - Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. - Total access rate - The access rate represents the population who have access to electricity expressed as a percentage of the total population. - Total Population - The total population sums both the people with and without electricity access. In effect, it represents the total population of Africa.
Default AFELA Model (Default)	#54 L	**Population without Electricity Access** (People) = ∫Electricity access loss rate+Population growth-Electricity access rate *dt* + [INITIAL POPULATION WITHOUT ELECTRICITY ACCESS] **Description:** *This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.* **Present in 1 view:**

			x Demand/Population sector **Used by:** x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases. x Total Population - The total population sums both the people with and without electricity access. In effect, it represents the total population of Africa.
Default	AFELA Model (Default)	#60 A	**Price Change** (Dmnl) = (Electricity Price/REFERENCE ELECTRICITY PRICE)*Learning effect **Description:** *It is the percentage change in price multiplied by the learning effect.* **Present in 1 view:** x Demand/Population sector **Used by:** x Effect of price on consumption - It calculates how average consumption will respond to price changes.
Default	AFELA Model (Default)	#61 F,A	**Production completion** (Gwh/year) = (Capacity completion*Gw to Gwh conversion)*(UTILISATION FACTOR+STEP(UTILISATION FACTOR SENSITIVITY, 2019)) **Description:** *This flow calculates the additional energy or increment as a result of new plants completed. This also indicates how many new connections to electricity can be attained.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses. x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	AFELA Model (Default)	#62 F,A	**Production decommissioning** (Gwh/year) = Actual Energy Utilised/AVERAGE PLANT LIFE **Description:** *This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:**

			x Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses. x Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.
Default	AFELA Model (Default)	#63 A	**REFERENCE ELECTRICITY PRICE** (US$/Gwh) = REFERENCE ELECTRICITY PRICE in kWh/kWh to GWh conversion **Description:** *This refers to the average price of electricity at the start time.(Estimated based on Trimbel et al. 2016 electricity cost in African countries)* **Present in 1 view:** x Demand/Population sector **Used by:** x Price Change - It is the percentage change in price multiplied by the learning effect.
Default	AFELA Model (Default)	#64 C	**REFERENCE ELECTRICITY PRICE in kWh** (US$/kWh) = 0.5 **Present in 1 view:** x Demand/Population sector **Used by:** x Electricity Price in kWh x REFERENCE ELECTRICITY PRICE - This refers to the average price of electricity at the start time.(Estimated based on Trimbel et al. 2016 electricity cost in African countries)
Default	Control	#68 C	**TIME STEP** (year [0,?]) = 0.0625 **Description:** *The time step for the simulation.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors. x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.

			x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	AFELA Model (Default)	#69 A	**Total access rate** (Dmnl) = (Population with Electricity Access/Total Population)*100 **Description:** *The access rate represents the population who have access to electricity expressed as a percentage of the total population.* **Present in 1 view:** x Demand/Population sector **Used by:** **This is a supplementary variable.**
Default	AFELA Model (Default)	#70 A	**Total Population** (People) = Population with Electricity Access+Population without Electricity Access **Description:** *The total population sums both the people with and without electricity access. In effect, it represents the total population of Africa.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. x Total access rate - The access rate represents the population who have access to electricity expressed as a percentage of the total population.
TOP	**Capital/Investment sector** (25 variables)		
Module	Group	Type	Variable Name and Description
Default	AFELA Model (Default)	#2 L	**African GDP** (US$) $= \int$ GDP Growth dt + [INITIAL GDP] **Description:** *This is the total GDP of Africa for the model simulation time (2001 - 2040).* **Present in 1 view:** x Capital/Investment sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.

			x GDP Growth - This is the yearly GDP growth (from the beginning to the final simulation time)
Default	AFELA Model (Default)	#3 F,A	**Annual capacity demand deficit** (Gw/year) = MAX(Indicated new capacity requirement, 0) **Description:** *It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated annual investment - This is the investment required annually besides that already accounted for in the investment backlog. x Power Capacity Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	AFELA Model (Default)	#4 F,A	**Annual investment** (US$/year) = MIN((African GDP*(INVESTMENT RATE+STEP(INVESTMENT RATE SENSITIVITY, 2019))), (Indicated Investment Backlog/TIME STEP)) **Description:** *This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Cumulative Investment - This stock accumulates all investment made in power sector from 2001 to the end of the simulation time. x Indicated Investment Backlog - This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation
Default	AFELA Model (Default)	#11 A	**Change in Capacity** (Dmnl) = (Power Capacity Decommissioned+Power Capacity Installed)/INITIAL CAPACITY INSTALLED **Description:** *This calculates the change in capacity over time.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Learning effect - It is the overall learning accumulated through the change in capacity over time, and the rate of learning that occur with each unit addition.

Default	AFELA Model (Default)	#13 A	**Cost per GW unit** (US$/Gw) = (INITIAL COST PER GW UNIT+STEP(GW UNIT COST SENSITIVITY, 2019))*Learning effect **Description:** *This is the actual GW unit cost at any given point in time of the simulation.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Indicated annual investment - This is the investment required annually besides that already accounted for in the investment backlog.
Default	AFELA Model (Default)	#14 L	**Cumulative Investment** (US$) $= \int$ Annual investment $dt + [0]$ **Description:** *This stock accumulates all investment made in power sector from 2001 to the end of the simulation time.* **Present in 1 view:** x Capital/Investment sector **Used by:** **This is a supplementary variable.**
Default	AFELA Model (Default)	#19 F,A	**Electricity access loss rate** (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) **Description:** *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Population with Electricity Access - This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#24 A	**Expected Capacity Addition** (Gw/year) = (Population growth*AVERAGE CONSUMPTION PER ACCESS PERSON)/Gw to Gwh conversion **Description:** *This is the new power capacity required annually as a result of*

			population growth. **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	AFELA Model (Default)	#25 A	**Expected Capacity Loss** (Gw/year) = Capacity decommissioning **Description:** *This is the power capacity that is expected to be lost annually through plants aging.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	AFELA Model (Default)	#27 F,A	**GDP Growth** (US$/year) = African GDP*GDP GROWTH RATE **Description:** *This is the yearly GDP growth (from the beginning to the final simulation time)* **Present in 1 view:** x Capital/Investment sector **Used by:** x African GDP - This is the total GDP of Africa for the model simulation time (2001 - 2040).
Default	AFELA Model (Default)	#28 C	**GDP GROWTH RATE** (Dmnl/year) = 0.046 **Description:** *It is the average annual GDP growth rate in Africa (African Economic Outlook 2016 and IMF Economic Outlook, 2017)* **Present in 1 view:** x Capital/Investment sector **Used by:** x GDP Growth - This is the yearly GDP growth (from the beginning to the final simulation time)
Default	AFELA Model (Default)	#30 C	**GW UNIT COST SENSITIVITY** (US$/Gw) = 0 **Description:** *A sensitivity parameter on GW unit cost changes* **Present in 1 view:**

			x Capital/Investment sector **Used by:** x Cost per GW unit - This is the actual GW unit cost at any given point in time of the simulation.
Default	AFELA Model (Default)	#31 F,A	**Indicated annual investment** (US$/year) = Annual capacity demand deficit*Cost per GW unit **Description:** *This is the investment required annually besides that already accounted for in the investment backlog.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated Investment Backlog - This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation
Default	AFELA Model (Default)	#33 L	**Indicated Investment Backlog** (US$) $= \int$ Indicated annual investment-Annual investment *dt* + [INITIAL INVESTMENT BACKLOG] **Description:** *This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation* **Present in 1 view:** x Capital/Investment sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.
Default	AFELA Model (Default)	#39 C	**INITIAL COST PER GW UNIT** (US$/Gw) = 2e+009 **Description:** *The initial cost per GW unit is the estimated average unit cost for the different energy sources for generating electricity in Africa.* **Present in 1 view:** x Capital/Investment sector **Used by:** x Cost per GW unit - This is the actual GW unit cost at any given point in time of the simulation.
Default	AFELA Model (Default)	#40 LI,C	**INITIAL GDP** (US$) = 1.2085e+012 **Description:** *This is the total GDP of Africa in the base year.* **Present in 1 view:**

			x Capital/Investment sector **Used by:** x African GDP - This is the total GDP of Africa for the model simulation time (2001 - 2040).
Default	AFELA Model (Default)	#41 LI,I	**INITIAL INVESTMENT BACKLOG** (US$) = INITIAL(3.5e+011) **Description:** *It is the investment required for universal access to electricity as at the beginning of the simulation.* **Present in 1 view:** x Capital/Investment sector **Used by:** x Indicated Investment Backlog - This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation
Default	AFELA Model (Default)	#46 C	**INVESTMENT RATE** (Dmnl/year [0,1,0.001]) = 0.01 **Description:** *It is the average annual fraction of GDP that is investment in the power sector.(Rosnes, O. and Shkaratan, M., 2011. Africa's power infrastructure: investment, integration, efficiency. World Bank Publications).* **Present in 1 view:** x Capital/Investment sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.
Default	AFELA Model (Default)	#47 C	**INVESTMENT RATE SENSITIVITY** (Dmnl/year [0,0.05,0.005]) = 0 **Description:** *This is the investment rate sensitivity parameter.* **Present in 1 view:** x Capital/Investment sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.
Default	AFELA Model (Default)	#49 A	**Learning effect** (Dmnl) = Change in Capacity^(LN(1-LEARNING RATE)/LN(2)) **Description:** *It is the overall learning accumulated through the change in capacity over time, and the rate of learning that occur with each unit addition.* **Present in 2 views:**

			x Demand/Population sector x Capital/Investment sector **Used by:** x Cost per GW unit - This is the actual GW unit cost at any given point in time of the simulation. x Electricity Price in kWh x Price Change - It is the percentage change in price multiplied by the learning effect.
Default	AFELA Model (Default)	#50 C	**LEARNING RATE** (Dmnl [0,0.95,0.05]) = 0.05 **Description:** *This rate predicts the slope of cost decline as learning effect is accounted for through economies of scale.* **Present in 1 view:** x Capital/Investment sector **Used by:** x Learning effect - It is the overall learning accumulated through the change in capacity over time, and the rate of learning that occur with each unit addition.
Default	AFELA Model (Default)	#52 F,A	**Population growth** (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) **Description:** *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* **Present in 4 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector x CLD **Used by:** x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#62 F,A	**Production decommissioning** (Gwh/year) = Actual Energy Utilised/AVERAGE PLANT LIFE **Description:** *This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector

			• Supply/Power sector **Used by:** • Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses. • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.
Default	Control	#68 C	**TIME STEP** (year [0,?]) = 0.0625 **Description:** *The time step for the simulation.* **Present in 3 views:** • Demand/Population sector • Capital/Investment sector • Supply/Power sector **Used by:** • Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors. • Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
TOP	**Supply/Power sector** (46 variables)		
Module	Group	Type	Variable Name and Description
Default	AFELA Model (Default)	#1 L	**Actual Energy Utilised** (Gwh) $= \int$ Production completion-Production decommissioning *dt* + [INITIAL PRODUCTION] **Description:** *This is the total amount of energy consumed each year. It does not include transmission losses.* **Present in 2 views:** • Demand/Population sector • Supply/Power sector **Used by:** • Production decommissioning - This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.
Default	AFELA Model (Default)	#3 F,A	**Annual capacity demand deficit** (Gw/year) = MAX(Indicated new capacity requirement, 0)

			Description: *It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated annual investment - This is the investment required annually besides that already accounted for in the investment backlog. x Power Capacity Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	AFELA Model (Default)	#4 F,A	**Annual investment** (US$/year) = MIN((African GDP*(INVESTMENT RATE+STEP(INVESTMENT RATE SENSITIVITY, 2019))), (Indicated Investment Backlog/TIME STEP)) **Description:** *This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Cumulative Investment - This stock accumulates all investment made in power sector from 2001 to the end of the simulation time. x Indicated Investment Backlog - This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation
Default	AFELA Model (Default)	#5 C	**AVERAGE CONSUMPTION PER ACCESS PERSON** (Gwh/People [0,0.0025]) = 0.00131 **Description:** *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population.

			x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	AFELA Model (Default)	#7 C	**AVERAGE PLANT LIFE** (year [10,80]) = 60 **Description:** *This is the average amount of time a power plant would be in operation before being scrapped/decommissioned.* **Present in 1 view:** x Supply/Power sector **Used by:** x Capacity decommissioning - It is the annual capacity that is scrapped or decommissioned because of depreciation. x Production decommissioning - This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.
Default	AFELA Model (Default)	#8 F,A	**Capacity commencement** (Gw/year) = MIN((Annual investment/Cost per GW unit) , (Power Capacity Backlog/TIME STEP)) **Description:** *It is the annual amount of new capacity initiated for construction as a result of investment made.* **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Backlog - It is the outstanding capacity needed at any given point in time of the simulation. x Power Capacity Construction - This is the total amount of power capacity that is under construction.
Default	AFELA Model (Default)	#9 F,A	**Capacity completion** (Gw/year) = Power Capacity Construction/CONSTRUCTION TIME **Description:** *This is the annual amount of power capacity that is completed and commissioned for use.* **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Construction - This is the total amount of power capacity that is under construction. x Power Capacity Installed - This is the total amount of power installed and generating energy. x Production completion - This flow calculates the additional energy or increment as a result of new plants completed. This also indicates how many new connections to electricity can be attained.
Default	AFELA Model (Default)	#10 F,A	**Capacity decommissioning** (Gw/year) = Power Capacity Installed/AVERAGE PLANT LIFE **Description:** *It is the annual capacity that is scrapped or decommissioned because of depreciation.* **Present in 1 view:**

			x Supply/Power sector **Used by:** x Expected Capacity Loss - This is the power capacity that is expected to be lost annually through plants aging. x Power Capacity Decommissioned - This is the cumulative power capacity decommissioned throughout the simulation time. x Power Capacity Installed - This is the total amount of power installed and generating energy.
Default	AFELA Model (Default)	#11 A	**Change in Capacity** (Dmnl) = (Power Capacity Decommissioned+Power Capacity Installed)/INITIAL CAPACITY INSTALLED **Description:** *This calculates the change in capacity over time.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Learning effect - It is the overall learning accumulated through the change in capacity over time, and the rate of learning that occur with each unit addition.
Default	AFELA Model (Default)	#12 C	**CONSTRUCTION TIME** (year) = 3 **Description:** *The time it takes to complete the construction of a power plant unit.* **Present in 1 view:** x Supply/Power sector **Used by:** x Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use.
Default	AFELA Model (Default)	#13 A	**Cost per GW unit** (US$/Gw) = (INITIAL COST PER GW UNIT+STEP(GW UNIT COST SENSITIVITY, 2019))*Learning effect **Description:** *This is the actual GW unit cost at any given point in time of the simulation.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Indicated annual investment - This is the investment required annually besides that already accounted for in the investment backlog.

Default	AFELA Model (Default)	#15 A	**Desired Acquisition rate** (Gw) = Indicated Acquisition rate*EXPECTED ACQUISITION DELAY **Description:** *The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.* **Present in 1 view:** x Supply/Power sector **Used by:** x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Indicated new capacity requirement - It is the capacity required annually after accounting for the delays in the supply line.
Default	AFELA Model (Default)	#16 A	**Desired power Capacity** (Gw) = (((AVERAGE CONSUMPTION PER ACCESS PERSON*Total Population)/UTILISATION FACTOR)/Gw to Gwh conversion)+Desired Acquisition rate **Description:** *This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population.* **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Gap - It is the difference between desired and actual power capacity.
Default	AFELA Model (Default)	#17 A	**Effect of price on consumption** (Dmnl) = Effect of price on consumption TABLE(Price Change) **Description:** *It calculates how average consumption will respond to price changes.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand.
Default	AFELA Model (Default)	#19 F,A	**Electricity access loss rate** (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) **Description:** *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* **Present in 3 views:**

			x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Population with Electricity Access - This represents the total number of people who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#23 C	**EXPECTED ACQUISITION DELAY** (year) = 2 **Description:** *The estimated time delay between realising the need for a power unit and actually investment in securing it.* **Present in 1 view:** x Supply/Power sector **Used by:** x Desired Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.
Default	AFELA Model (Default)	#24 A	**Expected Capacity Addition** (Gw/year) = (Population growth*AVERAGE CONSUMPTION PER ACCESS PERSON)/Gw to Gwh conversion **Description:** *This is the new power capacity required annually as a result of population growth.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	AFELA Model (Default)	#25 A	**Expected Capacity Loss** (Gw/year) = Capacity decommissioning **Description:** *This is the power capacity that is expected to be lost annually through plants aging.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:**

			x Indicated Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	AFELA Model (Default)	#29 C	**Gw to Gwh conversion** (Gwh/Gw) = 8760 **Present in 1 view:** x Supply/Power sector **Used by:** x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. x Production completion - This flow calculates the additional energy or increment as a result of new plants completed. This also indicates how many new connections to electricity can be attained.
Default	AFELA Model (Default)	#31 F,A	**Indicated annual investment** (US$/year) = Annual capacity demand deficit*Cost per GW unit **Description:** *This is the investment required annually besides that already accounted for in the investment backlog.* **Present in 2 views:** x Capital/Investment sector x Supply/Power sector **Used by:** x Indicated Investment Backlog - This represents the investment required to clear the capacity backlog or attain universal access at any point in time of the simulation
Default	AFELA Model (Default)	#32 A	**Indicated Acquisition rate** (Gw/year) = Expected Capacity Loss+Expected Capacity Addition **Description:** *The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.* **Present in 1 view:** x Supply/Power sector **Used by:** x Desired Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.
Default	AFELA Model (Default)	#34 A	**Indicated new capacity requirement** (Gw/year) = MAX(Supply Line Adjustment, Desired Acquisition rate)/SUPPLY LINE ADJUSTMENT TIME **Description:** *It is the capacity required annually after accounting for the delays in*

			the supply line. **Present in 1 view:** x Supply/Power sector **Used by:** x Annual capacity demand deficit - It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line.
Default	AFELA Model (Default)	#35 LI,C	**INITIAL CAPACITY BACKLOG** (Gw) = 155 **Description:** *It is the capacity required for full access at the beginning of the simulation.* **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	AFELA Model (Default)	#36 LI,C	**INITIAL CAPACITY CONSTRUCTION** (Gw) = 10 **Description:** *It is the total power capacity under construction at the start of simulation.* **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Construction - This is the total amount of power capacity that is under construction.
Default	AFELA Model (Default)	#37 LI,C	**INITIAL CAPACITY DECOMMISSIONED** (Gw) = 0 **Present in 1 view:** x Supply/Power sector **Used by:** x Power Capacity Decommissioned - This is the cumulative power capacity decommissioned throughout the simulation time.
Default	AFELA Model (Default)	#38 LI,I	**INITIAL CAPACITY INSTALLED** (Gw) = INITIAL(101) **Description:** *It is the total power capacity installed as at the start of the simulation (2001).* **Present in 1 view:** x Supply/Power sector **Used by:**

			x Change in Capacity - This calculates the change in capacity over time. x Power Capacity Installed - This is the total amount of power installed and generating energy.
Default	AFELA Model (Default)	#44 LI,I	**INITIAL PRODUCTION** (Gwh) = INITIAL(407370) **Description:** *It is the total amount of energy utilised in the base year (2001).* **Present in 1 view:** x Supply/Power sector **Used by:** x Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses.
Default	AFELA Model (Default)	#52 F,A	**Population growth** (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) **Description:** *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* **Present in 4 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector x CLD **Used by:** x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	AFELA Model (Default)	#55 L	**Power Capacity Backlog** (Gw) = $\int$ Annual capacity demand deficit-Capacity commencement *dt* + [INITIAL CAPACITY BACKLOG] **Description:** *It is the outstanding capacity needed at any given point in time of the simulation.* **Present in 1 view:** x Supply/Power sector **Used by:** x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Supply Line Adjustment - This is an adjustment to prevent 'over-investment' in the power sector by comparing the capacity installed and in the pipeline to the desired capacity.

Default	AFELA Model (Default)	#56 L	**Power Capacity Construction** (Gw) $= \int$ Capacity commencement-Capacity completion *dt* + [INITIAL CAPACITY CONSTRUCTION] **Description:** *This is the total amount of power capacity that is under construction.* **Present in 1 view:** x Supply/Power sector **Used by:** x Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. x Supply Line Adjustment - This is an adjustment to prevent 'over-investment' in the power sector by comparing the capacity installed and in the pipeline to the desired capacity.
Default	AFELA Model (Default)	#57 L	**Power Capacity Decommissioned** (Gw) $= \int$ Capacity decommissioning *dt* + [INITIAL CAPACITY DECOMMISSIONED] **Description:** *This is the cumulative power capacity decommissioned throughout the simulation time.* **Present in 1 view:** x Supply/Power sector **Used by:** x Change in Capacity - This calculates the change in capacity over time.
Default	AFELA Model (Default)	#58 A	**Power Capacity Gap** (Gw) = MAX((Desired power Capacity-Power Capacity Installed), 0) **Description:** *It is the difference between desired and actual power capacity.* **Present in 1 view:** x Supply/Power sector **Used by:** x Supply Line Adjustment - This is an adjustment to prevent 'over-investment' in the power sector by comparing the capacity installed and in the pipeline to the desired capacity.
Default	AFELA Model (Default)	#59 L	**Power Capacity Installed** (Gw) $= \int$ Capacity completion-Capacity decommissioning *dt* + [INITIAL CAPACITY INSTALLED] **Description:** *This is the total amount of power installed and generating energy.* **Present in 1 view:** x Supply/Power sector **Used by:** x Capacity decommissioning - It is the annual capacity that is scrapped or decommissioned because of depreciation.

			x Change in Capacity - This calculates the change in capacity over time. x Power Capacity Gap - It is the difference between desired and actual power capacity.
Default	AFELA Model (Default)	#61 F,A	**Production completion** (Gwh/year) = (Capacity completion*Gw to Gwh conversion)*(UTILISATION FACTOR+STEP(UTILISATION FACTOR SENSITIVITY, 2019)) **Description:** *This flow calculates the additional energy or increment as a result of new plants completed. This also indicates how many new connections to electricity can be attained.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses. x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	AFELA Model (Default)	#62 F,A	**Production decommissioning** (Gwh/year) = Actual Energy Utilised/AVERAGE PLANT LIFE **Description:** *This computes the decline in energy year-on-year as a result of aging and decommissioning of plants. It also indicates how many connections would be lost as a result.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Actual Energy Utilised - This is the total amount of energy consumed each year. It does not include transmission losses. x Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.
Default	AFELA Model (Default)	#66 A	**Supply Line Adjustment** (Gw) = Power Capacity Gap-(Power Capacity Backlog+Power Capacity Construction) **Description:** *This is an adjustment to prevent 'over-investment' in the power sector by comparing the capacity installed and in the pipeline to the desired capacity.* **Present in 1 view:** x Supply/Power sector **Used by:** x Indicated new capacity requirement - It is the capacity required annually after accounting for the delays in the supply line.

Default	AFELA Model (Default)	#67 C	**SUPPLY LINE ADJUSTMENT TIME** (year) = 1 **Description:** *This is how long it takes before the supply line is adjusted.* **Present in 1 view:** x Supply/Power sector **Used by:** x Indicated new capacity requirement - It is the capacity required annually after accounting for the delays in the supply line.
Default	Control	#68 C	**TIME STEP** (year [0,?]) = 0.0625 **Description:** *The time step for the simulation.* **Present in 3 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector **Used by:** x Annual investment - This is the yearly amount of investment committed to power supply. It is a fraction of GDP, and is composed of three key funding sources: domestic/national governments, multi- and bilateral aids, and private sector investors. x Capacity commencement - It is the annual amount of new capacity initiated for construction as a result of investment made. x Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. x Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	AFELA Model (Default)	#70 A	**Total Population** (People) = Population with Electricity Access+Population without Electricity Access **Description:** *The total population sums both the people with and without electricity access. In effect, it represents the total population of Africa.* **Present in 2 views:** x Demand/Population sector x Supply/Power sector **Used by:** x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. x Total access rate - The access rate represents the population who have access to electricity expressed as a percentage of the total population.

Default	AFELA Model (Default)	#71 C	**UTILISATION FACTOR** (Dmnl [0.2,1,0.01]) = 0.48 **Description:** *This is the fraction of energy utilised compared to the total potential energy that could be supplied.(Energy Statistics Yearbook https://unstats.un.org/unsd/energy/yearbook/default.htm)* **Present in 1 view:** x Supply/Power sector **Used by:** x Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. x Production completion - This flow calculates the additional energy or increment as a result of new plants completed. This also indicates how many new connections to electricity can be attained.
Default	AFELA Model (Default)	#72 C	**UTILISATION FACTOR SENSITIVITY** (Dmnl [0,0.5]) = 0 **Description:** *This is a sensitivity parameter for the utilisation factor.* **Present in 1 view:** x Supply/Power sector **Used by:** x Production completion - This flow calculates the additional energy or increment as a result of new plants completed.This also indicates how many new connections to electricity can be attained.
TOP	**Results - A** (0 variables)		
Module	Group	Type	Variable Name and Description
TOP	**Results B** (0 variables)		
Module	Group	Type	Variable Name and Description
TOP	**CLD** (1 variables)		
Module	Group	Type	Variable Name and Description
Default	AFELA Model (Default)	#52 F,A	**Population growth** (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) **Description:** *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* **Present in 4 views:** x Demand/Population sector x Capital/Investment sector x Supply/Power sector x CLD **Used by:** x Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. x Population without Electricity Access - This represents the total number of people without electricity access at any given point in time. It increases

			with population growth and connection loss, and decreases with electricity connection.

List of 5 Undocumented Variables

Module	Group	Type	Variable (5)
Default	AFELA Model	A	Electricity Price in kWh (US$/kWh)
Default	AFELA Model	C	Gw to Gwh conversion (Gwh/Gw)
Default	AFELA Model	LI,C	INITIAL CAPACITY DECOMMISSIONED (Gw)
Default	AFELA Model	C	kWh to GWh conversion (Gwh/kWh)
Default	AFELA Model	C	REFERENCE ELECTRICITY PRICE in kWh (US$/kWh)

List of 2 Supplementary Variables

Module	Group	Type	Variable (2)
Default	AFELA Model	L	Cumulative Investment (US$)
Default	AFELA Model	A	Total access rate (Dmnl)

List of 8 Variables Using MIN or MAX Functions

Module	Group	Type	Variable (8)
Default	AFELA Model	F,A	Annual capacity demand deficit (Gw/year)
Default	AFELA Model	F,A	Annual investment (US$/year)
Default	AFELA Model	F,A	Capacity commencement (Gw/year)
Default	AFELA Model	F,A	Electricity access loss rate (People/year)
Default	AFELA Model	F,A	Electricity access rate (People/year)
Default	AFELA Model	A	Indicated new capacity requirement (Gw/year)
Default	AFELA Model	F,A	Population growth (People/year)
Default	AFELA Model	A	Power Capacity Gap (Gw)

List of 63 Variables Without Predefined Min or Max Values

Module	Group	Type	Variable (63)
Default	AFELA Model	L	Actual Energy Utilised (Gwh)
Default	AFELA Model	L	African GDP (US$)
Default	AFELA Model	F,A	Annual capacity demand deficit (Gw/year)
Default	AFELA Model	F,A	Annual investment (US$/year)
Default	AFELA Model	A	Average Consumption per person (Gwh/People)
Default	AFELA Model	F,A	Capacity commencement (Gw/year)
Default	AFELA Model	F,A	Capacity completion (Gw/year)
Default	AFELA Model	F,A	Capacity decommissioning (Gw/year)
Default	AFELA Model	A	Change in Capacity (Dmnl)
Default	AFELA Model	C	CONSTRUCTION TIME (year)
Default	AFELA Model	A	Cost per GW unit (US$/Gw)
Default	AFELA Model	L	Cumulative Investment (US$)
Default	AFELA Model	A	Desired Acquisition rate (Gw)
Default	AFELA Model	A	Desired power Capacity (Gw)
Default	AFELA Model	A	Effect of price on consumption (Dmnl)
Default	AFELA Model	L	Effect of price on consumption TABLE (Dmnl)
Default	AFELA Model	F,A	Electricity access loss rate (People/year)

Default	AFELA Model	F,A	Electricity access rate (People/year)
Default	AFELA Model	A	Electricity Price (US$/Gwh)
Default	AFELA Model	A	Electricity Price in kWh (US$/kWh)
Default	AFELA Model	C	EXPECTED ACQUISITION DELAY (year)
Default	AFELA Model	A	Expected Capacity Addition (Gw/year)
Default	AFELA Model	A	Expected Capacity Loss (Gw/year)
Default	Control	C	FINAL TIME (year)
Default	AFELA Model	F,A	GDP Growth (US$/year)
Default	AFELA Model	C	GDP GROWTH RATE (Dmnl/year)
Default	AFELA Model	C	Gw to Gwh conversion (Gwh/Gw)
Default	AFELA Model	C	GW UNIT COST SENSITIVITY (US$/Gw)
Default	AFELA Model	F,A	Indicated annual investment (US$/year)
Default	AFELA Model	A	Indicated Acquisition rate (Gw/year)
Default	AFELA Model	L	Indicated Investment Backlog (US$)
Default	AFELA Model	A	Indicated new capacity requirement (Gw/year)
Default	AFELA Model	LI,C	INITIAL CAPACITY BACKLOG (Gw)
Default	AFELA Model	LI,C	INITIAL CAPACITY CONSTRUCTION (Gw)
Default	AFELA Model	LI,C	INITIAL CAPACITY DECOMMISSIONED (Gw)
Default	AFELA Model	LI,I	INITIAL CAPACITY INSTALLED (Gw)
Default	AFELA Model	C	INITIAL COST PER GW UNIT (US$/Gw)
Default	AFELA Model	LI,C	INITIAL GDP (US$)
Default	AFELA Model	LI,I	INITIAL INVESTMENT BACKLOG (US$)
Default	AFELA Model	LI,I	INITIAL POPULATION WITH ELECTRICITY ACCESS (People)
Default	AFELA Model	LI,I	INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (People)
Default	AFELA Model	LI,I	INITIAL PRODUCTION (Gwh)
Default	Control	C	INITIAL TIME (year)
Default	AFELA Model	C	kWh to GWh conversion (Gwh/kWh)
Default	AFELA Model	A	Learning effect (Dmnl)
Default	AFELA Model	C	NET POPULATION GROWTH RATE (Dmnl/year)
Default	AFELA Model	F,A	Population growth (People/year)
Default	AFELA Model	L	Population with Electricity Access (People)
Default	AFELA Model	L	Population without Electricity Access (People)
Default	AFELA Model	L	Power Capacity Backlog (Gw)
Default	AFELA Model	L	Power Capacity Construction (Gw)
Default	AFELA Model	L	Power Capacity Decommissioned (Gw)
Default	AFELA Model	A	Power Capacity Gap (Gw)
Default	AFELA Model	L	Power Capacity Installed (Gw)
Default	AFELA Model	A	Price Change (Dmnl)
Default	AFELA Model	F,A	Production completion (Gwh/year)
Default	AFELA Model	F,A	Production decommissioning (Gwh/year)
Default	AFELA Model	A	REFERENCE ELECTRICITY PRICE (US$/Gwh)
Default	AFELA Model	C	REFERENCE ELECTRICITY PRICE in kWh (US$/kWh)
Default	AFELA Model	A	Supply Line Adjustment (Gw)
Default	AFELA Model	C	SUPPLY LINE ADJUSTMENT TIME (year)
Default	AFELA Model	A	Total access rate (Dmnl)
Default	AFELA Model	A	Total Population (People)

List of 3 Variables with "Step", "Pulse", or related functions.

Module	Group	Type	Variable (3)
Default	AFELA Model	F,A	Annual investment (US$/year)
Default	AFELA Model	A	Cost per GW unit (US$/Gw)
Default	AFELA Model	F,A	Production completion (Gwh/year)

Formulation Complexity Summary (Violations of Richardson's Rule)

Module	Group	Type	Variable	Complexity Score
Default	AFELA Model	F,A	Production completion (Gwh/year)	4
Default	AFELA Model	F,A	Capacity commencement (Gw/year)	4
Default	AFELA Model	F,A	Electricity access rate (People/year)	4
Default	AFELA Model	F,A	Electricity access loss rate (People/year)	4
Default	AFELA Model	L	Population without Electricity Access (People)	4
Default	AFELA Model	F,A	Annual investment (US$/year)	5
Default	AFELA Model	A	Desired power Capacity (Gw)	5

List of 10 Equations with Embedded Data (0 and 1 constants ignored)

Module	Group	Type	Variable (10)
Default	AFELA Model	F,A	Annual investment (US$/year)
Default	AFELA Model	A	Cost per GW unit (US$/Gw)
Default	AFELA Model	LI,I	INITIAL CAPACITY INSTALLED (Gw)
Default	AFELA Model	LI,I	INITIAL INVESTMENT BACKLOG (US$)
Default	AFELA Model	LI,I	INITIAL POPULATION WITH ELECTRICITY ACCESS (People)
Default	AFELA Model	LI,I	INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (People)
Default	AFELA Model	LI,I	INITIAL PRODUCTION (Gwh)
Default	AFELA Model	A	Learning effect (Dmnl)
Default	AFELA Model	F,A	Production completion (Gwh/year)
Default	AFELA Model	A	Total access rate (Dmnl)

List of 1 Lookup Variable with Non-Zero End Sloped Lookup Functions

Module	Group	Type	Variable (1)
Default	AFELA Model	L	Effect of price on consumption TABLE (Dmnl)

List of 10 State Variables

Module	Group	Type	Variable
Default	AFELA Model	L	Actual Energy Utilised (Gwh)
Default	AFELA Model	L	African GDP (US$)
Default	AFELA Model	L	Cumulative Investment (US$)
Default	AFELA Model	L	Indicated Investment Backlog (US$)
Default	AFELA Model	L	Population with Electricity Access (People)
Default	AFELA Model	L	Population without Electricity Access (People)
Default	AFELA Model	L	Power Capacity Backlog (Gw)
Default	AFELA Model	L	Power Capacity Construction (Gw)
Default	AFELA Model	L	Power Capacity Decommissioned (Gw)
Default	AFELA Model	L	Power Capacity Installed (Gw)

List of 4 Views and Their 72 Variables

Demand/Population sector	26 vars (36.1%)
Capital/Investment sector	25 vars (34.7%)
Supply/Power sector	46 vars (63.9%)
CLD	1 vars (1.4%)

	Demand/Population sector	Capital/Investment sector	Supply/Power sector	CLD
Total:	**26**	**25**	**46**	**1**

Actual Energy Utilised (in 2 views)	■		■	
African GDP (in 1 view)		■		
Annual capacity demand deficit (in 2 views)		■	■	
Annual investment (in 2 views)		■	■	
AVERAGE CONSUMPTION PER ACCESS PERSON (in 2 views)	■		■	
Average Consumption per person (in 1 view)	■			
AVERAGE PLANT LIFE (in 1 view)			■	
Capacity commencement (in 1 view)			■	
Capacity completion (in 1 view)			■	
Capacity decommissioning (in 1 view)			■	
Change in Capacity (in 2 views)		■	■	
CONSTRUCTION TIME (in 1 view)			■	
Cost per GW unit (in 2 views)		■	■	
Cumulative Investment (in 1 view)		■		
Desired Acquisition rate (in 1 view)			■	
Desired power Capacity (in 1 view)			■	
Effect of price on consumption (in 2 views)	■		■	
Effect of price on consumption TABLE (in 1 view)	■			
Electricity access loss rate (in 3 views)	■	■	■	
Electricity access rate (in 1 view)	■			
Electricity Price (in 1 view)	■			
Electricity Price in kWh (in 1 view)	■			
EXPECTED ACQUISITION DELAY (in 1 view)			■	
Expected Capacity Addition (in 2 views)		■	■	
Expected Capacity Loss (in 2 views)		■	■	
FINAL TIME (in 0 views)				
GDP Growth (in 1 view)		■		
GDP GROWTH RATE (in 1 view)		■		
Gw to Gwh conversion (in 1 view)			■	
GW UNIT COST SENSITIVITY (in 1 view)		■		
Indicated annual investment (in 2 views)		■	■	
Indicated Acquisition rate (in 1 view)			■	
Indicated Investment Backlog (in 1 view)		■		
Indicated new capacity requirement (in 1 view)			■	
INITIAL CAPACITY BACKLOG (in 1 view)			■	
INITIAL CAPACITY CONSTRUCTION (in 1 view)			■	
INITIAL CAPACITY DECOMMISSIONED (in 1 view)			■	
INITIAL CAPACITY INSTALLED (in 1 view)			■	
INITIAL COST PER GW UNIT (in 1 view)		■		
INITIAL GDP (in 1 view)		■		
INITIAL INVESTMENT BACKLOG (in 1 view)		■		
INITIAL POPULATION WITH ELECTRICITY ACCESS (in 1 view)	■			
INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (in 1 view)	■			
INITIAL PRODUCTION (in 1 view)			■	
INITIAL TIME (in 0 views)				
INVESTMENT RATE (in 1 view)		■		
INVESTMENT RATE SENSITIVITY (in 1 view)		■		
kWh to GWh conversion (in 1 view)	■			
Learning effect (in 2 views)	■	■		
LEARNING RATE (in 1 view)		■		
NET POPULATION GROWTH RATE (in 1 view)	■			
Population growth (in 4 views)	■	■	■	■
Population with Electricity Access (in 1 view)	■			
Population without Electricity Access (in 1 view)	■			
Power Capacity Backlog (in 1 view)			■	

Power Capacity Construction (in 1 view)			■	
Power Capacity Decommissioned (in 1 view)			■	
Power Capacity Gap (in 1 view)			■	
Power Capacity Installed (in 1 view)			■	
Price Change (in 1 view)	■			
Production completion (in 2 views)	■		■	
Production decommissioning (in 3 views)	■	■	■	
REFERENCE ELECTRICITY PRICE (in 1 view)	■			
REFERENCE ELECTRICITY PRICE in kWh (in 1 view)	■			
SAVEPER (in 0 views)				
Supply Line Adjustment (in 1 view)			■	
SUPPLY LINE ADJUSTMENT TIME (in 1 view)			■	
TIME STEP (in 3 views)	■	■	■	
Total access rate (in 1 view)	■			
Total Population (in 2 views)	■		■	
UTILISATION FACTOR (in 1 view)			■	
UTILISATION FACTOR SENSITIVITY (in 1 view)			■	
Total:	**26**	**25**	**46**	**1**
	Demand/Population sector	Capital/Investment sector	Supply/Power sector	CLD

* Includes *Time*, if used in a view. Excludes variables not present in any view.

Level Structure †

Actual Energy Utilised = ∫Production completion-Production decommissioning *dt* + [INITIAL PRODUCTION]
INITIAL PRODUCTION = INITIAL(407370)
  Production completion = (Capacity completion*Gw to Gwh conversion)*(UTILISATION FACTOR+STEP(UTILISATION FACTOR SENSITIVITY, 2019))
  Production decommissioning = Actual Energy Utilised/AVERAGE PLANT LIFE

African GDP = ∫GDP Growth *dt* + [INITIAL GDP]
INITIAL GDP = 1.2085e+012
  GDP Growth = African GDP*GDP GROWTH RATE

Cumulative Investment = ∫Annual investment *dt* + [0]
  Annual investment = MIN((African GDP*(INVESTMENT RATE+STEP(INVESTMENT RATE SENSITIVITY, 2019))), (Indicated Investment Backlog/TIME STEP))

Indicated Investment Backlog = ∫Indicated annual investment-Annual investment *dt* + [INITIAL INVESTMENT BACKLOG]
INITIAL INVESTMENT BACKLOG = INITIAL(3.5e+011)
  Indicated annual investment = Annual capacity demand deficit*Cost per GW unit

Population with Electricity Access = ∫Electricity access rate-Electricity access loss rate *dt* + [INITIAL POPULATION WITH ELECTRICITY ACCESS]
INITIAL POPULATION WITH ELECTRICITY ACCESS = INITIAL(3.1e+008)
  Electricity access loss rate = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP))
  Electricity access rate = MAX(MIN((Production completion/ Average Consumption per person), (Population without Electricity Access/TIME STEP)), 0)

Population without Electricity Access = ∫Electricity access loss rate+Population growth-Electricity access rate *dt* + [INITIAL POPULATION WITHOUT ELECTRICITY ACCESS]
INITIAL POPULATION WITHOUT ELECTRICITY ACCESS = INITIAL(5.2332e+008)
Population growth = MAX((Total Population*NET POPULATION GROWTH RATE), 0)

Power Capacity Backlog = ∫Annual capacity demand deficit-Capacity commencement *dt* + [INITIAL CAPACITY BACKLOG]
INITIAL CAPACITY BACKLOG = 155
Annual capacity demand deficit = MAX(Indicated new capacity requirement, 0)
Capacity commencement = MIN((Annual investment/Cost per GW unit) , (Power Capacity Backlog/TIME STEP))

Power Capacity Construction = ∫Capacity commencement-Capacity completion *dt* + [INITIAL CAPACITY CONSTRUCTION]
INITIAL CAPACITY CONSTRUCTION = 10
Capacity completion = Power Capacity Construction/CONSTRUCTION TIME

Power Capacity Decommissioned = ∫Capacity decommissioning *dt* + [INITIAL CAPACITY DECOMMISSIONED]
INITIAL CAPACITY DECOMMISSIONED = 0
Capacity decommissioning = Power Capacity Installed/AVERAGE PLANT LIFE

Power Capacity Installed = ∫Capacity completion-Capacity decommissioning *dt* + [INITIAL CAPACITY INSTALLED]
INITIAL CAPACITY INSTALLED = INITIAL(101)

† ***Level Structure Report* still under development.**

List of 13 Equations with Dimensionless Units

Module	Group	Type	Variable
Default	AFELA Model	A	Change in Capacity (Dmnl)
Default	AFELA Model	A	Effect of price on consumption (Dmnl)
Default	AFELA Model	L	Effect of price on consumption TABLE (Dmnl)
Default	AFELA Model	C	GDP GROWTH RATE (Dmnl/year)
Default	AFELA Model	C	INVESTMENT RATE (Dmnl/year [0,1,0.001])
Default	AFELA Model	C	INVESTMENT RATE SENSITIVITY (Dmnl/year [0,0.05,0.005])
Default	AFELA Model	A	Learning effect (Dmnl)
Default	AFELA Model	C	LEARNING RATE (Dmnl [0,0.95,0.05])
Default	AFELA Model	C	NET POPULATION GROWTH RATE (Dmnl/year)
Default	AFELA Model	A	Price Change (Dmnl)
Default	AFELA Model	A	Total access rate (Dmnl)
Default	AFELA Model	C	UTILISATION FACTOR (Dmnl [0.2,1,0.01])
Default	AFELA Model	C	UTILISATION FACTOR SENSITIVITY (Dmnl [0,0.5])

Source file: AFELA Model.mdl (2Mar2018 - 8:37:41 PM)
Report Created on 2/Mar/2018 - 8:58:23 PM
SDM-Doc Tool Version 5.0
Decision and Information Sciences Division
Argonne National Laboratory

Documentation of GELA Model

View the 158 variables sorted by type, module, group, variable name, module/group/name, Level Structure, or in a view summary.

Model Assessment Results

Model Information	Number
Total Number of Variables	158
Total Number of State Variables (Level+Smooth+Delay Variables)	21 (13.3%)
Total Number of Stocks (Stocks in Level+Smooth+Delay Variables) †	21 (13.3%)
Total Number of Macros	0
Variables with Source Information	0
Variables with Dimensionless Units	37 (23.4%)
Variables without Predefined Min or Max Values	145 (91.8%)
Function Sensitivity Parameters	0
Data Lookup Tables	0
Time Unit	year
Initial Time	2006
Final Time	2030
Reported Time Interval	1
Time Step	0.0625
Model Is Fully Formulated	Yes
Modeler-Defined Groups	- No -
VPM File Available	- No -

Warnings	Number
Undocumented Equations	0
Equations with Embedded Data (0 and 1 constants ignored)	19 (12%)
Equations With Unit Errors or Warnings	Unavailable
Variables Not in Any View	0
Incompletely Defined Subscripted Variables	0
Nonmonotonic Lookup Functions	0
Cascading (Chained) Lookup Functions	0
Non-Zero End Sloped Lookup Functions	0
Equations with "IF THEN ELSE" Functions	0
Equations with "MIN" or "MAX" Functions	11 (7%)
Equations with "STEP", "PULSE", or Related Functions	7 (4.4%)

Potential Omissions	Number
Unused Variables	0
Supplementary Variables	13
Supplementary Variables Being Used	0
Complex Variable Formulations (Richardson's Rule = 3)	10
Complex Stock Formulations	0

Types:

L : Level (21 / 21) *	SM : Smooth (0 / 0) *	DE : Delay (0 / 0) * †	LI : Level Initial (20)	I : Initial (10)
C : Constant (51)	F : Flow (27)	A : Auxiliary (76)	[sub] Sub: Subscripts (0)	D : Data (0)
G : Game (0)	T : Lookup (0 / 0) ††			

* (state variables / total stocks)

† Total stocks do not include fixed delay variables. †† (lookup variables / lookup tables).

Groups:

Control (4) Simulation Control Parameters	GELA Model (154) (Default)	

Modules: Default (158)

Views:

INTERFACE (0)	POWER SYSTEM LAYOUT (0)	Hydro Power sub-sector (42)	Thermal Power sub-sector (34)	Solar Power sub-sector (35)
Supply/Power sector (73)	Demand/Population sector (29)	Capital/Investment sector (32)	General CLD (1)	Results - A (0)
Results B (0)				

TOP	INTERFACE (0 variables)
Module	Group Type Variable Name and Description
TOP	POWER SYSTEM LAYOUT (0 variables)
Module	Group Type Variable Name and Description
TOP	

	Hydro Power sub-sector (42 variables)		
Module	**Group**	**Type**	**Variable Name and Description**
Default	GELA Model (Default)	#1 A VAB	**Actual investment in Hydro (US$/year)** = MIN(Anual investment in Hydro, Maximum possible investment in Hydro) Description: *The annual amount in US$ that is actually invested in Hydro power.* Present in 2 views: • Hydro Power sub-sector • Capital/Investment sector Used by: • Fractional investment in Hydro - The fraction of the total annual investment directed towards Hydro power • Hydro Capacity commencement - The amount of new Hydro power units commenced annually
Default	GELA Model (Default)	#2 C VAB	**Adjustment time (year)** = 1 Description: *The time it takes to adjust capacity* Present in 4 views: • Hydro Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Capacity decommissioning - It is the annual capacity that is scrapped or decommissioned because of depreciation. • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#6 A VAB	**Anual investment in Hydro (US$/year)** = Annual investment*Maximum Hydro investment fraction Description: *This is the annual amount in US$ that is available for investment towards Hydro power.* Present in 2 views: • Hydro Power sub-sector • Capital/Investment sector Used by: • Actual investment in Hydro - The annual amount in US$ that is actually invested in Hydro power.
Default	GELA Model (Default)	#7 A VAB	**Available Hydro potential (MW)** = Hydro potential total-Hydro potential developed Description: *The is the total amount of Hydro power that has not yet been developed.* Present in 1 view: • Hydro Power sub-sector Used by: • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana.
Default	GELA Model (Default)	#8 C VAB	**AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People)** = 0.52 Description: *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	GELA Model (Default)	#17 A VAB	**Cost per MW Hydro (US$/MW)** = (Initial Cost Per MW Hydro*Learning effect on Hydro)+(Initial Cost Per MW Hydro*Effect of plant size on Hydro cost) Description: *The average cost of installing a MW unit of Hydro power.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Capacity commencement - The amount of new Hydro power units commenced annually • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana.
Default			**Effect of plant size on Hydro cost (Dmnl)** = 0.1

	GELA Model (Default)	#23 C	Description: *This is an estimation of the plant size on the MW unit cost of Hydro.The smaller a Hydro plant, the higher its unit cost. Because Ghana's remaining Hydro sites are smaller than those already developed, a 10% cost increment is proposed.* **Present in 1 view:** • Hydro Power sub-sector **Used by:** • Cost per MW Hydro - The average cost of installing a MW unit of Hydro power.
Default	GELA Model (Default)	#24 F,A	**Electricity access loss rate (People/year)** = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) Description: *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* **Present in 6 views:** • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector **Used by:** • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#39 C	**Hydro AVERAGE PLANT LIFE (year [10,80])** = 80 Description: *This is the average amount of time a Hydro power plant would be in operation before being scrapped/decommissiond.* **Present in 1 view:** • Hydro Power sub-sector **Used by:** • Hydro Capacity decommissioning - It is the annual Hydro capacity that is scrapped or decommissioned because of depreciation. • Hydro Production decommissioning - This computes the decline in Hydro energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#40 F,A	**Hydro Capacity commencement (MW/year)** = Actual investment in Hydro/Cost per MW Hydro Description: *The amount of new Hydro power units commenced annually* **Present in 2 views:** • Hydro Power sub-sector • Supply/Power sector **Used by:** • Capacity commencement - The amount of new power units commenced annually • Hydro Power Construction - This is the total amount of power capacity that is under construction.
Default	GELA Model (Default)	#41 F,A	**Hydro Capacity completion (MW/year)** = Hydro Power Construction/Hydro CONSTRUCTION TIME Description: *This is the annual amount of Hydro power capacity that is completed and commissioned for use.* **Present in 2 views:** • Hydro Power sub-sector • Supply/Power sector **Used by:** • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Hydro Power Construction - This is the total amount of power capacity that is under construction. • Hydro Power Installed - This is the total amount of Hydro power installed and generating energy. • Hydro Production completion - This calculates the additional Hydro energy as a result of new plants completed.
Default	GELA Model (Default)	#42 F,A	**Hydro Capacity decommissioning (MW/year)** = Hydro Power Installed/Hydro AVERAGE PLANT LIFE Description: *It is the annual Hydro capacity that is scrapped or decommissioned because of depreciation.* **Present in 2 views:** • Hydro Power sub-sector • Supply/Power sector **Used by:** • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Hydro Power Decommissioned - This is the cumulative Hydro power capacity decommissioned throughout the simulation time. • Hydro Power Installed - This is the total amount of Hydro power installed and generating energy.
Default	GELA Model (Default)	#43 A	**Hydro Change in Capacity (Dmnl)** = (Hydro Power Decommissioned+Hydro Power Installed)/Hydro INITIAL POWER INSTALLED Description: *This calculates the change in Hydro capacity over time.* **Present in 1 view:** • Hydro Power sub-sector

			Used by: • Learning effect on Hydro - The effect of learning and economies of scale on the MW unit cost of Hydro power.
Default	GELA Model (Default)	#44 C	Hydro CONSTRUCTION TIME (year) = 4 Description: *The time it takes to complete the construction of a unit of Hydro power plant.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Capacity completion - This is the annual amount of Hydro power capacity that is completed and commissioned for use.
Default	GELA Model (Default)	#45 L	Hydro Energy Generated (MWh) = ∫ Hydro Production completion Hydro Production decommissioning dt + [Hydro INITIAL Generation] Description: *This is the total amount of Hydro energy consumed each year. It does not include transmission losses.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Production decommissioning - This computes the decline in Hydro energy year-on-year as a result of aging and decommissioning of plants. • "Peak power demand - Hydro" - The peak demand of Hydro Power based on the Hydro energy generated. • Share of Hydro energy - This is the fraction of Hydro energy in the total energy generated.
Default	GELA Model (Default)	#46 LI,I	Hydro INITIAL Generation (MWh) = INITIAL(5.619e+006) Description: *It is the total amount of energy utilised in the base year (2001).* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Energy Generated - This is the total amount of Hydro energy consumed each year. It does not include transmission losses.
Default	GELA Model (Default)	#47 LI,C	Hydro INITIAL POWER CONSTRUCTION (MW) = 50 Description: *It is the total Hydro power capacity under construction at the start of simulation.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Power Construction - This is the total amount of power capacity that is under construction.
Default	GELA Model (Default)	#48 LI,C	Hydro INITIAL POWER DECOMMISSIONED (MW) = 0 Description: *This is the amount of Hydro power capacity decommissioned at the start of the simulation.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Power Decommissioned - This is the cumulative Hydro power capacity decommissioned throughout the simulation time.
Default	GELA Model (Default)	#49 LI,I	Hydro INITIAL POWER INSTALLED (MW) = INITIAL(1180) Description: *It is the total Hydro power capacity installed as at the start of the simulation (2006).* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Change in Capacity - This calculates the change in Hydro capacity over time. • Hydro Power Installed - This is the total amount of Hydro power installed and generating energy.
Default	GELA Model (Default)	#51 C	Hydro Learning rate (Dmnl) = 0.01 Description: *The estimated learning rate associated with Hydro power.* Present in 1 view: • Hydro Power sub-sector Used by: • Learning effect on Hydro - The effect of learning and economies of scale on the MW unit cost of Hydro power.
Default	GELA Model (Default)	#52 C	Hydro MW to MWh conversion (MWh/MW) = 8760 Description: *The conversion of Hydro from MW (power) to MWh (energy).* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Production completion - This calculates the additional Hydro energy as a result of new plants completed. • "Peak power demand - Hydro" - The peak demand of Hydro Power based on the Hydro energy generated.
Default			Hydro potential developed (MW) = Hydro Power Decommissioned+Hydro Power Installed+Hydro Power Construction

	GELA Model (Default)	#53 A	Description: *The is the total amount of Hydro power that has already been developed.* Present in 1 view: • Hydro Power sub-sector Used by: • Available Hydro potential - The is the total amount of Hydro power that has not yet been developed.
Default	GELA Model (Default)	#54 C	Hydro potential total (MW) = 2480 Description: *This is the total potential of Hydro power that can be developed in Ghana (ECREEE, 2012).* Present in 1 view: • Hydro Power sub-sector Used by: • Available Hydro potential - The is the total amount of Hydro power that has not yet been developed.
Default	GELA Model (Default)	#55 L	Hydro Power Construction (MW) $= \int$ Hydro Capacity commencement - Hydro Capacity completion dt + [Hydro INITIAL POWER CONSTRUCTION] Description: *This is the total amount of power capacity that is under construction.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Capacity completion - This is the annual amount of Hydro power capacity that is completed and commissioned for use. • Hydro potential developed - The is the total amount of Hydro power that has already been developed.
Default	GELA Model (Default)	#56 L	Hydro Power Decommissioned (MW) $= \int$ Hydro Capacity decommissioning dt + [Hydro INITIAL POWER DECOMMISSIONED] Description: *This is the cumulative Hydro power capacity decommissioned throughout the simulation time.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Change in Capacity - This calculates the change in Hydro capacity over time. • Hydro potential developed - The is the total amount of Hydro power that has already been developed.
Default	GELA Model (Default)	#57 L	Hydro Power Installed (MW) $= \int$ Hydro Capacity completion - Hydro Capacity decommissioning dt + [Hydro INITIAL POWER INSTALLED] Description: *This is the total amount of Hydro power installed and generating energy.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Capacity decommissioning - It is the annual Hydro capacity that is scrapped or decommissioned because of depreciation. • Hydro Change in Capacity - This calculates the change in Hydro capacity over time. • Hydro potential developed - The is the total amount of Hydro power that has already been developed. • Share of Hydro power - This is the fraction of Hydro power in the total power installed.
Default	GELA Model (Default)	#58 F,A	Hydro Production completion (MWh/year) = (Hydro Capacity completion*Hydro MW to MWh conversion)*(Hydro UTILISATION FACTOR+STEP(Hydro SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Hydro energy as a result of new plants completed.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Energy Generated - This is the total amount of Hydro energy consumed each year. It does not include transmission losses. • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result.
Default	GELA Model (Default)	#59 F,A	Hydro Production decommissioning (MWh/year) = Hydro Energy Generated/Hydro AVERAGE PLANT LIFE Description: *This computes the decline in Hydro energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Energy Generated - This is the total amount of Hydro energy consumed each year. It does not include transmission losses. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#60 C	Hydro SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5]) = 0 Description: *This is a sensitivity parameter for the utilisation factor of Hydro power.* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Production completion - This calculates the additional Hydro energy as a result of new plants completed.

Default	GELA Model (Default)	#61 C	Hydro UTILISATION FACTOR (Dmnl [0.2,1,0.01]) = 0.6 Description: *This is the fraction of Hydro energy utilised compared to the total potential Hydro energy that could be supplied.STEP(-0.1, 2007)+STEP(0.2, 2008)* Present in 1 view: • Hydro Power sub-sector Used by: • Hydro Production completion - This calculates the additional Hydro energy as a result of new plants completed.
Default	GELA Model (Default)	#65 C	Initial Cost Per MW Hydro (US$/MW) = 1.8e+006 Description: *The initial average cost of installing a MW unit of Hydro power.* Present in 1 view: • Hydro Power sub-sector Used by: • Cost per MW Hydro - The average cost of installing a MW unit of Hydro power.
Default	GELA Model (Default)	#80 A	Learning effect on Hydro (Dmnl) = Hydro Change in Capacity^(LN(1-Hydro Learning rate)/LN(2)) Description: *The effect of learning and economies of scale on the MW unit cost of Hydro power.* Present in 1 view: • Hydro Power sub-sector Used by: • Cost per MW Hydro - The average cost of installing a MW unit of Hydro power.
Default	GELA Model (Default)	#85 A	Maximum possible investment in Hydro (US$/year) = Cost per MW Hydro*(Available Hydro potential/Adjustment time) Description: *It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana.* Present in 1 view: • Hydro Power sub-sector Used by: • Actual investment in Hydro - The annual amount in US$ that is actually invested in Hydro power.
Default	GELA Model (Default)	#89 A	"Peak power demand - Hydro" (MW) = Hydro Energy Generated/Hydro MW to MWh conversion Description: *The peak demand of Hydro Power based on the Hydro energy generated.* Present in 1 view: • Hydro Power sub-sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector • General CLD Used by: • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	Control	#155 C	TIME STEP (year [0,?]) = 0.0625 Description: *The time step for the simulation.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#157 A	Total Population (People) = Population with Electricity Access+Population without Electricity Access Description: *This is the total number of people in Ghana.* Present in 5 views: • Hydro Power sub-sector

			• Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity.
TOP	Thermal Power sub-sector (34 variables)		
Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#5 A	Annual investment in Thermal (US$/year) = Annual investment*Fractional investment in Thermal Description: *The annual amount in US$ invested in Thermal power* Present in 2 views: • Thermal Power sub-sector • Capital/Investment sector Used by: • Thermal Capacity commencement - The amount of new Thermal power units commenced annually
Default	GELA Model (Default)	#8 C	AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People) = 0.52 Description: *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	GELA Model (Default)	#19 A	Cost per MW Thermal (US$/MW) = Initial Cost Per MW Thermal*Learning effect on Thermal Description: *The average cost of installing a MW unit of Thermal power.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Capacity commencement - The amount of new Thermal power units commenced annually
Default	GELA Model (Default)	#24 F,A	Electricity access loss rate (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) Description: *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#67 C	Initial Cost Per MW Thermal (US$/MW) = 1.5e+006 Description: *The initial average cost of installing a MW unit of Thermal power.* Present in 1 view: • Thermal Power sub-sector Used by: • Cost per MW Thermal - The average cost of installing a MW unit of Thermal power.
Default			Learning effect on Thermal (Dmnl) = Thermal Change in Capacity^(LN(1-Thermal Learning rate)/LN(2))

	GELA Model (Default)	#82 A	Description: *The effect of learning and economies of scale on the MW unit cost of Thermal power.* Present in 1 view: • Thermal Power sub-sector Used by: • Cost per MW Thermal - The average cost of installing a MW unit of Thermal power.
Default	GELA Model (Default)	#91 A	"Peak power demand - Thermal" (MW) = Thermal Energy Generated/Thermal MW to MWh conversion Description: *The peak demand of Thermal Power based on the Thermal energy generated.* Present in 1 view: • Thermal Power sub-sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector • General CLD Used by: • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#134 C	Thermal AVERAGE PLANT LIFE (year [10,80]) = 30 Description: *This is the average amount of time a Thermal power plant would be in operation before being scrapped/decommissiond.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Capacity decommissioning - It is the annual Thermal capacity that is scrapped or decommissioned because of depreciation. • Thermal Production decomissioning - This computes the decline in Thermal energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#135 F,A	Thermal Capacity commencement (MW/year) = Annual investment in Thermal/Cost per MW Thermal Description: *The amount of new Thermal power units commenced annually* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Capacity commencement - The amount of new power units commenced annually • Thermal Power Construction - This is the total amount of Thermal power capacity that is under construction.
Default	GELA Model (Default)	#136 F,A	Thermal Capacity completion (MW/year) = Thermal Power Construction/Thermal CONSTRUCTION TIME Description: *This is the annual amount of Thermal power capacity that is completed and commissioned for use.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Thermal Power Construction - This is the total amount of Thermal power capacity that is under construction. • Thermal Power Installed - This is the total amount of Thermal power installed and generating energy. • Thermal Production completion - This calculates the additional Thermal energy as a result of new plants completed.
Default	GELA Model (Default)	#137 F,A	Thermal Capacity decommissioning (MW/year) = Thermal Power Installed/Thermal AVERAGE PLANT LIFE Description: *It is the annual Thermal capacity that is scrapped or decommissioned because of depreciation.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Thermal Power Decommissioned - This is the cumulative Thermal power capacity decommissioned throughout the simulation time.

			• Thermal Power Installed - This is the total amount of Thermal power installed and generating energy.
Default	GELA Model (Default)	#138 A	Thermal Change in Capacity (Dmnl) = (Thermal Power Decommissioned+Thermal Power Installed)/Thermal INITIAL POWER INSTALLED Description: *This calculates the change in Thermal capacity over time.* Present in 1 view: • Thermal Power sub-sector Used by: • Learning effect on Thermal - The effect of learning and economies of scale on the MW unit cost of Thermal power.
Default	GELA Model (Default)	#139 C	Thermal CONSTRUCTION TIME (year) = 4 Description: *The time it takes to complete the construction of a unit of Thermal power plant.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Capacity completion - This is the annual amount of Thermal power capacity that is completed and commissioned for use.
Default	GELA Model (Default)	#140 L	Thermal Energy Generated (MWh) = ∫ Thermal Production completion Thermal Production decomissioning *dt* + [Thermal INITIAL Generation] Description: *This is the total amount of Thermal energy consumed each year. It does not include transimission losses.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • "Peak power demand - Thermal" - The peak demand of Thermal Power based on the Thermal energy generated. • Share of Thermal energy - This is the fraction of Thermal energy in the total energy generated. • Thermal Production decomissioning - This computes the decline in Thermal energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#141 LI,I	Thermal INITIAL Generation (MWh) = INITIAL(2.81e+006) Description: *It is the total amount of Thermal energy utilised in the base year (2006).* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Energy Generated - This is the total amount of Thermal energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#142 LI,C	Thermal INITIAL POWER CONSTRUCTION (MW) = 550 Description: *It is the total Thermal power capacity under construction at the start of simulation.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Power Construction - This is the total amount of Thermal power capacity that is under construction.
Default	GELA Model (Default)	#143 LI,C	Thermal INITIAL POWER DECOMMISSIONED (MW) = 0 Description: *This is the amount ot Thermal power capacity decommissioned at the start of the simulation.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Power Decommissioned - This is the cumulative Thermal power capacity decommissioned throughout the simulation time.
Default	GELA Model (Default)	#144 LI,I	Thermal INITIAL POWER INSTALLED (MW) = INITIAL(550) Description: *It is the total Thermal power capacity installed as at the start of the simulation (2006).* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Change in Capacity - This calculates the change in Thermal capacity over time. • Thermal Power Installed - This is the total amount of Thermal power installed and generating energy.
Default	GELA Model (Default)	#146 C	Thermal Learning rate (Dmnl) = 0.01 Description: *The estimated learning rate associated with Thermal power.* Present in 1 view: • Thermal Power sub-sector Used by: • Learning effect on Thermal - The effect of learning and economies of scale on the MW unit cost of Thermal power.
Default	GELA Model (Default)	#147 C	Thermal MW to MWh conversion (MWh/MW) = 8760 Description: *The conversion of Thermal from MW (power) to MWh (energy).* Present in 1 view: • Thermal Power sub-sector

			Used by: • "Peak power demand - Thermal" - The peak demand of Thermal Power based on the Thermal energy generated. • Thermal Production completion - This calculates the additional Thermal energy as a result of new plants completed.
Default	GELA Model (Default)	#148 L	Thermal Power Construction (MW) = ∫ Thermal Capacity commencement - Thermal Capacity completion dt + [Thermal INITIAL POWER CONSTRUCTION] Description: *This is the total amount of Thermal power capacity that is under construction.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Capacity completion - This is the annual amount of Thermal power capacity that is completed and commissioned for use.
Default	GELA Model (Default)	#149 L	Thermal Power Decommissioned (MW) = ∫ Thermal Capacity decommissioning dt + [Thermal INITIAL POWER DECOMMISSIONED] Description: *This is the cumulative Thermal power capacity decommissioned throughout the simulation time.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Change in Capacity - This calculates the change in Thermal capacity over time.
Default	GELA Model (Default)	#150 L	Thermal Power Installed (MW) = ∫ Thermal Capacity completion - Thermal Capacity decommissioning dt + [Thermal INITIAL POWER INSTALLED] Description: *This is the total amount of Thermal power installed and generating energy.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Share of Thermal Power - This is the fraction of Thermal power in the total power installed. • Thermal Capacity decommissioning - It is the annual Thermal capacity that is scrapped or decommissioned because of depreciation. • Thermal Change in Capacity - This calculates the change in Thermal capacity over time.
Default	GELA Model (Default)	#151 F,A	Thermal Production completion (MWh/year) = (Thermal Capacity completion*Thermal MW to MWh conversion)*(Thermal UTILISATION FACTOR+STEP (Thermal SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Thermal energy as a result of new plants completed.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result. • Thermal Energy Generated - This is the total amount of Thermal energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#152 F,A	Thermal Production decomissioning (MWh/year) = Thermal Energy Generated/Thermal AVERAGE PLANT LIFE Description: *This computes the decline in Thermal energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Thermal Energy Generated - This is the total amount of Thermal energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#153 C	Thermal SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5]) = 0 Description: *This is a sensitivity parameter for the utilisation factor of Thermal power.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Production completion - This calculates the additional Thermal energy as a result of new plants completed.
Default	GELA Model (Default)	#154 C	Thermal UTILISATION FACTOR (Dmnl [0.2,1,0.01]) = 0.33 Description: *This is the fraction of Thermal energy utilised compared to the total potential Thermal energy that could be supplied.* Present in 1 view: • Thermal Power sub-sector Used by: • Thermal Production completion - This calculates the additional Thermal energy as a result of new plants completed.
Default	Control		

		#155 C	TIME STEP (year [0,?]) = 0.0625 Description: *The time step for the simulation.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#157 A	Total Population (People) = Population with Electricity Access+Population without Electricity Access Description: *This is the total number of people in Ghana.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity.

TOP

Solar Power sub-sector (35 variables)

Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#4 A	Annual investment in Solar (US$/year) = Annual investment*"Fractional investment in solar/renewables" Description: *The annual amount in US$ invested in Solar power* Present in 2 views: • Solar Power sub-sector • Capital/Investment sector Used by: • Solar Capacity commencement - The amount of new Solar power units commenced annually
Default	GELA Model (Default)	#8 C	AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People) = 0.52 Description: *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	GELA Model (Default)	#18 A	Cost per MW Solar (US$/MW) = Initial Cost Per MW Solar*Learning effect on Solar Description: *The average cost of installing a MW unit of solar power.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Capacity commencement - The amount of new Solar power units commenced annually
Default	GELA Model (Default)	#24 F,A	Electricity access loss rate (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) Description: *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* Present in 6 views: • Hydro Power sub-sector

			• Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#66 C	Initial Cost Per MW Solar (US$/MW) = 4e+006 Description: *The initial average cost of installing a MW unit of solar power.* Present in 1 view: • Solar Power sub-sector Used by: • Cost per MW Solar - The average cost of installing a MW unit of solar power.
Default	GELA Model (Default)	#81 A	Learning effect on Solar (Dmnl) = Solar Change in Capacity^(LN(1-Solar Learning rate)/LN(2)) Description: *The effect of learning and economies of scale on the MW unit cost of Solar power.* Present in 1 view: • Solar Power sub-sector Used by: • Cost per MW Solar - The average cost of installing a MW unit of solar power.
Default	GELA Model (Default)	#90 A	"Peak power demand - Solar" (MW) = Solar Energy Generated/Solar MW to MWh conversion Description: *The peak demand of Solar Power based on the Solar energy generated.* Present in 1 view: • Solar Power sub-sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector • General CLD Used by: • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#112 C	Solar AVERAGE PLANT LIFE (year [10,80]) = 20 Description: *This is the average amount of time a Solar power plant would be in operation before being scrapped/decommissiond.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Capacity decommissioning - It is the annual Solar capacity that is scrapped or decommissioned because of depreciation. • Solar Production decomissioning - This computes the decline in Solar energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#113 F,A	Solar Capacity commencement (MW/year) = Annual investment in Solar/Cost per MW Solar Description: *The amount of new Solar power units commenced annually* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Capacity commencement - The amount of new power units commenced annually • Solar Power Construction - This is the total amount of Solar power capacity that is under construction.
Default	GELA Model (Default)	#114 F,A	Solar Capacity completion (MW/year) = Solar Power Construction/Solar CONSTRUCTION TIME Description: *This is the annual amount of Solar power capacity that is completed and commissioned for use.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector

			Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Solar Power Construction - This is the total amount of Solar power capacity that is under construction. • Solar Power Installed - This is the total amount of Solar power installed and generating energy. • Solar Production completion - This calculates the additional Solar energy as a result of new plants completed.
Default	GELA Model (Default)	#115 F,A	Solar Capacity decommissioning (MW/year) = Solar Power Installed/Solar AVERAGE PLANT LIFE Description: *It is the annual Solar capacity that is scrapped or decommissioned because of depreciation.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Solar Power Decommissioned - This is the cumulative Solar power capacity decommissioned throughout the simulation time. • Solar Power Installed - This is the total amount of Solar power installed and generating energy.
Default	GELA Model (Default)	#116 A	Solar Change in Capacity (Dmnl) = (Solar Power Decommissioned+Solar Power Installed)/Solar INITIAL POWER INSTALLED Description: *This calculates the change in Solar capacity over time.* Present in 1 view: • Solar Power sub-sector Used by: • Learning effect on Solar - The effect of learning and economies of scale on the MW unit cost of Solar power.
Default	GELA Model (Default)	#117 C	Solar CONSTRUCTION TIME (year) = 2 Description: *The time it takes to complete the construction of a unit of Solar power plant.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Capacity completion - This is the annual amount of Solar power capacity that is completed and commissioned for use.
Default	GELA Model (Default)	#118 L	Solar Energy Generated (MWh) = $\int$ Solar Production completion - Solar Production decomissioning dt + [Solar INITIAL Generation] Description: *This is the total amount of Solar energy consumed each year. It does not include transimission losses.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • "Peak power demand - Solar" - The peak demand of Solar Power based on the Solar energy generated. • Share of Solar energy - This is the fraction of Solar energy in the total energy generated. • Solar Production decomissioning - This computes the decline in Solar energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#119 LI,I	Solar INITIAL Generation (MWh) = INITIAL(0) Description: *It is the total amount of Solar energy utilised in the base year (2006).* Present in 1 view: • Solar Power sub-sector Used by: • Solar Energy Generated - This is the total amount of Solar energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#120 LI,C	Solar INITIAL POWER CONSTRUCTION (MW) = 0 Description: *It is the total Solar power capacity under construction at the start of simulation.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Power Construction - This is the total amount of Solar power capacity that is under construction.
Default	GELA Model (Default)	#121 LI,C	Solar INITIAL POWER DECOMMISSIONED (MW) = 0 Description: *This is the amount ot Solar power capacity decommissioned at the start of the simulation.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Power Decommissioned - This is the cumulative Solar power capacity decommissioned throughout the simulation time.
Default	GELA Model (Default)	#122 LI,I	Solar INITIAL POWER INSTALLED (MW) = INITIAL(1) Description: *It is the total Solar power capacity installed as at the start of the simulation (2006).* Present in 1 view: • Solar Power sub-sector

			Used by: • Solar Change in Capacity - This calculates the change in Solar capacity over time. • Solar Power Installed - This is the total amount of Solar power installed and generating energy.
Default	GELA Model (Default)	#123 C	Solar Learning rate (Dmnl) = 0.01 Description: *The estimated learning rate associated with Solar power.* Present in 1 view: • Solar Power sub-sector Used by: • Learning effect on Solar - The effect of learning and economies of scale on the MW unit cost of Solar power.
Default	GELA Model (Default)	#124 C	Solar MW to MWh conversion (MWh/MW) = 8760 Description: *The conversion of Solar from MW (power) to MWh (energy).* Present in 1 view: • Solar Power sub-sector Used by: • "Peak power demand - Solar" - The peak demand of Solar Power based on the Solar energy generated. • Solar Production completion - This calculates the additional Solar energy as a result of new plants completed.
Default	GELA Model (Default)	#125 L	Solar Power Construction (MW) $= \int$ Solar Capacity commencement Solar Capacity completion dt + [Solar INITIAL POWER CONSTRUCTION] Description: *This is the total amount of Solar power capacity that is under construction.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Capacity completion - This is the annual amount of Solar power capacity that is completed and commissioned for use.
Default	GELA Model (Default)	#126 L	Solar Power Decommissioned (MW) $= \int$ Solar Capacity decommissioning dt + [Solar INITIAL POWER DECOMMISSIONED] Description: *This is the cumulative Solar power capacity decommissioned throughout the simulation time.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Change in Capacity - This calculates the change in Solar capacity over time.
Default	GELA Model (Default)	#127 L	Solar Power Installed (MW) $= \int$ Solar Capacity completion - Solar Capacity decommissioning dt + [Solar INITIAL POWER INSTALLED] Description: *This is the total amount of Solar power installed and generating energy.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Share of Solar Power - This is the fraction of Solar power in the total power installed. • Solar Capacity decommissioning - It is the annual Solar capacity that is scrapped or decommissioned because of depreciation. • Solar Change in Capacity - This calculates the change in Solar capacity over time.
Default	GELA Model (Default)	#128 F,A	Solar Production completion (MWh/year) = (Solar Capacity completion*Solar MW to MWh conversion)*(Solar UTILISATION FACTOR+STEP(Solar SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Solar energy as a result of new plants completed.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result. • Solar Energy Generated - This is the total amount of Solar energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#129 F,A	Solar Production decomissioning (MWh/year) = Solar Energy Generated/Solar AVERAGE PLANT LIFE Description: *This computes the decline in Solar energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Solar Energy Generated - This is the total amount of Solar energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#130 C	Solar SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5]) = 0 Description: *This is a sensitivity parameter for the utilisation factor of Solar power.* Present in 1 view: • Solar Power sub-sector

			Used by: • Solar Production completion - This calculates the additional Solar energy as a result of new plants completed.
Default	GELA Model (Default)	#131 A	Solar UTILISATION FACTOR (Dmnl) = 0+STEP(0.15, 2013) Description: *This is the fraction of Solar energy utilised compared to the total potential Solar energy that could be supplied.* Present in 1 view: • Solar Power sub-sector Used by: • Solar Production completion - This calculates the additional Solar energy as a result of new plants completed.
Default	Control	#155 C	TIME STEP (year [0,?]) = 0.0625 Description: *The time step for the simulation.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#157 A	Total Population (People) = Population with Electricity Access+Population without Electricity Access Description: *This is the total number of people in Ghana.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity.

TOP

Supply/Power sector (73 variables)

Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#2 C	Adjustment time (year) = 1 Description: *The time it takes to adjust capacity* Present in 4 views: • Hydro Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#8 C	AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People) = 0.52 Description: *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy

			consumed per person is expected to increase in accordance with the economic principles of price and demand. • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	GELA Model (Default)	#11 F,A	Backlog clearance (MW/year) = MIN(Capacity commencement, Power Backlog/Adjustment time) Description: *The rate at which the outstanding capacity is depleted through investment* Present in 1 view: • Supply/Power sector Used by: • Power Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	GELA Model (Default)	#13 F,A	Capacity commencement (MW/year) = Hydro Capacity commencement+Solar Capacity commencement+Thermal Capacity commencement Description: *The amount of new power units commenced annually* Present in 1 view: • Supply/Power sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment • Indicated Annual capacity requirement - It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line. • Power Construction - This is the total amount of power capacity that is under construction.
Default	GELA Model (Default)	#14 F,A	Capacity completion (MW/year) = MIN((Hydro Capacity completion+Solar Capacity completion+Thermal Capacity completion), (Power Construction/Adjustment time)) Description: *This is the annual amount of power capacity that is completed and commissioned for use.* Present in 1 view: • Supply/Power sector Used by: • Power Construction - This is the total amount of power capacity that is under construction. • Power Installed - This is the total amount of power installed and generating energy.
Default	GELA Model (Default)	#15 F,A	Capacity decommissioning (MW/year) = MIN((Hydro Capacity decommissioning+Solar Capacity decommissioning+Thermal Capacity decommissioning), (Power Installed/Adjustment time)) Description: *It is the annual capacity that is scrapped or decommissiond because of depreciation.* Present in 1 view: • Supply/Power sector Used by: • Expected Capacity Loss - This is the power capacity that is expected to be lost annually through plants aging. • Power Decommissioned - This is the cumulative power capacity decommissioned throughout the simulation time. • Power Installed - This is the total amount of power installed and generating energy.
Default	GELA Model (Default)	#16 A	Change in Capacity (Dmnl) = (Power Decommissioned+Power Installed)/INITIAL POWER INSTALLED Description: *This calculates the change in capacity over time.* Present in 3 views: • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Learning effect - This is the effect of learning and economies of scale on the unit price of electricity.
Default	GELA Model (Default)	#21 A	Desired Acquisition rate (MW) = Indicated Aquisition rate*EXPECTED ACQUISITION DELAY Description: *The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.* Present in 1 view: • Supply/Power sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Supply Line Adjustment - It is the annual new power capacity required after accounting for the delay in the supply line.
Default	GELA Model (Default)	#22 A	Desired power Capacity (MW) = (((AVERAGE CONSUMPTION PER ACCESS PERSON*Total Population)/UTILISATION FACTOR)/MW to MWh conversion)+Desired Acquisition rate Description: *This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population.* Present in 1 view: • Supply/Power sector Used by: • Power Capacity Gap - It is the difference between desired and actual power capacity.
Default		#24 F,A	Electricity access loss rate (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity

	GELA Model (Default)		Access/TIME STEP)) Description: *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#28 L	Energy Generated (MWh) $= \int$ Production completion - Production decommissioning dt + [INITIAL Generation] Description: *The total amount of energy generated in a year based on the capacity of power installed* Present in 2 views: • Supply/Power sector • Demand/Population sector Used by: • Peak power demand - The peak demand of Power based on the energy generated. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Share of Hydro energy - This is the fraction of Hydro energy in the total energy generated. • Share of Solar energy - This is the fraction of Solar energy in the total energy generated. • Share of Thermal energy - This is the fraction of Thermal energy in the total energy generated.
Default	GELA Model (Default)	#29 C	EXPECTED ACQUISITION DELAY (year) = 3 Description: *The estimated time delay between realising the need for a power unit and actually investment in securing it.* Present in 1 view: • Supply/Power sector Used by: • Desired Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.
Default	GELA Model (Default)	#30 A	Expected Capacity Addition (MW/year) = (Population growth*AVERAGE CONSUMPTION PER ACCESS PERSON)/MW to MWh conversion Description: *This is the new power capacity required annually as a result of population growth.* Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • Indicated Aquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	GELA Model (Default)	#31 A	Expected Capacity Loss (MW/year) = Capacity decommissioning Description: *This is the power capacity that is expected to be lost annually through plants aging.* Present in 1 view: • Supply/Power sector Used by: • Indicated Aquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	GELA Model (Default)	#40 F,A	Hydro Capacity commencement (MW/year) = Actual investment in Hydro/Cost per MW Hydro Description: *The amount of new Hydro power units commenced annually* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Capacity commencement - The amount of new power units commenced annually • Hydro Power Construction - This is the total amount of power capacity that is under construction.
Default	GELA Model (Default)	#41 F,A	Hydro Capacity completion (MW/year) = Hydro Power Construction/Hydro CONSTRUCTION TIME Description: *This is the annual amount of Hydro power capacity that is completed and commissioned for use.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Hydro Power Construction - This is the total amount of power capacity that is under construction.

			• Hydro Power Installed - This is the total amount of Hydro power installed and generating energy. • Hydro Production completion - This calculates the additional Hydro energy as a result of new plants completed.
Default	GELA Model (Default)	#42 F,A	Hydro Capacity decommissioning (MW/year) = Hydro Power Installed/Hydro AVERAGE PLANT LIFE Description: *It is the annual Hydro capacity that is scrapped or decommissioned because of depreciation.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Hydro Power Decommissioned - This is the cumulative Hydro power capacity decommissioned throughout the simulation time. • Hydro Power Installed - This is the total amount of Hydro power installed and generating energy.
Default	GELA Model (Default)	#45 L	Hydro Energy Generated (MWh) = ∫ Hydro Production completion Hydro Production decommissioning *dt* + [Hydro INITIAL Generation] Description: *This is the total amount of Hydro energy consumed each year. It does not include transmission losses.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Production decommissioning - This computes the decline in Hydro energy year-on-year as a result of aging and decommissioning of plants. • "Peak power demand - Hydro" - The peak demand of Hydro Power based on the Hydro energy generated. • Share of Hydro energy - This is the fraction of Hydro energy in the total energy generated.
Default	GELA Model (Default)	#57 L	Hydro Power Installed (MW) = ∫ Hydro Capacity completion Hydro Capacity decommissioning *dt* + [Hydro INITIAL POWER INSTALLED] Description: *This is the total amount of Hydro power installed and generating energy.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Capacity decommissioning - It is the annual Hydro capacity that is scrapped or decommissioned because of depreciation. • Hydro Change in Capacity - This calculates the change in Hydro capacity over time. • Hydro potential developed - The is the total amount of Hydro power that has already been developed. • Share of Hydro power - This is the fraction of Hydro power in the total power installed.
Default	GELA Model (Default)	#58 F,A	Hydro Production completion (MWh/year) = (Hydro Capacity completion*Hydro MW to MWh conversion)*(Hydro UTILISATION FACTOR+STEP(Hydro SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Hydro energy as a result of new plants completed.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Energy Generated - This is the total amount of Hydro energy consumed each year. It does not include transmission losses. • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result.
Default	GELA Model (Default)	#59 F,A	Hydro Production decommissioning (MWh/year) = Hydro Energy Generated/Hydro AVERAGE PLANT LIFE Description: *This computes the decline in Hydro energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Hydro Power sub-sector • Supply/Power sector Used by: • Hydro Energy Generated - This is the total amount of Hydro energy consumed each year. It does not include transmission losses. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#62 F,A	Indicated Annual capacity requirement (MW/year) = MAX((Supply Line Adjustment-Capacity commencement), 0) Description: *It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line.* Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • Power Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	GELA Model (Default)	#63 A	Indicated Aquisition rate (MW/year) = Expected Capacity Loss+Expected Capacity Addition Description: *The amount of power units required annually as a result of the capacity that would be*

			decommissioned and population growth. Present in 1 view: • Supply/Power sector Used by: • Desired Acquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned, population growth, and the delay in making investment for such capacity.
Default	GELA Model (Default)	#69 LI,I	INITIAL Generation (MWh) = INITIAL(8.429e+006) Description: *It is the total amount of energy utilised in the base year (2001).* Present in 1 view: • Supply/Power sector Used by: • Energy Generated - The total amount of energy generated in a year based on the capacity of power installed
Default	GELA Model (Default)	#72 LI,C	INITIAL POWER BACKLOG (MW) = 1305 Description: *It is the capacity required for full access at the beginning of the simulation.* Present in 1 view: • Supply/Power sector Used by: • Power Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	GELA Model (Default)	#73 LI,C	INITIAL POWER CONSTRUCTION (MW) = 600 Description: *It is the total power capacity under construction at the start of simulation.* Present in 1 view: • Supply/Power sector Used by: • Power Construction - This is the total amount of power capacity that is under construction.
Default	GELA Model (Default)	#74 LI,C	INITIAL POWER DECOMMISSIONED (MW) = 0 Description: *This is the amount of power capacity decommissioned at the start of the simulation.* Present in 1 view: • Supply/Power sector Used by: • Power Decommissioned - This is the cumulative power capacity decommissioned throughout the simulation time.
Default	GELA Model (Default)	#75 LI,I	INITIAL POWER INSTALLED (MW) = INITIAL(1731) Description: *It is the total power capacity installed as at the start of the simulation (2006).* Present in 1 view: • Supply/Power sector Used by: • Change in Capacity - This calculates the change in capacity over time. • Power Installed - This is the total amount of power installed and generating energy.
Default	GELA Model (Default)	#86 C	MW to MWh conversion (MWh/MW) = 8760 Description: *It is the conversion from MW (power) to MWh (energy).* Present in 1 view: • Supply/Power sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Peak power demand - The peak demand of Power based on the energy generated.
Default	GELA Model (Default)	#88 A	Peak power demand (MW) = Energy Generated/MW to MWh conversion Description: *The peak demand of Power based on the energy generated.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector • General CLD

			Used by: • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#95 L	Power Backlog (MW) = $\int$ Indicated Annual capacity requirement Backlog clearance dt + [INITIAL POWER BACKLOG] Description: *It is the outstanding capacity needed at any given point in time of the simulation.* Present in 1 view: • Supply/Power sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment
Default	GELA Model (Default)	#96 A	Power Capacity Gap (MW) = MAX(Desired power Capacity-Power Installed-Power Construction, 0) Description: *It is the difference between desired and actual power capacity.* Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#97 L	Power Construction (MW) = $\int$ Capacity commencement Capacity completion dt + [INITIAL POWER CONSTRUCTION] Description: *This is the total amount of power capacity that is under construction.* Present in 1 view: • Supply/Power sector Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Power Capacity Gap - It is the difference between desired and actual power capacity.
Default	GELA Model L (Default)	#98	Power Decommissioned (MW) = $\int$ Capacity decommissioning dt + [INITIAL POWER DECOMMISSIONED] Description: *This is the cumulative power capacity decommissioned throughout the simulation time.* Present in 1 view: • Supply/Power sector Used by: • Change in Capacity - This calculates the change in capacity over time.
Default	GELA Model (Default)	#99 L	Power Installed (MW) = $\int$ Capacity completion Capacity decommissioning dt + [INITIAL POWER INSTALLED] Description: *This is the total amount of power installed and generating energy.* Present in 1 view: • Supply/Power sector Used by: • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Change in Capacity - This calculates the change in capacity over time. • Power Capacity Gap - It is the difference between desired and actual power capacity. • Share of Hydro power - This is the fraction of Hydro power in the total power installed. • Share of Solar Power - This is the fraction of Solar power in the total power installed. • Share of Thermal Power - This is the fraction of Thermal power in the total power installed.
Default	GELA Model (Default)	#101 F,A	Production completion (MWh/year) = Hydro Production completion+Solar Production completion+Thermal Production completion Description: *The quantity of energy added annually. It also indicates how many connections would be gained as a result.* Present in 2 views: • Supply/Power sector • Demand/Population sector Used by: • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases. • Energy Generated - The total amount of energy generated in a year based on the capacity of power installed
Default	GELA Model (Default)	#102 F,A	Production decommissioning (MWh/year) = MIN((Hydro Production decommissioning+Solar Production decomissioning+Thermal Production decomissioning), (Energy Generated/Adjustment time)) Description: *The quantity of energy lost annually. It also indicates how many connections would be lost as a result.* Present in 2 views: • Supply/Power sector • Demand/Population sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.

			• Energy Generated - The total amount of energy generated in a year based on the capacity of power installed
Default	GELA Model (Default)	#106 A	Share of Hydro energy (Dmnl) = Hydro Energy Generated/Energy Generated Description: *This is the fraction of Hydro energy in the total energy generated.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#107 A	Share of Hydro power (Dmnl) = Hydro Power Installed/Power Installed Description: *This is the fraction of Hydro power in the total power installed.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#108 A	Share of Solar energy (Dmnl) = Solar Energy Generated/Energy Generated Description: *This is the fraction of Solar energy in the total energy generated.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#109 A	Share of Solar Power (Dmnl) = Solar Power Installed/Power Installed Description: *This is the fraction of Solar power in the total power installed.* Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#110 A	Share of Thermal energy (Dmnl) = Thermal Energy Generated/Energy Generated Description: *This is the fraction of Thermal energy in the total energy generated.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#111 A	Share of Thermal Power (Dmnl) = Thermal Power Installed/Power Installed Description: *This is the fraction of Thermal power in the total power installed.* Present in 1 view: • Supply/Power sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#113 F,A	Solar Capacity commencement (MW/year) = Annual investment in Solar/Cost per MW Solar Description: *The amount of new Solar power units commenced annually* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Capacity commencement - The amount of new power units commenced annually • Solar Power Construction - This is the total amount of Solar power capacity that is under construction.
Default	GELA Model (Default)	#114 F,A	Solar Capacity completion (MW/year) = Solar Power Construction/Solar CONSTRUCTION TIME Description: *This is the annual amount of Solar power capacity that is completed and commissioned for use.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Solar Power Construction - This is the total amount of Solar power capacity that is under construction. • Solar Power Installed - This is the total amount of Solar power installed and generating energy. • Solar Production completion - This calculates the additional Solar energy as a result of new plants completed.
Default	GELA Model (Default)	#115 F,A	Solar Capacity decommissioning (MW/year) = Solar Power Installed/Solar AVERAGE PLANT LIFE Description: *It is the annual Solar capacity that is scrapped or decommissioned because of depreciation.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by:

			• Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Solar Power Decommissioned - This is the cumulative Solar power capacity decommissioned throughout the simulation time. • Solar Power Installed - This is the total amount of Solar power installed and generating energy.
Default	GELA Model (Default)	#118 L	Solar Energy Generated (MWh) = ∫ Solar Production completion - Solar Production decomissioning dt + [Solar INITIAL Generation] Description: *This is the total amount of Solar energy consumed each year. It does not include transimission losses.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • "Peak power demand - Solar" - The peak demand of Solar Power based on the Solar energy generated. • Share of Solar energy - This is the fraction of Solar energy in the total energy generated. • Solar Production decomissioning - This computes the decline in Solar energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#127 L	Solar Power Installed (MW) = ∫ Solar Capacity completion - Solar Capacity decommissioning dt + [Solar INITIAL POWER INSTALLED] Description: *This is the total amount of Solar power installed and generating energy.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Share of Solar Power - This is the fraction of Solar power in the total power installed. • Solar Capacity decommissioning - It is the annual Solar capacity that is scrapped or decommissioned because of depreciation. • Solar Change in Capacity - This calculates the change in Solar capacity over time.
Default	GELA Model (Default)	#128 F,A	Solar Production completion (MWh/year) = (Solar Capacity completion*Solar MW to MWh conversion)*(Solar UTILISATION FACTOR+STEP(Solar SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Solar energy as a result of new plants completed.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result. • Solar Energy Generated - This is the total amount of Solar energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#129 F,A	Solar Production decomissioning (MWh/year) = Solar Energy Generated/Solar AVERAGE PLANT LIFE Description: *This computes the decline in Solar energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Solar Power sub-sector • Supply/Power sector Used by: • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Solar Energy Generated - This is the total amount of Solar energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#132 A	Supply Line Adjustment (MW/year) = Desired Acquisition rate/SUPPLY LINE ADJUSTMENT TIME Description: *It is the annual new power capacity required after accounting for the delay in the supply line.* Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • Indicated Annual capacity requirement - It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line. • Indicated Investment - This is the annual amount of investment that should be made towards power infrastructure based on the power capacity gap.
Default	GELA Model (Default)	#133 C	SUPPLY LINE ADJUSTMENT TIME (year) = 1 Description: *It is the duration it takes to adjust the supply line.* Present in 1 view: • Supply/Power sector Used by: • Supply Line Adjustment - It is the annual new power capacity required after accounting for the delay in the supply line.
Default	GELA Model (Default)	#135 F,A	Thermal Capacity commencement (MW/year) = Annual investment in Thermal/Cost per MW Thermal Description: *The amount of new Thermal power units commenced annually* Present in 2 views: • Thermal Power sub-sector

			• Supply/Power sector Used by: • Capacity commencement - The amount of new power units commenced annually • Thermal Power Construction - This is the total amount of Thermal power capacity that is under construction.
Default	GELA Model (Default)	#136 F,A	Thermal Capacity completion (MW/year) = Thermal Power Construction/Thermal CONSTRUCTION TIME Description: *This is the annual amount of Thermal power capacity that is completed and commissioned for use.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Thermal Power Construction - This is the total amount of Thermal power capacity that is under construction. • Thermal Power Installed - This is the total amount of Thermal power installed and generating energy. • Thermal Production completion - This calculates the additional Thermal energy as a result of new plants completed.
Default	GELA Model (Default)	#137 F,A	Thermal Capacity decommissioning (MW/year) = Thermal Power Installed/Thermal AVERAGE PLANT LIFE Description: *It is the annual Thermal capacity that is scrapped or decommissioned because of depreciation.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Thermal Power Decommissioned - This is the cumulative Thermal power capacity decommissioned throughout the simulation time. • Thermal Power Installed - This is the total amount of Thermal power installed and generating energy.
Default	GELA Model (Default)	#140 L	Thermal Energy Generated (MWh) = ∫ Thermal Production completion Thermal Production decomissioning *dt* + [Thermal INITIAL Generation] Description: *This is the total amount of Thermal energy consumed each year. It does not include transimission losses.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • "Peak power demand - Thermal" - The peak demand of Thermal Power based on the Thermal energy generated. • Share of Thermal energy - This is the fraction of Thermal energy in the total energy generated. • Thermal Production decomissioning - This computes the decline in Thermal energy year-on-year as a result of aging and decommissioning of plants.
Default	GELA Model (Default)	#150 L	Thermal Power Installed (MW) = ∫ Thermal Capacity completion Thermal Capacity decommissioning *dt* + [Thermal INITIAL POWER INSTALLED] Description: *This is the total amount of Thermal power installed and generating energy.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Share of Thermal Power - This is the fraction of Thermal power in the total power installed. • Thermal Capacity decommissioning - It is the annual Thermal capacity that is scrapped or decommissioned because of depreciation. • Thermal Change in Capacity - This calculates the change in Thermal capacity over time.
Default	GELA Model (Default)	#151 F,A	Thermal Production completion (MWh/year) = (Thermal Capacity completion*Thermal MW to MWh conversion)*(Thermal UTILISATION FACTOR+STEP(Thermal SENSITIVITY OF UTILISATION FACTOR, 2019)) Description: *This calculates the additional Thermal energy as a result of new plants completed.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector Used by: • Production completion - The quantity of energy added annually. It also indicates how many connections would be gained as a result. • Thermal Energy Generated - This is the total amount of Thermal energy consumed each year. It does not include transimission losses.
Default	GELA Model (Default)	#152 F,A	Thermal Production decomissioning (MWh/year) = Thermal Energy Generated/Thermal AVERAGE PLANT LIFE Description: *This computes the decline in Thermal energy year-on-year as a result of aging and decommissioning of plants.* Present in 2 views: • Thermal Power sub-sector • Supply/Power sector

			Used by: • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Thermal Energy Generated - This is the total amount of Thermal energy consumed each year. It does not include transimission losses.
Default	Control	#155 C	TIME STEP (year [0,?]) = 0.0625 Description: *The time step for the simulation.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#157 A	Total Population (People) = Population with Electricity Access+Population without Electricity Access Description: *This is the total number of people in Ghana.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity.
Default	GELA Model (Default)	#158 C	UTILISATION FACTOR (Dmnl) = 0.3 Description: *This is the fraction of Power capacity utilised compared to the total potential energy that could be supplied.* Present in 1 view: • Supply/Power sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population.

TOP

Demand/Population sector (29 variables)

Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#2 C	Adjustment time (year) = 1 Description: *The time it takes to adjust capacity* Present in 4 views: • Hydro Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#8 C	AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People) = 0.52 Description: *The average consumption per access person is the total energy consumed in the base year divided by the number of people with electricity access.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector

			Used by: • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand. • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
Default	GELA Model (Default)	#9 A	Average Consumption per person (MWh/People) = AVERAGE CONSUMPTION PER ACCESS PERSON*(1+(1-Price Change)) Description: *This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand.* Present in 1 view: • Demand/Population sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#16 A	Change in Capacity (Dmnl) = (Power Decommissioned+Power Installed)/INITIAL POWER INSTALLED Description: *This calculates the change in capacity over time.* Present in 3 views: • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Learning effect - This is the effect of learning and economies of scale on the unit price of electricity.
Default	GELA Model (Default)	#24 F,A	Electricity access loss rate (People/year) = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) Description: *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#25 F,A	Electricity access rate (People/year) = MAX(MIN((Population completion/Average Consumption per person), (Population without Electricity Access/TIME STEP)), 0) Description: *This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.* Present in 1 view: • Demand/Population sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#26 A	Electricity Price (US$/MWh) = Electricity Price in kWh/kWh to MWh conversion Description: *This is the actual electricity price which accounts for the effect of learning - it declines over time.* Present in 1 view: • Demand/Population sector Used by: • Price Change - It is the percentage change in price multiplied by the learning effect.
Default	GELA Model (Default)	#27 A	Electricity Price in kWh (US$/kWh) = REFERENCE ELECTRICITY PRICE in kWh*Learning effect Description: *This is the price per KWh of electricity.* Present in 1 view: • Demand/Population sector

			Used by: • Electricity Price - This is the actual electricity price which accounts for the effect of learning - it declines over time.
Default	GELA Model (Default)	#28 L	**Energy Generated (MWh)** $= \int$ Production completion - Production decommissioning dt + [INITIAL Generation] Description: *The total amount of energy generated in a year based on the capacity of power installed* Present in 2 views: • Supply/Power sector • Demand/Population sector Used by: • Peak power demand - The peak demand of Power based on the energy generated. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result. • Share of Hydro energy - This is the fraction of Hydro energy in the total energy generated. • Share of Solar energy - This is the fraction of Solar energy in the total energy generated. • Share of Thermal energy - This is the fraction of Thermal energy in the total energy generated.
Default	GELA Model (Default)	#38 L	**Ghana GDP (US$)** $= \int$ GDP Growth dt + [INITIAL GDP] Description: *This is the total GDP of Ghana for the model simulation time (2001 - 2030).* Present in 2 views: • Demand/Population sector • Capital/Investment sector Used by: • Budgeted investment - This is the annual budget designated for investment into power infrastructure. • GDP Growth - This is the yearly GDP growth (from the beginning to the final simulation time)
Default	GELA Model (Default)	#70 LI,I	**INITIAL POPULATION WITH ELECTRICITY ACCESS (People)** = INITIAL(1.2483e+007) Description: *This refers to the population with access in the base year.* Present in 1 view: • Demand/Population sector Used by: • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss.
Default	GELA Model (Default)	#71 LI,I	**INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (People)** = INITIAL(9.417e+006) Description: *This refers to the population without access in the base year.* Present in 1 view: • Demand/Population sector Used by: • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#78 C	**kWh to MWh conversion (MWh/kWh)** = 1000 Description: *It is the conversion of electricity from KWh to MWh.* Present in 1 view: • Demand/Population sector Used by: • Electricity Price - This is the actual electricity price which accounts for the effect of learning - it declines over time. • REFERENCE ELECTRICITY PRICE - This refers to the average price of electricity at the start time. (Estimated based on Trimbel et al. 2016 electricity cost in African countries)
Default	GELA Model (Default)	#79 A	**Learning effect (Dmnl)** = Change in Capacity^(LN(1-LEARNING RATE)/LN(2)) Description: *This is the effect of learning and economies of scale on the unit price of electricity.* Present in 1 view: • Demand/Population sector Used by: • Electricity Price in kWh - This is the price per KWh of electricity. • Price Change - It is the percentage change in price multiplied by the learning effect.
Default	GELA Model (Default)	#83 C	**LEARNING RATE (Dmnl)** = 0.1 Description: *It is the rate at which electricity price declines.* Present in 1 view: • Demand/Population sector Used by: • Learning effect - This is the effect of learning and economies of scale on the unit price of electricity.
Default	GELA Model (Default)	#87 C	**NET POPULATION GROWTH RATE (Dmnl/year)** = 0.026 Description: *The net population growth aggregates factors including deaths, births, and migration on the total population. The data for this parameter is obtained from worldometers (http://www.worldometers.info/world-population/africa-population/), which compute population growth in real time.* Present in 1 view: • Demand/Population sector

			Used by: • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.
Default	GELA Model (Default)	#92 F,A	**Population growth (People/year)** = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: *It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity.* **Present in 7 views:** • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector • General CLD **Used by:** • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#93 L	**Population with Electricity Access (People)** $= \int$ Electricity access rate - Electricity access loss rate dt + [INITIAL POPULATION WITH ELECTRICITY ACCESS] Description: *This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss.* **Present in 1 view:** • Demand/Population sector **Used by:** • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity. • Total Population - This is the total number of people in Ghana.
Default	GELA Model (Default)	#94 L	**Population without Electricity Access (People)** $= \int$ Electricity access loss rate + Population growth - Electricity access rate dt + [INITIAL POPULATION WITHOUT ELECTRICITY ACCESS] Description: *This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.* **Present in 1 view:** • Demand/Population sector **Used by:** • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases. • Total Population - This is the total number of people in Ghana.
Default	GELA Model (Default)	#100 A	**Price Change (Dmnl)** = (Electricity Price/REFERENCE ELECTRICITY PRICE)*Learning effect Description: *It is the percentage change in price multiplied by the learning effect.* **Present in 1 view:** • Demand/Population sector **Used by:** • Average Consumption per person - This is the product of average consumption per access person and the effect of price on consumption. As electricity price declines over time, the average amount of energy consumed per person is expected to increase in accordance with the economic principles of price and demand.
Default	GELA Model (Default)	#101 F,A	**Production completion (MWh/year)** = Hydro Production completion+Solar Production completion+Thermal Production completion Description: *The quantity of energy added annually. It also indicates how many connections would be gained as a result.* **Present in 2 views:** • Supply/Power sector • Demand/Population sector **Used by:** • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases. • Energy Generated - The total amount of energy generated in a year based on the capacity of power installed
Default	GELA Model (Default)	#102 F,A	**Production decommissioning (MWh/year)** = MIN((Hydro Production decommissioning+Solar Production decomissioning+Thermal Production decomissioning), (Energy Generated/Adjustment time)) Description: *The quantity of energy lost annually. It also indicates how many connections would be lost as a result.* **Present in 2 views:** • Supply/Power sector • Demand/Population sector

			Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Energy Generated - The total amount of energy generated in a year based on the capacity of power installed
Default	GELA Model (Default)	#103 A	REFERENCE ELECTRICITY PRICE (US$/MWh) = REFERENCE ELECTRICITY PRICE in kWh/kWh to MWh conversion Description: *This refers to the average price of electricity at the start time.(Estimated based on Trimbel et al. 2016 electricity cost in African countries)* Present in 1 view: • Demand/Population sector Used by: • Price Change - It is the percentage change in price multiplied by the learning effect.
Default	GELA Model (Default)	#104 C	REFERENCE ELECTRICITY PRICE in kWh (US$/kWh) = 0.2 Description: *This is the initial price of a KWh of electricity.* Present in 1 view: • Demand/Population sector Used by: • Electricity Price in kWh - This is the price per KWh of electricity. • REFERENCE ELECTRICITY PRICE - This refers to the average price of electricity at the start time. (Estimated based on Trimbel et al. 2016 electricity cost in African countries)
Default	Control	#155 C	TIME STEP (year [0,?]) = 0.0625 Description: *The time step for the simulation.* Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#156 A	Total electricity access rate (Dmnl) = Population with Electricity Access/Total Population Description: *This is the fraction of Ghanaians who have access to electricity.* Present in 2 views: • Demand/Population sector • Capital/Investment sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#157 A	Total Population (People) = Population with Electricity Access+Population without Electricity Access Description: *This is the total number of people in Ghana.* Present in 5 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector Used by: • Desired power Capacity - This is the total amount of power capacity desired at any given point in time. It takes into account the supply line, utilisation factor, average consumption per person, and the total population. • Population growth - It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. • Total electricity access rate - This is the fraction of Ghanaians who have access to electricity.

TOP

Capital/Investment sector (32 variables)

Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#1 A	Actual investment in Hydro (US$/year) = MIN(Anual investment in Hydro, Maximum possible investment in Hydro) Description: *The annual amount in US$ that is actually invested in Hydro power.* Present in 2 views: • Hydro Power sub-sector • Capital/Investment sector Used by: • Fractional investment in Hydro - The fraction of the total annual investment directed towards Hydro power • Hydro Capacity commencement - The amount of new Hydro power units commenced annually
Default			

	GELA Model (Default)	#2 C	Adjustment time (year) = 1 Description: *The time it takes to adjust capacity* Present in 4 views: • Hydro Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Backlog clearance - The rate at which the outstanding capacity is depleted through investment • Capacity completion - This is the annual amount of power capacity that is completed and commissioned for use. • Capacity decommissioning - It is the annual capacity that is scrapped or decommissiond because of depreciation. • Maximum possible investment in Hydro - It is the total amount in US$ that is required to develop the remaining Hydro power potential in Ghana. • Production decommissioning - The quantity of energy lost annually. It also indicates how many connections would be lost as a result.
Default	GELA Model (Default)	#3 A	Annual investment (US$/year) = MIN(Budgeted investment, Indicated Investment) Description: *This is the actual amount of investment made in power infrastructure, subject to budget and capacity requirement constraints.* Present in 1 view: • Capital/Investment sector Used by: • Annual investment in Solar - The annual amount in US$ invested in Solar power • Annual investment in Thermal - The annual amount in US$ invested in Thermal power • Anual investment in Hydro - This is the annual amount in US$ that is available for investment towards Hydro power. • Fractional investment in Hydro - The fraction of the total annual investment directed towards Hydro power
Default	GELA Model (Default)	#4 A	Annual investment in Solar (US$/year) = Annual investment*"Fractional investment in solar/renewables" Description: *The annual amount in US$ invested in Solar power* Present in 2 views: • Solar Power sub-sector • Capital/Investment sector Used by: • Solar Capacity commencement - The amount of new Solar power units commenced annually
Default	GELA Model (Default)	#5 A	Annual investment in Thermal (US$/year) = Annual investment*Fractional investment in Thermal Description: *The annual amount in US$ invested in Thermal power* Present in 2 views: • Thermal Power sub-sector • Capital/Investment sector Used by: • Thermal Capacity commencement - The amount of new Thermal power units commenced annually
Default	GELA Model (Default)	#6 A	Anual investment in Hydro (US$/year) = Annual investment*Maximum Hydro investment fraction Description: *This is the annual amount in US$ that is available for investment towards Hydro power.* Present in 2 views: • Hydro Power sub-sector • Capital/Investment sector Used by: • Actual investment in Hydro - The annual amount in US$ that is actually invested in Hydro power.
Default	GELA Model (Default)	#10 C	Average cost per MW (US$/MW) = 2e+006 Description: *The average cost for installing a MW unit of power* Present in 1 view: • Capital/Investment sector Used by: • Indicated Investment - This is the annual amount of investment that should be made towards power infrastructure based on the power capacity gap.
Default	GELA Model (Default)	#12 F,A	Budgeted investment (US$/year) = Ghana GDP*INVESTMENT RATE Description: *This is the annual budget designated for investment into power infrastructure.* Present in 1 view: • Capital/Investment sector Used by: • Annual investment - This is the actual amount of investment made in power infrastructure, subject to budget and capacity requirement constraints. • Cumulative Investment - It is the sum of annual investment made available for the power sector.
Default	GELA Model (Default)	#16 A	Change in Capacity (Dmnl) = (Power Decommissioned+Power Installed)/INITIAL POWER INSTALLED Description: *This calculates the change in capacity over time.* Present in 3 views: • Supply/Power sector

			• Demand/Population sector • Capital/Investment sector **Used by:** • Learning effect - This is the effect of learning and economies of scale on the unit price of electricity.
Default	GELA Model (Default)	#20 L	**Cumulative Investment (US$)** = ∫ Budgeted investment *dt* + [0] **Description:** *It is the sum of annual investment made available for the power sector.* **Present in 1 view:** • Capital/Investment sector **Used by:** • This is a supplementary variable.
Default	GELA Model (Default)	#24 F,A	**Electricity access loss rate (People/year)** = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP)) **Description:** *As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate.* **Present in 6 views:** • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector **Used by:** • Population with Electricity Access - This represents the total number of Ghanaians who have access to electricity at any given point in time. It increases with electricity connection, and decrease when there is connection loss. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#30 A	**Expected Capacity Addition (MW/year)** = (Population growth*AVERAGE CONSUMPTION PER ACCESS PERSON)/MW to MWh conversion Description: *This is the new power capacity required annually as a result of population growth.* **Present in 2 views:** • Supply/Power sector • Capital/Investment sector **Used by:** • Indicated Aquisition rate - The amount of power units required annually as a result of the capacity that would be decommissioned and population growth.
Default	GELA Model (Default)	#33 A	**Fractional investment in Hydro (Dmnl)** = (Actual investment in Hydro/Annual investment)-STEP(Actual investment in Hydro/Annual investment*HYDRO INVESTMENT SWITCH, 2019) Description: *The fraction of the total annual investment directed towards Hydro power* **Present in 1 view:** • Capital/Investment sector **Used by:** • "Fractional investment in solar/renewables" - The fraction of the total annual investment directed towards Solar power
Default	GELA Model (Default)	#34 A	**"Fractional investment in solar/renewables" (Dmnl)** = 1-(Fractional investment in Hydro+Fractional investment in Thermal) **Description:** *The fraction of the total annual investment directed towards Solar power* **Present in 1 view:** • Capital/Investment sector **Used by:** • Annual investment in Solar - The annual amount in US$ invested in Solar power
Default	GELA Model (Default)	#35 A	**Fractional investment in Thermal (Dmnl)** = 0.65+STEP(-THERMAL INVESTMENT SWITCH, 2019) **Description:** *The fraction of the total annual investment directed towards Thermal power* **Present in 1 view:** • Capital/Investment sector **Used by:** • Annual investment in Thermal - The annual amount in US$ invested in Thermal power • "Fractional investment in solar/renewables" - The fraction of the total annual investment directed towards Solar power
Default	GELA Model (Default)	#36 F,A	**GDP Growth (US$/year)** = Ghana GDP*GDP GROWTH RATE **Description:** *This is the yearly GDP growth (from the beginning to the final simulation time)* **Present in 1 view:** • Capital/Investment sector **Used by:** • Ghana GDP - This is the total GDP of Ghana for the model simulation time (2001 - 2030).
Default	GELA Model (Default)	#37 C	**GDP GROWTH RATE (Dmnl/year)** = 0.085 **Description:** *It is the average annual GDP growth rate in Ghana (African Economic Outlook 2016 and IMF*

			Economic Outlook, 2017)+RAMP(0.1, 2010, 2011)+RAMP(-0.035, 2011, 2014) Present in 1 view: • Capital/Investment sector Used by: • GDP Growth - This is the yearly GDP growth (from the beginning to the final simulation time)
Default	GELA Model (Default)	#38 L	Ghana GDP (US$) $= \int$ GDP Growth dt + [INITIAL GDP] Description: This is the total GDP of Ghana for the model simulation time (2001 - 2030). Present in 2 views: • Demand/Population sector • Capital/Investment sector Used by: • Budgeted investment - This is the annual budget designated for investment into power infrastructure. • GDP Growth - This is the yearly GDP growth (from the beginning to the final simulation time)
Default	GELA Model (Default)	#50 C	HYDRO INVESTMENT SWITCH (Dmnl [-0.25,0,0.01]) = 0 Description: This is the sensitivity parameter of Hydro investment fraction. Present in 1 view: • Capital/Investment sector Used by: • Fractional investment in Hydro - The fraction of the total annual investment directed towards Hydro power • Maximum Hydro investment fraction - This is the maximum fraction of investment that can be allocated towards Hydro power.
Default	GELA Model (Default)	#62 F,A	Indicated Annual capacity requirement (MW/year) = MAX((Supply Line Adjustment-Capacity commencement), 0) Description: It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line. Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • Power Backlog - It is the outstanding capacity needed at any given point in time of the simulation.
Default	GELA Model (Default)	#64 A	Indicated Investment (US$/year) = Average cost per MW*Supply Line Adjustment Description: This is the annual amount of investment that should be made towards power infrastructure based on the power capacity gap. Present in 1 view: • Capital/Investment sector Used by: • Annual investment - This is the actual amount of investment made in power infrastructure, subject to budget and capacity requirement constraints.
Default	GELA Model (Default)	#68 LI,C	INITIAL GDP (US$) = 2.04e+010 Description: This is the total GDP of Ghana in the base year. Present in 1 view: • Capital/Investment sector Used by: • Ghana GDP - This is the total GDP of Ghana for the model simulation time (2001 - 2030).
Default	GELA Model (Default)	#77 C	INVESTMENT RATE (Dmnl/year [0,1,0.001]) = 0.014 Description: It is the average annual fraction of GDP that is investment in the power sector.(Rosnes and Vennemo, 2008. Africa's power infrastructure: investment, integration, efficiency. World Bank Publications). Present in 1 view: • Capital/Investment sector Used by: • Budgeted investment - This is the annual budget designated for investment into power infrastructure.
Default	GELA Model (Default)	#84 A	Maximum Hydro investment fraction (Dmnl) = 0.35+STEP(-0.1, 2013)+STEP(HYDRO INVESTMENT SWITCH, 2019) Description: This is the maximum fraction of investment that can be allocated towards Hydro power. Present in 1 view: • Capital/Investment sector Used by: • Anual investment in Hydro - This is the annual amount in US$ that is available for investment towards Hydro power.
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector

			• Capital/Investment sector • General CLD Used by: • Expected Capacity Addition - This is the new power capacity required annually as a result of population growth. • Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.
Default	GELA Model (Default)	#96 A	Power Capacity Gap (MW) = MAX(Desired power Capacity-Power Installed-Power Construction, 0) Description: It is the difference between desired and actual power capacity. Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#109 A	Share of Solar Power (Dmnl) = Solar Power Installed/Power Installed Description: This is the fraction of Solar power in the total power installed. Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • This is a supplementary variable.
Default	GELA Model (Default)	#132 A	Supply Line Adjustment (MW/year) = Desired Acquisition rate/SUPPLY LINE ADJUSTMENT TIME Description: It is the annual new power capacity required after accounting for the delay in the supply line. Present in 2 views: • Supply/Power sector • Capital/Investment sector Used by: • Indicated Annual capacity requirement - It is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity after accounting for the supply line. • Indicated Investment - This is the annual amount of investment that should be made towards power infrastructure based on the power capacity gap.
Default	GELA Model (Default)	#145 C	THERMAL INVESTMENT SWITCH (Dmnl [0,0.65,0.01]) = 0 Description: This is the sensitivity parameter of Thermal investment fraction. Present in 1 view: • Capital/Investment sector Used by: • Fractional investment in Thermal - The fraction of the total annual investment directed towards Thermal power
Default	Control	#155 C	TIME STEP (year [0,?]) = 0.0625 Description: The time step for the simulation. Present in 6 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector • Supply/Power sector • Demand/Population sector • Capital/Investment sector Used by: • Electricity access loss rate - As power plants deteriorates and eventually get decommissioned, some people would lose access and become part of the population without access. This conceptualisation is captured by the connection loss rate. • Electricity access rate - This represents the yearly number of people who gain access to electricity. It increases when the plant completion rate increases and/or the consumption per access decreases.
Default	GELA Model (Default)	#156 A	Total electricity access rate (Dmnl) = Population with Electricity Access/Total Population Description: This is the fraction of Ghanaians who have access to electricity. Present in 2 views: • Demand/Population sector • Capital/Investment sector Used by: • This is a supplementary variable.

TOP

General CLD (1 variables)

Module	Group	Type	Variable Name and Description
Default	GELA Model (Default)	#92 F,A	Population growth (People/year) = MAX((Total Population*NET POPULATION GROWTH RATE), 0) Description: It refers to the net increment in the total population after taking into account net migration, births, and deaths. This additional population is counted as part of the population without electricity. Present in 7 views: • Hydro Power sub-sector • Thermal Power sub-sector • Solar Power sub-sector

- Supply/Power sector
- Demand/Population sector
- Capital/Investment sector
- General CLD

Used by:

- Expected Capacity Addition - This is the new power capacity required annually as a result of population growth.
- Population without Electricity Access - This represents the total number of Ghanaians without electricity access at any given point in time. It increases with population growth and connection loss, and decreases with electricity connection.

TOP	Results - A (0 variables)		
Module	Group	Type	Variable Name and Description
TOP	Results	B (0	variables)
Module	Group	Type	Variable Name and Description

List of 13 Supplementary Variables

Module	Group	Type	Variable (13)
Default	GELA Model	L	Cumulative Investment (US$)
Default	GELA Model	A	Peak power demand (MW)
Default	GELA Model	A	"Peak power demand - Hydro" (MW)
Default	GELA Model	A	"Peak power demand - Solar" (MW)
Default	GELA Model	A	"Peak power demand - Thermal" (MW)
Default	GELA Model	A	Power Capacity Gap (MW)
Default	GELA Model	A	Share of Hydro energy (Dmnl)
Default	GELA Model	A	Share of Hydro power (Dmnl)
Default	GELA Model	A	Share of Solar energy (Dmnl)
Default	GELA Model	A	Share of Solar Power (Dmnl)
Default	GELA Model	A	Share of Thermal energy (Dmnl)
Default	GELA Model	A	Share of Thermal Power (Dmnl)
Default	GELA Model	A	Total electricity access rate (Dmnl)

List of 11 Variables Using MIN or MAX Functions

Module	Group	Type	Variable (11)
Default	GELA Model	A	Actual investment in Hydro (US$/year)
Default	GELA Model	A	Annual investment (US$/year)
Default	GELA Model	F,A	Backlog clearance (MW/year)
Default	GELA Model	F,A	Capacity completion (MW/year)
Default	GELA Model	F,A	Capacity decommissioning (MW/year)
Default	GELA Model	F,A	Electricity access loss rate (People/year)
Default	GELA Model	F,A	Electricity access rate (People/year)
Default	GELA Model	F,A	Indicated Annual capacity requirement (MW/year)
Default	GELA Model	F,A	Population growth (People/year)
Default	GELA Model	A	Power Capacity Gap (MW)
Default	GELA Model	F,A	Production decommissioning (MWh/year)

List of 145 Variables Without Predefined Min or Max Values

Module	Group	Type	Variable (145)
Default	GELA Model	A	Actual investment in Hydro (US$/year)
Default	GELA Model	C	Adjustment time (year)
Default	GELA Model	A	Annual investment (US$/year)
Default	GELA Model	A	Annual investment in Solar (US$/year)
Default	GELA Model	A	Annual investment in Thermal (US$/year)
Default	GELA Model	A	Anual investment in Hydro (US$/year)
Default	GELA Model	A	Available Hydro potential (MW)
Default	GELA Model	C	AVERAGE CONSUMPTION PER ACCESS PERSON (MWh/People)
Default	GELA Model	A	Average Consumption per person (MWh/People)
Default	GELA Model	C	Average cost per MW (US$/MW)
Default	GELA Model	F,A	Backlog clearance (MW/year)
Default	GELA Model	F,A	Budgeted investment (US$/year)
Default	GELA Model	F,A	Capacity commencement (MW/year)
Default	GELA Model	F,A	Capacity completion (MW/year)
Default	GELA Model	F,A	Capacity decommissioning (MW/year)
Default	GELA Model	A	Change in Capacity (Dmnl)
Default	GELA Model	A	Cost per MW Hydro (US$/MW)
Default	GELA Model	A	Cost per MW Solar (US$/MW)
Default	GELA Model	A	Cost per MW Thermal (US$/MW)
Default	GELA Model	L	Cumulative Investment (US$)
Default	GELA Model	A	Desired Acquisition rate (MW)
Default	GELA Model	A	Desired power Capacity (MW)
Default	GELA Model	C	Effect of plant size on Hydro cost (Dmnl)
Default	GELA Model	F,A	Electricity access loss rate (People/year)
Default	GELA Model	F,A	Electricity access rate (People/year)
Default	GELA Model	A	Electricity Price (US$/MWh)
Default	GELA Model	A	Electricity Price in kWh (US$/kWh)

Default	GELA Model	L	Energy Generated (MWh)
Default	GELA Model	C	EXPECTED ACQUISITION DELAY (year)
Default	GELA Model	A	Expected Capacity Addition (MW/year)
Default	GELA Model	A	Expected Capacity Loss (MW/year)
Default	Control	C	FINAL TIME (year)
Default	GELA Model	A	Fractional investment in Hydro (Dmnl)
Default	GELA Model	A	"Fractional investment in solar/renewables" (Dmnl)
Default	GELA Model	A	Fractional investment in Thermal (Dmnl)
Default	GELA Model	F,A	GDP Growth (US$/year)
Default	GELA Model	C	GDP GROWTH RATE (Dmnl/year)
Default	GELA Model	L	Ghana GDP (US$)
Default	GELA Model	F,A	Hydro Capacity commencement (MW/year)
Default	GELA Model	F,A	Hydro Capacity completion (MW/year)
Default	GELA Model	F,A	Hydro Capacity decommissioning (MW/year)
Default	GELA Model	A	Hydro Change in Capacity (Dmnl)
Default	GELA Model	C	Hydro CONSTRUCTION TIME (year)
Default	GELA Model	L	Hydro Energy Generated (MWh)
Default	GELA Model	LI,I	Hydro INITIAL Generation (MWh)
Default	GELA Model	LI,C	Hydro INITIAL POWER CONSTRUCTION (MW)
Default	GELA Model	LI,C	Hydro INITIAL POWER DECOMMISSIONED (MW)
Default	GELA Model	LI,I	Hydro INITIAL POWER INSTALLED (MW)
Default	GELA Model	C	Hydro Learning rate (Dmnl)
Default	GELA Model	C	Hydro MW to MWh conversion (MWh/MW)
Default	GELA Model	A	Hydro potential developed (MW)
Default	GELA Model	C	Hydro potential total (MW)
Default	GELA Model	L	Hydro Power Construction (MW)
Default	GELA Model	L	Hydro Power Decommissioned (MW)
Default	GELA Model	L	Hydro Power Installed (MW)
Default	GELA Model	F,A	Hydro Production completion (MWh/year)
Default	GELA Model	F,A	Hydro Production decommissioning (MWh/year)
Default	GELA Model	F,A	Indicated Annual capacity requirement (MW/year)
Default	GELA Model	A	Indicated Aquisition rate (MW/year)
Default	GELA Model	A	Indicated Investment (US$/year)
Default	GELA Model	C	Initial Cost Per MW Hydro (US$/MW)
Default	GELA Model	C	Initial Cost Per MW Solar (US$/MW)
Default	GELA Model	C	Initial Cost Per MW Thermal (US$/MW)
Default	GELA Model	LI,C	INITIAL GDP (US$)
Default	GELA Model	LI,I	INITIAL Generation (MWh)
Default	GELA Model	LI,I	INITIAL POPULATION WITH ELECTRICITY ACCESS (People)
Default	GELA Model	LI,I	INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (People)
Default	GELA Model	LI,C	INITIAL POWER BACKLOG (MW)
Default	GELA Model	LI,C	INITIAL POWER CONSTRUCTION (MW)
Default	GELA Model	LI,C	INITIAL POWER DECOMMISSIONED (MW)
Default	GELA Model	LI,I	INITIAL POWER INSTALLED (MW)
Default	Control	C	INITIAL TIME (year)
Default	GELA Model	C	kWh to MWh conversion (MWh/kWh)
Default	GELA Model	A	Learning effect (Dmnl)
Default	GELA Model	A	Learning effect on Hydro (Dmnl)
Default	GELA Model	A	Learning effect on Solar (Dmnl)
Default	GELA Model	A	Learning effect on Thermal (Dmnl)
Default	GELA Model	C	LEARNING RATE (Dmnl)
Default	GELA Model	A	Maximum Hydro investment fraction (Dmnl)
Default	GELA Model	A	Maximum possible investment in Hydro (US$/year)
Default	GELA Model	C	MW to MWh conversion (MWh/MW)
Default	GELA Model	C	NET POPULATION GROWTH RATE (Dmnl/year)
Default	GELA Model	A	Peak power demand (MW)
Default	GELA Model	A	"Peak power demand - Hydro" (MW)
Default	GELA Model	A	"Peak power demand - Solar" (MW)
Default	GELA Model	A	"Peak power demand - Thermal" (MW)
Default	GELA Model	F,A	Population growth (People/year)
Default	GELA Model	L	Population with Electricity Access (People)
Default	GELA Model	L	Population without Electricity Access (People)
Default	GELA Model	L	Power Backlog (MW)
Default	GELA Model	A	Power Capacity Gap (MW)
Default	GELA Model	L	Power Construction (MW)
Default	GELA Model	L	Power Decommissioned (MW)
Default	GELA Model	L	Power Installed (MW)
Default	GELA Model	A	Price Change (Dmnl)
Default	GELA Model	F,A	Production completion (MWh/year)
Default	GELA Model	F,A	Production decommissioning (MWh/year)
Default	GELA Model	A	REFERENCE ELECTRICITY PRICE (US$/MWh)
Default	GELA Model	C	REFERENCE ELECTRICITY PRICE in kWh (US$/kWh)
Default	GELA Model	A	Share of Hydro energy (Dmnl)
Default	GELA Model	A	Share of Hydro power (Dmnl)
Default	GELA Model	A	Share of Solar energy (Dmnl)
Default	GELA Model	A	Share of Solar Power (Dmnl)
Default	GELA Model	A	Share of Thermal energy (Dmnl)
Default	GELA Model	A	Share of Thermal Power (Dmnl)
Default	GELA Model	F,A	Solar Capacity commencement (MW/year)

Default	GELA Model	F,A	Solar Capacity completion (MW/year)
Default	GELA Model	F,A	Solar Capacity decommissioning (MW/year)
Default	GELA Model	A	Solar Change in Capacity (Dmnl)
Default	GELA Model	C	Solar CONSTRUCTION TIME (year)
Default	GELA Model	L	Solar Energy Generated (MWh)
Default	GELA Model	LI,I	Solar INITIAL Generation (MWh)
Default	GELA Model	LI,C	Solar INITIAL POWER CONSTRUCTION (MW)
Default	GELA Model	LI,C	Solar INITIAL POWER DECOMMISSIONED (MW)
Default	GELA Model	LI,I	Solar INITIAL POWER INSTALLED (MW)
Default	GELA Model	C	Solar Learning rate (Dmnl)
Default	GELA Model	C	Solar MW to MWh conversion (MWh/MW)
Default	GELA Model	L	Solar Power Construction (MW)
Default	GELA Model	L	Solar Power Decommissioned (MW)
Default	GELA Model	L	Solar Power Installed (MW)
Default	GELA Model	F,A	Solar Production completion (MWh/year)
Default	GELA Model	F,A	Solar Production decomissioning (MWh/year)
Default	GELA Model	A	Solar UTILISATION FACTOR (Dmnl)
Default	GELA Model	A	Supply Line Adjustment (MW/year)
Default	GELA Model	C	SUPPLY LINE ADJUSTMENT TIME (year)
Default	GELA Model	F,A	Thermal Capacity commencement (MW/year)
Default	GELA Model	F,A	Thermal Capacity completion (MW/year)
Default	GELA Model	F,A	Thermal Capacity decommissioning (MW/year)
Default	GELA Model	A	Thermal Change in Capacity (Dmnl)
Default	GELA Model	C	Thermal CONSTRUCTION TIME (year)
Default	GELA Model	L	Thermal Energy Generated (MWh)
Default	GELA Model	LI,I	Thermal INITIAL Generation (MWh)
Default	GELA Model	LI,C	Thermal INITIAL POWER CONSTRUCTION (MW)
Default	GELA Model	LI,C	Thermal INITIAL POWER DECOMMISSIONED (MW)
Default	GELA Model	LI,I	Thermal INITIAL POWER INSTALLED (MW)
Default	GELA Model	C	Thermal Learning rate (Dmnl)
Default	GELA Model	C	Thermal MW to MWh conversion (MWh/MW)
Default	GELA Model	L	Thermal Power Construction (MW)
Default	GELA Model	L	Thermal Power Decommissioned (MW)
Default	GELA Model	L	Thermal Power Installed (MW)
Default	GELA Model	F,A	Thermal Production completion (MWh/year)
Default	GELA Model	F,A	Thermal Production decomissioning (MWh/year)
Default	GELA Model	A	Total electricity access rate (Dmnl)
Default	GELA Model	A	Total Population (People)
Default	GELA Model	C	UTILISATION FACTOR (Dmnl)

List of 7 Variables with "Step", "Pulse", or related functions.

Module	Group	Type	Variable (7)
Default	GELA Model	A	Fractional investment in Hydro (Dmnl)
Default	GELA Model	A	Fractional investment in Thermal (Dmnl)
Default	GELA Model	F,A	Hydro Production completion (MWh/year)
Default	GELA Model	A	Maximum Hydro investment fraction (Dmnl)
Default	GELA Model	F,A	Solar Production completion (MWh/year)
Default	GELA Model	A	Solar UTILISATION FACTOR (Dmnl)
Default	GELA Model	F,A	Thermal Production completion (MWh/year)

Formulation Complexity Summary (Violations of Richardson's Rule)

Module	Group	Type	Variable	Complexity Score
Default	GELA Model	F,A	Electricity access rate (People/year)	4
Default	GELA Model	L	Population without Electricity Access (People)	4
Default	GELA Model	F,A	Electricity access loss rate (People/year)	4
Default	GELA Model	F,A	Solar Production completion (MWh/year)	4
Default	GELA Model	F,A	Thermal Production completion (MWh/year)	4
Default	GELA Model	F,A	Hydro Production completion (MWh/year)	4
Default	GELA Model	F,A	Capacity decommissioning (MW/year)	5
Default	GELA Model	A	Desired power Capacity (MW)	5
Default	GELA Model	F,A	Production decommissioning (MWh/year)	5
Default	GELA Model	F,A	Capacity completion (MW/year)	5

List of 19 Equations with Embedded Data (0 and 1 constants ignored)

Module	Group	Type	Variable (19)
Default	GELA Model	A	Fractional investment in Hydro (Dmnl)
Default	GELA Model	A	Fractional investment in Thermal (Dmnl)
Default	GELA Model	LI,I	Hydro INITIAL Generation (MWh)
Default	GELA Model	LI,I	Hydro INITIAL POWER INSTALLED (MW)
Default	GELA Model	F,A	Hydro Production completion (MWh/year)
Default	GELA Model	LI,I	INITIAL Generation (MWh)
Default	GELA Model	LI,I	INITIAL POPULATION WITH ELECTRICITY ACCESS (People)
Default	GELA Model	LI,I	INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (People)
Default	GELA Model	LI,I	INITIAL POWER INSTALLED (MW)
Default	GELA Model	A	Learning effect (Dmnl)
Default	GELA Model	A	Learning effect on Hydro (Dmnl)
Default	GELA Model	A	Learning effect on Solar (Dmnl)
Default	GELA Model	A	Learning effect on Thermal (Dmnl)
Default	GELA Model	A	Maximum Hydro investment fraction (Dmnl)

Default	GELA Model	F,A	Solar Production completion (MWh/year)
Default	GELA Model	A	Solar UTILISATION FACTOR (Dmnl)
Default	GELA Model	LI,I	Thermal INITIAL Generation (MWh)
Default	GELA Model	LI,I	Thermal INITIAL POWER INSTALLED (MW)
Default	GELA Model	F,A	Thermal Production completion (MWh/year)

List of 21 State Variables

Module	Group	Type	Variable
Default	GELA Model	L	Cumulative Investment (US$)
Default	GELA Model	L	Energy Generated (MWh)
Default	GELA Model	L	Ghana GDP (US$)
Default	GELA Model	L	Hydro Energy Generated (MWh)
Default	GELA Model	L	Hydro Power Construction (MW)
Default	GELA Model	L	Hydro Power Decommissioned (MW)
Default	GELA Model	L	Hydro Power Installed (MW)
Default	GELA Model	L	Population with Electricity Access (People)
Default	GELA Model	L	Population without Electricity Access (People)
Default	GELA Model	L	Power Backlog (MW)
Default	GELA Model	L	Power Construction (MW)
Default	GELA Model	L	Power Decommissioned (MW)
Default	GELA Model	L	Power Installed (MW)
Default	GELA Model	L	Solar Energy Generated (MWh)
Default	GELA Model	L	Solar Power Construction (MW)
Default	GELA Model	L	Solar Power Decommissioned (MW)
Default	GELA Model	L	Solar Power Installed (MW)
Default	GELA Model	L	Thermal Energy Generated (MWh)
Default	GELA Model	L	Thermal Power Construction (MW)
Default	GELA Model	L	Thermal Power Decommissioned (MW)
Default	GELA Model	L	Thermal Power Installed (MW)

List of 7 Views and Their 158 Variables

Hydro Power sub-sector	42 vars (26.6%)
Thermal Power sub-sector	34 vars (21.5%)
Solar Power sub-sector	35 vars (22.2%)
Supply/Power sector	73 vars (46.2%)
Demand/Population sector	29 vars (18.4%)
Capital/Investment sector	32 vars (20.3%)
General CLD	1 vars (0.6%)

	Hydro Power sub-sector	Thermal Power sub-sector	Solar Power sub-sector	Supply/Power sector	Demand/Population sector	Capital/Investment sector	General CLD	
Total:	42	34	35	73	29	32	1	:Total
Actual investment in Hydro (in 2 views)	X					X		Actual investment in Hydro (in 2 views)
Adjustment time (in 4 views)	X			X	X	X		Adjustment time (in 4 views)
Annual investment (in 1 view)						X		Annual investment (in 1 view)
Annual investment in Solar (in 2 views)			X			X		Annual investment in Solar (in 2 views)
Annual investment in Thermal (in 2 views)		X				X		Annual investment in Thermal (in 2 views)
Anual investment in Hydro (in 2 views)	X					X		Anual investment in Hydro (in 2 views)
Available Hydro potential (in 1 view)	X							Available Hydro potential (in 1 view)
AVERAGE CONSUMPTION PER ACCESS PERSON (in 5 views)	X	X	X	X	X			AVERAGE CONSUMPTION PER ACCESS PERSON (in 5 views)
Average Consumption per person (in 1 view)					X			Average Consumption per person (in 1 view)
Average cost per MW (in 1 view)						X		Average cost per MW (in 1 view)
Backlog clearance (in 1 view)				X				Backlog clearance (in 1 view)
Budgeted investment (in 1 view)						X		Budgeted investment (in 1 view)
				X				

Capacity commencement (in 1 view)								Capacity commencement (in 1 view)
Capacity completion (in 1 view)				X				Capacity completion (in 1 view)
Capacity decommissioning (in 1 view)				X				Capacity decommissioning (in 1 view)
Change in Capacity (in 3 views)				X	X	X		Change in Capacity (in 3 views)
Cost per MW Hydro (in 1 view)	X							Cost per MW Hydro (in 1 view)
Cost per MW Solar (in 1 view)			X					Cost per MW Solar (in 1 view)
Cost per MW Thermal (in 1 view)		X						Cost per MW Thermal (in 1 view)
Cumulative Investment (in 1 view)						X		Cumulative Investment (in 1 view)
Desired Acquisition rate (in 1 view)				X				Desired Acquisition rate (in 1 view)
Desired power Capacity (in 1 view)				X				Desired power Capacity (in 1 view)
Effect of plant size on Hydro cost (in 1 view)	X							Effect of plant size on Hydro cost (in 1 view)
Electricity access loss rate (in 6 views)	X	X	X	X	X	X		Electricity access loss rate (in 6 views)
Electricity access rate (in 1 view)					X			Electricity access rate (in 1 view)
Electricity Price (in 1 view)					X			Electricity Price (in 1 view)
Electricity Price in kWh (in 1 view)					X			Electricity Price in kWh (in 1 view)
Energy Generated (in 2 views)				X	X			Energy Generated (in 2 views)
EXPECTED ACQUISITION DELAY (in 1 view)				X				EXPECTED ACQUISITION DELAY (in 1 view)
Expected Capacity Addition (in 2 views)				X		X		Expected Capacity Addition (in 2 views)
Expected Capacity Loss (in 1 view)				X				Expected Capacity Loss (in 1 view)
FINAL TIME (in 0 views)								FINAL TIME (in 0 views)
Fractional investment in Hydro (in 1 view)						X		Fractional investment in Hydro (in 1 view)
Fractional investment in solar/renewables (in 1 view)						X		Fractional investment in solar/renewables (in 1 view)
Fractional investment in Thermal (in 1 view)						X		Fractional investment in Thermal (in 1 view)
GDP Growth (in 1 view)						X		GDP Growth (in 1 view)
GDP GROWTH RATE (in 1 view)						X		GDP GROWTH RATE (in 1 view)
Ghana GDP (in 2 views)					X	X		Ghana GDP (in 2 views)
Hydro AVERAGE PLANT LIFE (in 1 view)	X							Hydro AVERAGE PLANT LIFE (in 1 view)
Hydro Capacity commencement (in 2 views)	X			X				Hydro Capacity commencement (in 2 views)
Hydro Capacity completion (in 2 views)	X			X				Hydro Capacity completion (in 2 views)
Hydro Capacity decommissioning (in 2 views)	X			X				Hydro Capacity decommissioning (in 2 views)
Hydro Change in Capacity (in 1 view)	X							Hydro Change in Capacity (in 1 view)
Hydro CONSTRUCTION TIME (in 1 view)	X							Hydro CONSTRUCTION TIME (in 1 view)
Hydro Energy Generated (in 2 views)	X			X				Hydro Energy Generated (in 2 views)
	X							

Hydro INITIAL Generation (in 1 view)								Hydro INITIAL Generation (in 1 view)
Hydro INITIAL POWER CONSTRUCTION (in 1 view)	X							Hydro INITIAL POWER CONSTRUCTION (in 1 view)
Hydro INITIAL POWER DECOMMISSIONED (in 1 view)	X							Hydro INITIAL POWER DECOMMISSIONED (in 1 view)
Hydro INITIAL POWER INSTALLED (in 1 view)	X							Hydro INITIAL POWER INSTALLED (in 1 view)
HYDRO INVESTMENT SWITCH (in 1 view)						X		HYDRO INVESTMENT SWITCH (in 1 view)
Hydro Learning rate (in 1 view)	X							Hydro Learning rate (in 1 view)
Hydro MW to MWh conversion (in 1 view)	X							Hydro MW to MWh conversion (in 1 view)
Hydro potential developed (in 1 view)	X							Hydro potential developed (in 1 view)
Hydro potential total (in 1 view)	X							Hydro potential total (in 1 view)
Hydro Power Construction (in 1 view)	X							Hydro Power Construction (in 1 view)
Hydro Power Decommissioned (in 1 view)	X							Hydro Power Decommissioned (in 1 view)
Hydro Power Installed (in 2 views)	X			X				Hydro Power Installed (in 2 views)
Hydro Production completion (in 2 views)	X			X				Hydro Production completion (in 2 views)
Hydro Production decommissioning (in 2 views)	X			X				Hydro Production decommissioning (in 2 views)
Hydro SENSITIVITY OF UTILISATION FACTOR (in 1 view)	X							Hydro SENSITIVITY OF UTILISATION FACTOR (in 1 view)
Hydro UTILISATION FACTOR (in 1 view)	X							Hydro UTILISATION FACTOR (in 1 view)
Indicated Annual capacity requirement (in 2 views)				X		X		Indicated Annual capacity requirement (in 2 views)
Indicated Aquisition rate (in 1 view)				X				Indicated Aquisition rate (in 1 view)
Indicated Investment (in 1 view)						X		Indicated Investment (in 1 view)
Initial Cost Per MW Hydro (in 1 view)	X							Initial Cost Per MW Hydro (in 1 view)
Initial Cost Per MW Solar (in 1 view)			X					Initial Cost Per MW Solar (in 1 view)
Initial Cost Per MW Thermal (in 1 view)		X						Initial Cost Per MW Thermal (in 1 view)
INITIAL GDP (in 1 view)						X		INITIAL GDP (in 1 view)
INITIAL Generation (in 1 view)				X				INITIAL Generation (in 1 view)
INITIAL POPULATION WITH ELECTRICITY ACCESS (in 1 view)					X			INITIAL POPULATION WITH ELECTRICITY ACCESS (in 1 view)
INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (in 1 view)					X			INITIAL POPULATION WITHOUT ELECTRICITY ACCESS (in 1 view)
INITIAL POWER BACKLOG (in 1 view)				X				INITIAL POWER BACKLOG (in 1 view)
INITIAL POWER CONSTRUCTION (in 1 view)				X				INITIAL POWER CONSTRUCTION (in 1 view)
INITIAL POWER DECOMMISSIONED (in 1 view)				X				INITIAL POWER DECOMMISSIONED (in 1 view)

INITIAL POWER INSTALLED (in 1 view)				X				INITIAL POWER INSTALLED (in 1 view)
INITIAL TIME (in 0 views)								INITIAL TIME (in 0 views)
INVESTMENT RATE (in 1 view)						X		INVESTMENT RATE (in 1 view)
kWh to MWh conversion (in 1 view)					X			kWh to MWh conversion (in 1 view)
Learning effect (in 1 view)					X			Learning effect (in 1 view)
Learning effect on Hydro (in 1 view)	X							Learning effect on Hydro (in 1 view)
Learning effect on Solar (in 1 view)			X					Learning effect on Solar (in 1 view)
Learning effect on Thermal (in 1 view)		X						Learning effect on Thermal (in 1 view)
LEARNING RATE (in 1 view)					X			LEARNING RATE (in 1 view)
Maximum Hydro investment fraction (in 1 view)						X		Maximum Hydro investment fraction (in 1 view)
Maximum possible investment in Hydro (in 1 view)	X							Maximum possible investment in Hydro (in 1 view)
MW to MWh conversion (in 1 view)				X				MW to MWh conversion (in 1 view)
NET POPULATION GROWTH RATE (in 1 view)					X			NET POPULATION GROWTH RATE (in 1 view)
Peak power demand (in 1 view)				X				Peak power demand (in 1 view)
Peak power demand - Hydro (in 1 view)	X							Peak power demand - Hydro (in 1 view)
Peak power demand - Solar (in 1 view)			X					Peak power demand - Solar (in 1 view)
Peak power demand - Thermal (in 1 view)		X						Peak power demand - Thermal (in 1 view)
Population growth (in 7 views)	X	X	X	X	X	X	X	Population growth (in 7 views)
Population with Electricity Access (in 1 view)					X			Population with Electricity Access (in 1 view)
Population without Electricity Access (in 1 view)					X			Population without Electricity Access (in 1 view)
Power Backlog (in 1 view)				X				Power Backlog (in 1 view)
Power Capacity Gap (in 2 views)				X		X		Power Capacity Gap (in 2 views)
Power Construction (in 1 view)				X				Power Construction (in 1 view)
Power Decommissioned (in 1 view)				X				Power Decommissioned (in 1 view)
Power Installed (in 1 view)				X				Power Installed (in 1 view)
Price Change (in 1 view)					X			Price Change (in 1 view)
Production completion (in 2 views)				X	X			Production completion (in 2 views)
Production decommissioning (in 2 views)				X	X			Production decommissioning (in 2 views)
REFERENCE ELECTRICITY PRICE (in 1 view)					X			REFERENCE ELECTRICITY PRICE (in 1 view)
REFERENCE ELECTRICITY PRICE in kWh (in 1 view)					X			REFERENCE ELECTRICITY PRICE in kWh (in 1 view)
SAVEPER (in 0 views)								SAVEPER (in 0 views)
Share of Hydro energy (in 1 view)				X				Share of Hydro energy (in 1 view)
Share of Hydro power (in 1 view)				X				Share of Hydro power (in 1 view)
Share of Solar energy (in 1 view)				X				Share of Solar energy (in 1 view)

Share of Solar Power (in 2 views)				X		X		Share of Solar Power (in 2 views)
Share of Thermal energy (in 1 view)				X				Share of Thermal energy (in 1 view)
Share of Thermal Power (in 1 view)				X				Share of Thermal Power (in 1 view)
Solar AVERAGE PLANT LIFE (in 1 view)			X					Solar AVERAGE PLANT LIFE (in 1 view)
Solar Capacity commencement (in 2 views)			X	X				Solar Capacity commencement (in 2 views)
Solar Capacity completion (in 2 views)			X	X				Solar Capacity completion (in 2 views)
Solar Capacity decommissioning (in 2 views)			X	X				Solar Capacity decommissioning (in 2 views)
Solar Change in Capacity (in 1 view)			X					Solar Change in Capacity (in 1 view)
Solar CONSTRUCTION TIME (in 1 view)			X					Solar CONSTRUCTION TIME (in 1 view)
Solar Energy Generated (in 2 views)			X	X				Solar Energy Generated (in 2 views)
Solar INITIAL Generation (in 1 view)			X					Solar INITIAL Generation (in 1 view)
Solar INITIAL POWER CONSTRUCTION (in 1 view)			X					Solar INITIAL POWER CONSTRUCTION (in 1 view)
Solar INITIAL POWER DECOMMISSIONED (in 1 view)			X					Solar INITIAL POWER DECOMMISSIONED (in 1 view)
Solar INITIAL POWER INSTALLED (in 1 view)			X					Solar INITIAL POWER INSTALLED (in 1 view)
Solar Learning rate (in 1 view)			X					Solar Learning rate (in 1 view)
Solar MW to MWh conversion (in 1 view)			X					Solar MW to MWh conversion (in 1 view)
Solar Power Construction (in 1 view)			X					Solar Power Construction (in 1 view)
Solar Power Decommissioned (in 1 view)			X					Solar Power Decommissioned (in 1 view)
Solar Power Installed (in 2 views)			X	X				Solar Power Installed (in 2 views)
Solar Production completion (in 2 views)			X	X				Solar Production completion (in 2 views)
Solar Production decomissioning (in 2 views)			X	X				Solar Production decomissioning (in 2 views)
Solar SENSITIVITY OF UTILISATION FACTOR (in 1 view)			X					Solar SENSITIVITY OF UTILISATION FACTOR (in 1 view)
Solar UTILISATION FACTOR (in 1 view)			X					Solar UTILISATION FACTOR (in 1 view)
Supply Line Adjustment (in 2 views)				X		X		Supply Line Adjustment (in 2 views)
SUPPLY LINE ADJUSTMENT TIME (in 1 view)				X				SUPPLY LINE ADJUSTMENT TIME (in 1 view)
Thermal AVERAGE PLANT LIFE (in 1 view)		X						Thermal AVERAGE PLANT LIFE (in 1 view)
Thermal Capacity commencement (in 2 views)		X		X				Thermal Capacity commencement (in 2 views)
Thermal Capacity completion (in 2 views)		X		X				Thermal Capacity completion (in 2 views)
		X		X				

Thermal Capacity decommissioning (in 2 views)								Thermal Capacity decommissioning (in 2 views)
Thermal Change in Capacity (in 1 view)		X						Thermal Change in Capacity (in 1 view)
Thermal CONSTRUCTION TIME (in 1 view)		X						Thermal CONSTRUCTION TIME (in 1 view)
Thermal Energy Generated (in 2 views)		X		X				Thermal Energy Generated (in 2 views)
Thermal INITIAL Generation (in 1 view)		X						Thermal INITIAL Generation (in 1 view)
Thermal INITIAL POWER CONSTRUCTION (in 1 view)		X						Thermal INITIAL POWER CONSTRUCTION (in 1 view)
Thermal INITIAL POWER DECOMMISSIONED (in 1 view)		X						Thermal INITIAL POWER DECOMMISSIONED (in 1 view)
Thermal INITIAL POWER INSTALLED (in 1 view)		X						Thermal INITIAL POWER INSTALLED (in 1 view)
THERMAL INVESTMENT SWITCH (in 1 view)						X		THERMAL INVESTMENT SWITCH (in 1 view)
Thermal Learning rate (in 1 view)		X						Thermal Learning rate (in 1 view)
Thermal MW to MWh conversion (in 1 view)		X						Thermal MW to MWh conversion (in 1 view)
Thermal Power Construction (in 1 view)		X						Thermal Power Construction (in 1 view)
Thermal Power Decommissioned (in 1 view)		X						Thermal Power Decommissioned (in 1 view)
Thermal Power Installed (in 2 views)		X		X				Thermal Power Installed (in 2 views)
Thermal Production completion (in 2 views)		X		X				Thermal Production completion (in 2 views)
Thermal Production decomissioning (in 2 views)		X		X				Thermal Production decomissioning (in 2 views)
Thermal SENSITIVITY OF UTILISATION FACTOR (in 1 view)		X						Thermal SENSITIVITY OF UTILISATION FACTOR (in 1 view)
Thermal UTILISATION FACTOR (in 1 view)		X						Thermal UTILISATION FACTOR (in 1 view)
TIME STEP (in 6 views)	X	X	X	X	X	X		TIME STEP (in 6 views)
Total electricity access rate (in 2 views)					X	X		Total electricity access rate (in 2 views)
Total Population (in 5 views)	X	X	X	X	X			Total Population (in 5 views)
UTILISATION FACTOR (in 1 view)				X				UTILISATION FACTOR (in 1 view)
Total:	42	34	35	73	29	32	1	:Total
	Hydro Power sub-sector	Thermal Power sub-sector	Solar Power sub-sector	Supply/Power sector	Demand/Population sector	Capital/Investment sector	General CLD	

* Includes *Time*, if used in a view. Excludes variables not present in any view.

Level Structure †

Cumulative Investment = $\int$ Budgeted investment *dt* + [0]

Budgeted investment = Ghana GDP*INVESTMENT RATE

Energy Generated = $\int$ Production completion-Production decommissioning *dt* + [INITIAL Generation]

INITIAL Generation = INITIAL(8.429e+006)

Production completion = Hydro Production completion+Solar Production completion+Thermal Production completion

Production decommissioning = MIN((Hydro Production decommissioning+Solar Production decomissioning+Thermal Production decomissioning), (Energy Generated/Adjustment time))

Ghana GDP = $\int$ GDP Growth dt + [INITIAL GDP]
INITIAL GDP = 2.04e+010
GDP Growth = Ghana GDP*GDP GROWTH RATE

Hydro Energy Generated = $\int$ Hydro Production completion-Hydro Production decommissioning dt + [Hydro INITIAL Generation]
Hydro INITIAL Generation = INITIAL(5.619e+006)
Hydro Production completion = (Hydro Capacity completion*Hydro MW to MWh conversion)*(Hydro UTILISATION FACTOR+STEP(Hydro SENSITIVITY OF UTILISATION FACTOR, 2019))
Hydro Production decommissioning = Hydro Energy Generated/Hydro AVERAGE PLANT LIFE

Hydro Power Construction = $\int$ Hydro Capacity commencement-Hydro Capacity completion dt + [Hydro INITIAL POWER CONSTRUCTION]
Hydro INITIAL POWER CONSTRUCTION = 50
Hydro Capacity commencement = Actual investment in Hydro/Cost per MW Hydro Hydro
Capacity completion = Hydro Power Construction/Hydro CONSTRUCTION TIME

Hydro Power Decommissioned = $\int$ Hydro Capacity decommissioning dt + [Hydro INITIAL POWER DECOMMISSIONED]
Hydro INITIAL POWER DECOMMISSIONED = 0
Hydro Capacity decommissioning = Hydro Power Installed/Hydro AVERAGE PLANT LIFE

Hydro Power Installed = $\int$ Hydro Capacity completion-Hydro Capacity decommissioning dt + [Hydro INITIAL POWER INSTALLED]
Hydro INITIAL POWER INSTALLED = INITIAL(1180)

Population with Electricity Access = $\int$ Electricity access rate-Electricity access loss rate dt + [INITIAL POPULATION WITH ELECTRICITY ACCESS]
INITIAL POPULATION WITH ELECTRICITY ACCESS = INITIAL(1.2483e+007)
Electricity access loss rate = MIN((Production decommissioning/Average Consumption per person), (Population with Electricity Access/TIME STEP))
Electricity access rate = MAX(MIN((Production completion/Average Consumption per person), (Population without Electricity Access/TIME STEP)), 0)

Population without Electricity Access = $\int$ Electricity access loss rate+Population growth-Electricity access rate dt + [INITIAL POPULATION WITHOUT ELECTRICITY ACCESS]
INITIAL POPULATION WITHOUT ELECTRICITY ACCESS = INITIAL(9.417e+006)
Population growth = MAX((Total Population*NET POPULATION GROWTH RATE), 0)

Power Backlog = $\int$ Indicated Annual capacity requirement-Backlog clearance dt + [INITIAL POWER BACKLOG]
INITIAL POWER BACKLOG = 1305
Backlog clearance = MIN(Capacity commencement, Power Backlog/Adjustment time)
Indicated Annual capacity requirement = MAX((Supply Line Adjustment-Capacity commencement), 0)

Power Construction = $\int$ Capacity commencement-Capacity completion dt + [INITIAL POWER CONSTRUCTION]
INITIAL POWER CONSTRUCTION = 600
Capacity commencement = Hydro Capacity commencement+Solar Capacity commencement+Thermal Capacity commencement
Capacity completion = MIN((Hydro Capacity completion+Solar Capacity completion+Thermal Capacity completion), (Power Construction/Adjustment time))

Power Decommissioned = $\int$ Capacity decommissioning dt + [INITIAL POWER DECOMMISSIONED]
INITIAL POWER DECOMMISSIONED = 0
Capacity decommissioning = MIN((Hydro Capacity decommissioning+Solar Capacity decommissioning+Thermal Capacity decommissioning), (Power Installed/Adjustment time))

Power Installed = $\int$ Capacity completion-Capacity decommissioning dt + [INITIAL POWER INSTALLED]
INITIAL POWER INSTALLED = INITIAL(1731)

Solar Energy Generated = $\int$ Solar Production completion-Solar Production decomissioning dt + [Solar INITIAL Generation]
Solar INITIAL Generation = INITIAL(0)
Solar Production completion = (Solar Capacity completion*Solar MW to MWh conversion)*(Solar UTILISATION FACTOR+STEP(Solar SENSITIVITY OF UTILISATION FACTOR, 2019))
Solar Production decomissioning = Solar Energy Generated/Solar AVERAGE PLANT LIFE

Solar Power Construction = $\int$ Solar Capacity commencement-Solar Capacity completion dt + [Solar INITIAL POWER CONSTRUCTION]
Solar INITIAL POWER CONSTRUCTION = 0
Solar Capacity commencement = Annual investment in Solar/Cost per MW Solar Solar
Capacity completion = Solar Power Construction/Solar CONSTRUCTION TIME

Solar Power Decommissioned = $\int$ Solar Capacity decommissioning dt + [Solar INITIAL POWER DECOMMISSIONED]
Solar INITIAL POWER DECOMMISSIONED = 0
Solar Capacity decommissioning = Solar Power Installed/Solar AVERAGE PLANT LIFE

Solar Power Installed = ∫Solar Capacity completion-Solar Capacity decommissioning *dt* + [Solar INITIAL POWER INSTALLED]

Solar INITIAL POWER INSTALLED = INITIAL(1)

Thermal Energy Generated = ∫Thermal Production completion-Thermal Production decomissioning *dt* + [Thermal INITIAL Generation]

Thermal INITIAL Generation = INITIAL(2.81e+006)

Thermal Production completion = (Thermal Capacity completion*Thermal MW to MWh conversion)*(Thermal UTILISATION FACTOR+STEP(Thermal SENSITIVITY OF UTILISATION FACTOR, 2019))

Thermal Production decomissioning = Thermal Energy Generated/Thermal AVERAGE PLANT LIFE

Thermal Power Construction = ∫Thermal Capacity commencement-Thermal Capacity completion *dt* + [Thermal INITIAL POWER CONSTRUCTION]

Thermal INITIAL POWER CONSTRUCTION = 550

Thermal Capacity commencement = Annual investment in Thermal/Cost per MW Thermal

Thermal Capacity completion = Thermal Power Construction/Thermal CONSTRUCTION TIME

Thermal Power Decommissioned = ∫Thermal Capacity decommissioning *dt* + [Thermal INITIAL POWER DECOMMISSIONED]

Thermal INITIAL POWER DECOMMISSIONED = 0

Thermal Capacity decommissioning = Thermal Power Installed/Thermal AVERAGE PLANT LIFE

Thermal Power Installed = ∫Thermal Capacity completion-Thermal Capacity decommissioning *dt* + [Thermal INITIAL POWER INSTALLED]

Thermal INITIAL POWER INSTALLED = INITIAL(550)

† *Level Structure Report* still under development.

List of 37 Equations with Dimensionless Units

Module	Group	Type	Variable
Default	GELA Model	A	Change in Capacity (Dmnl)
Default	GELA Model	C	Effect of plant size on Hydro cost (Dmnl)
Default	GELA Model	A	Fractional investment in Hydro (Dmnl)
Default	GELA Model	A	"Fractional investment in solar/renewables" (Dmnl)
Default	GELA Model	A	Fractional investment in Thermal (Dmnl)
Default	GELA Model	C	GDP GROWTH RATE (Dmnl/year)
Default	GELA Model	A	Hydro Change in Capacity (Dmnl)
Default	GELA Model	C	HYDRO INVESTMENT SWITCH (Dmnl [-0.25,0,0.01])
Default	GELA Model	C	Hydro Learning rate (Dmnl)
Default	GELA Model	C	Hydro SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5])
Default	GELA Model	C	Hydro UTILISATION FACTOR (Dmnl [0.2,1,0.01])
Default	GELA Model	C	INVESTMENT RATE (Dmnl/year [0,1,0.001])
Default	GELA Model	A	Learning effect (Dmnl)
Default	GELA Model	A	Learning effect on Hydro (Dmnl)
Default	GELA Model	A	Learning effect on Solar (Dmnl)
Default	GELA Model	A	Learning effect on Thermal (Dmnl)
Default	GELA Model	C	LEARNING RATE (Dmnl)
Default	GELA Model	A	Maximum Hydro investment fraction (Dmnl)
Default	GELA Model	C	NET POPULATION GROWTH RATE (Dmnl/year)
Default	GELA Model	A	Price Change (Dmnl)
Default	GELA Model	A	Share of Hydro energy (Dmnl)
Default	GELA Model	A	Share of Hydro power (Dmnl)
Default	GELA Model	A	Share of Solar energy (Dmnl)
Default	GELA Model	A	Share of Solar Power (Dmnl)
Default	GELA Model	A	Share of Thermal energy (Dmnl)
Default	GELA Model	A	Share of Thermal Power (Dmnl)
Default	GELA Model	A	Solar Change in Capacity (Dmnl)
Default	GELA Model	C	Solar Learning rate (Dmnl)
Default	GELA Model	C	Solar SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5])
Default	GELA Model	A	Solar UTILISATION FACTOR (Dmnl)
Default	GELA Model	A	Thermal Change in Capacity (Dmnl)
Default	GELA Model	C	THERMAL INVESTMENT SWITCH (Dmnl [0,0.65,0.01])
Default	GELA Model	C	Thermal Learning rate (Dmnl)
Default	GELA Model	C	Thermal SENSITIVITY OF UTILISATION FACTOR (Dmnl [0,0.5])
Default	GELA Model	C	Thermal UTILISATION FACTOR (Dmnl [0.2,1,0.01])
Default	GELA Model	A	Total electricity access rate (Dmnl)
Default	GELA Model	C	UTILISATION FACTOR (Dmnl)

Source file: GELA Model.mdl (30Jul2018 - 10:42:36 AM)
Report Created on 30/Jul/2018 - 6:19:31 PM
SDM-Doc Tool Version 5.0
Decision and Information Sciences Division
Argonne National Laboratory