ENERGY SYSTEM MODELS FOR SUB-SAHARAN AFRICAN COUNTRIES – A SYSTEMATIC REVIEW

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Abstract - The demand for energy in Sub-Saharan African (SSA) countries is rapidly increasing. This can be attributed to the increase in human population and standard of living in the region. Owing to the increasing energy demand, there is a need for proper energy planning. Energy system models are used in exploring the energy futures of countries and regions. Use of the wrong models has resulted in unrealistic projections and consequently poor energy policies. It is against this backdrop that this study was conceived. This paper aims to identify what class of energy system models that are most suitable for energy system analysis in SSA countries. Literature was initially reviewed to understand the basic characteristics of the energy systems of SSA countries. The paper then heads on to systematically identify what types of energy system models have been used in SSA countries, using the Scopus database search platform. The result of this extensive review suggests that the bottom-up optimization and the accounting framework class of energy models are best suited for SSA countries. However, the paper further opine that the existing energy system models are not capable of characterizing the energy system of SSA countries fully. Hence, there is a need to develop new energy system models or modify the already existing ones in order to capture all the features of SSA countries. Thus, this study will be of importance to energy analysts, researchers and policy makers when selecting energy system models.

Keywords: Energy system models, Energy policy, Energy planning, Sub-Saharan Africa.

1. INTRODUCTION

Energy is an indispensable component in the socio-economic development of any nation and as such should be analyzed with an in-depth knowledge. The demand for energy in developing countries most especially SSA countries in the past decades is rapidly increasing as a result of population expansion, economic development, and improvement in the standard of living. At the same time, there is now growing concerns globally about the finite nature of fossil fuels and climate change and this has greatly affected the energy supply system of SSA countries [1]. In order to tackle this challenge, there is a need for a broad understanding of the present and future energy-economy-environment nexus. One way to do this is through the use of energy system models, which describes and explores the futures of energy sector of a particular region; showing the human-environment interaction and also help policy makers in making appropriate energy decisions.

Over the years, a large number of energy system models have been developed to address this issue and many have already been used in making national and regional energy policies. The energy system models are very important tools in planning and formulation of energy policies. However, in energy assessment of countries, some of these models tend to produce results which are not actually correct due to the incorrect input data used for the study and also, the inherent limitations of the models. There could be other reasons why the models produce wrong results like in the case of the energy demand models, which could be attributed to partial social and environmental impacts coverage, inadequate technological reports, unrealistic characterization of the economic behavior etc. [2]. A study reviewed different energy demand models in the United States and reported that most of the models overestimated the demand by over 100% [3]. In SSA countries, these wrong results can be attributed to the non-availability of data and poor sources of data. Given this challenge, there is the need for a model that can capture both the formal and informal sectors of the economies of SSA countries.

A lot of models have been developed over the years by the International Institute of Applied System Analysis (IIASA), International Atomic Energy Agency (IAEA), different laboratories, companies and government agencies for energy system modelling and many countries have adopted these models in making their energy policies. For examples: In 2006, the Energy Commission, Ghana made use of the LEAP model in conducting some studies for estimation of the optimum amount of energy and fuel that will be required to drive the economy to achieve her USD 1000 per capita and also remain a middle-income country by 2020. The studies reported that in the long term (2020), Ghana will have an electricity demand of 20,100 –22,300 GWh [4]. The Institute of Energy, Vietnam, conducted a study tagged “Master plan for power development stage V” with the WASP III model. The study explored the least-cost expansion path for a number of fuel prices and energy demand scenarios for the period of 2000-2020 [5]. Further, Tsinghua University in cooperation with the Princeton University conducted a study for China with the MARKAL model to explore the prospects for China sustainable socio-economic development between the years 1995 – 2050 [6].

In recent times, a wide variety of energy models has been developed as a result of advancement in technology and the specific needs for them. As a consequence, these models vary considerably and the question "which model is most suited for a certain purpose or situation" arises [7]. It will therefore only be needful to have an updated review of energy system models from the perspective of SSA countries. So far, the author is unaware of any work that has been done in reviewing energy system models specifically from the paradigm of SSA countries. This study is therefore aimed at bridging this knowledge gap by providing a comparative overview of existing energy system models in order to identify which category of energy system models are best suited for SSA countries.

The remaining sections of this study is structured as follows: Section 2 gives an overview of SSA economies and energy sector. Section 3 discusses the evolution of energy models and their categorization. Section 4 highlights the methodology that was used in selecting different energy models and a brief description of each selected model. Section 5 synthesized the study and stated the relevant conclusions.

2. CHARACTERISTICS OF SUB- SAHARAN AFRICAN COUNTRIES

This section focuses on the characteristics of the energy sector and economies of SSA countries. SSA is the home to many energy producers like South Africa, Nigeria, and Angola, yet, the region remains the central point of global energy poverty [8]. The energy sector is a fundamental element in the future development of SSA nations and yet it remains one of the least understood in the global energy context. We shall, therefore, examine some features of the energy sector and economies of the SSA region which are key elements in energy modelling.

2.1Energy

In order to improve the quality of living, access to modern energy is very important. Modern energy provides services like heating, lighting, better health and all-round developments which help improve the standard of living. In SSA, two out of every three people do not have access to electricity, and it is this energy poverty that is crippling the region's economic development. According to the International Energy Agency [8], over 620 million people in SSA which make up about half of the entire human population do not have access to electricity. About 80% of those who don't have access to electricity in SSA are the rural dwellers, which is an important note when modelling energy supply strategies for SSA countries. Access to electricity in West Africa ranges from below 20% in Liberia to over 70% in Ghana. In Nigeria, over 55% of the population do not have access to electricity. Most Nigerians rely on the fossil-fuel powered generator sets for their electricity need. In central Africa, the figures vary from around 3% in the Central African Republic to 66% in Equatorial Guinea. In East Africa, over 80% of the sub-region are without electricity while in Southern Africa, South Africa has the best percentage with about 85% of the population having access to electricity [8].

Over 2.5 billion people in the world still rely on traditional solid biomass for cooking, usually making use of inefficient stoves. SSA and developing Asia make up over 90% of this figure. Though the number of people using solid biomass is more in Asia, SSA still dominates in terms of percentage with over 80% still relying on solid biomass for cooking and other domestic energy activities [9]. The use of traditional biomass leads to a lot of health problems. Almost 2 million deaths worldwide are attributed to lung infections on an annual basis which is as a result of exposure to polluted indoor air coming from cooking with traditional biomass and coal. This phenomenon has also contributed to global warming and climate change as a result of incomplete combustion of carbon in the process [10].

Energy demand in SSA has increased since 2002 reaching about 570 Mtoe in 2012, yet this figure is just about 4% of the entire world total demand. Nigeria and South-Africa have the largest energy demand, both having 141 Mtoe which when combined is over 40% of the total demand within the region. Bioenergy and coal constitute the major components in SSA energy mix, having shares of about 60% and 30% respectively. Natural gas contributes a small percentage of about 4%, with Nigeria having over 60% of the total. Renewable energy sources are at a very nascent stage of development in SSA and accounts for below 2% of the energy mix. However, some countries like Kenya and South Africa are scaling up efforts in this regard [8].

Energy consumption in SSA is mainly in the residential sector. The residential sector accounts for about two-third of the total energy use which is usually for cooking. The transport sector accounts for 11% while other sectors combined accounts for about 21% [8].

The power supply in the region is characterized by frequent power outages, low voltage which results to epileptic supply. Transmission and distribution (T&D) losses also constitute to the constraints to power supply in the region. For example, Nigeria has about 35% of the electricity generated lost during Transmission and Distribution [11]. Also, poor maintenance of power equipment, seasonality, corruption in the power sector among others, are the main challenges facing the SSA power sector.

2.2Economy

Many African countries are in economic transition; however, the informal economy and non-monetary transactions still remain a key component in most SSA countries. In some SSA countries, the share of the informal economy is greater than the formal economy. The informal economy provides job for about 90% of the people [12]. The problem is that the dynamics of the informal economy is not well understood. The informal economy refers to those economic activities that takes place in a country but are not accounted for in the nation's economic statistics like the GDP. The informal economy can hardly be quantified because of its disorganized manner. It is sometimes called underground economic activities [12]. It is also important to note that the informal economy doesn't necessarily refer to fraudulent activities; it also constitutes legal activities in the economy that are not accounted for officially. The distinction is given in Table 2.1.

Table 2.1 Categorization of Informal Economic Activities. Lifted from [12]

Activity	Example of transactions			
	Monetary		Non-monetary	
Illegal	Trade with stolen goods; drug dealing and manufacturing, gambling, prostitution etc.		Drugs barter, stolen goods, smuggling etc. Production of drugs for own use; theft for own use	
legal	Tax evasion	Tax avoidance	Tax avoidance	Tax evasion
	Unreported income, wages, salaries and assets related to legal services and goods.	Employee discounts and fringe benefits	Barter of legal goods and services	All do-it-yourself work and neighbour help.

2.3 Societal Structural Defects

Many SSA countries are faced with structural problems such as rural-urban divide, inequality, poverty, poor technology diffusion and corruption. Rural-urban divide refers to the great developmental gaps between the urban areas and the rural areas in SSA countries compared to the western world. In SSA countries, the capital cities are usually well developed with basic amenities like good health services, schools and pipe-borne water, whereas the rural areas are the sharp opposites as they lack most of these basic amenities. Inequality and poverty is also another great defect in SSA. There is a massive gap between the rich and the poor. In most cases, the wealth of the nation's rests in the hands of the few 'rich' while the bulk of the masses remain in poverty. Also, technology diffusion is usually limited as a result of high illiterate population in the region.

In sum, we can say that the major features of SSA countries are: power supply shortage, low per capita income and inequality, existence of chronic mass poverty, poor rate of capital formation, increase in population pressure, backwardness in agriculture, problem of mass unemployment, unexploited natural resources, shortage of technology and skills, poor infrastructural development, lack of industrialization, lack of proper market, mass illiteracy, poor socio-economic condition and inefficient administrative set up [13]. It is therefore seen that the SSA energy-economy sector is very complicated and thus requires an energy system model that can capture these features identified, for the purpose of making realistic energy plans. The geographic location of SSA in the African continent is shown in Figure 2.1.

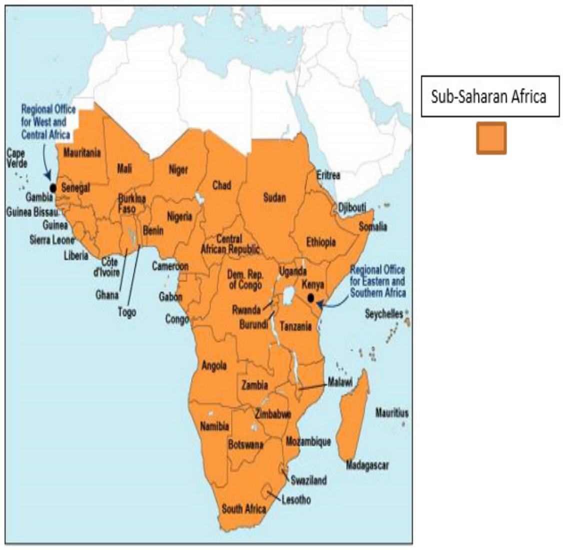

Figure. 2.1 Location of Sub-Saharan Africa in African Continent [14]

3. ENERGY SYSTEM MODELS

3.1 Origin

A model of a system or a process is a mathematical representation of the system's functioning in order to make the understanding of how the system works and behaves under various conditions possible [15]. Computer energy system models often make use of scenario analysis in investigating the various assumptions about techno-economic conditions at play. These models can be used for feasibility studies, GHG emissions, energy efficiency and financial analysis of energy projects among other uses. Energy models make use of broad engineering and economics techniques [16]. Energy system models can be used for national and regional energy planning. They can also be used for analysis of single projects [17]. Energy system models can be used to simulate market penetration, policy and choices of technology that may influence the supply and demand of energy and also investments in energy systems [18].

The origin of energy system models can be traced back to the early 1970s when there was oil crisis. This problem made many countries especially the developed countries to pay special attention to the rational use of their energy resources and long-term energy planning. However, before the 1970's, some energy models have been developed but they were only based on a single sector and a single energy vector. Therefore, these kinds of models were no longer sufficient and thus the concept of coordinated energy planning received attention. Efforts were geared towards integrating models either by connecting different models or by developing a stand-alone model [16]. This effort resulted to a new series of energy system models such as EFOM, MARKAL, MESSAGE and energy demand models like MAED and MEDEE. More attention was later paid to energy models with the growing concerns of environmental pollution resulting from the increase in energy consumption. Aggregated energy-related activities account for 80% of total GHG effect [19]. This created the need for incorporating environmental problems into energy system models. New tools such as EFOM-ENV was created to address the environmental aspect of energy activities. In the 1980s, global warming analysis and climate change mitigation strategies were then incorporated in energy system models [20].

3.2 Classification

A lot of scholars have classified energy system models using different criteria such as time horizon, theoretical foundation, and data requirements. Generally, no energy model belongs to a particular category. However, from a broader perspective, we can say that energy models belong to 2 classes [20].

i) Engineering bottom-up models

ii) Macroeconomic top-down models

i) **Engineering bottom-up models:**Bottom-up models describe technologies in detail but do not account for micro-economic decision making and macro-economic system feedbacks. They usually employ disaggregated data on specific technologies and this makes it typically possible to identify the least-cost option. The bottom-up models are further classified by [18,21] as:

- Optimization models
- Simulation models/Accounting framework models
- Multi-agent models

Optimization models

Optimization methodologies involve finding the good choice out of a set of alternatives by minimizing or maximizing the real functions [22]. The results are directly determined by the input and the outcome represents the best option or solution for a particular variable with respect to the given constraints. The users require high mathematical skills as optimization models often make use of Linear Programming (LP). The model chooses between technologies based on their lifecycle costs. Optimization methodologies are often limited to discrete energy conversion technologies and they also neglect the imperfections of market and obstacles in many final energy sectors and this result to unrealistic projections [18] Examples are: MESSAGE, MARKAL, EFOM and WASP.

Simulation models or often called Accounting framework models

This allowsusers to simulate the consumer and producers' behaviors under various signals like income and prices. The models are usually used in scenario analysis to investigate technology oriented measures [23]. This kind of models investigate the implications of a scenario that achieves a given market share. This method is usually applied in projecting future energy demand and related emissions. However, because of their simplicity, simulation models are not usually employed in decision processes [18]. Simulation models use exogenously specific outcomes set by the user in carrying out an accounting balance for the flow of energy from resources, extraction, and transformation and to end users or consumers [24]. Examples are: LEAP, MEDEE, MESAP

Multi-agent models

The multi-agent *models* are a broader modeling class than the optimization models, they look at the imperfections in the market like strategic behavior and asymmetric information. They are however limited to energy conversion technologies [18].

ii) **Macroeconomic top-down models:**Top-down models describe the energy system in aggregate relationships gotten from historical data empirically. They are used to assume competitive equilibrium and optimize the consumers and producers' behavior. They typically examine variables like GDP, imports, exports, public finances etc. [25]. Top-down models, in general, can be grouped into four main classes [18].

- Input-output models
- Econometric models
- General Equilibrium models
- System dynamic models

Input-output models

The input-output models have long been used for energy-economy analysis. They provide a balanced framework for analysis through sectorial-linkages in the economy. These models are capable of capturing energy demand as well as indirect energy demand thus, requires extensive data. Input-output models use disaggregated approach. Despite their analytical structures, they rarely capture rural-urban divide, therefore, making it difficult to use them for new demand or technologies [26].

Econometric models

These models work with time series analysis and make estimates based on statistical relations between economic variables over time in order to calculate projections from the resulting model. Examples are: regression models, time-series models, panel data models, probit and logit models.

General Equilibrium models

This type of model simulates consumers and producers' behaviors under various indicators like policies, income levels, and energy prices. Demand and supply functions describe the market relations. The intersection of the two curves indicates the equilibrium where the market optimum price and quantities are indicated. *Partial Equilibrium Model* is used when the analysis is for one sector, e.g. the Transport sector. General equilibrium models are useful in analyzing the energy sector relationship with the overall economy [24].

System dynamic models

They have pre-defined rules for the behavior of different actors in the model, and are able to make complex non-linear simulations on this basis. The approach begins with defining problems dynamically, proceeds through mapping and modelling stages, to steps for building confidence in the model and its policy implications. Computationally, the traditional structure of a formal system dynamics computer simulation model is a system of coupled, non-linear, first-order differential/integral equations [27]. Examples are: TIMER and SUSCLIME. The main features of bottom-up and top down models are presented in Table 3.1

Table 3.1 Main Features of Top-down and Bottom-up models. Lifted from [7]

Top-down	Bottom-up
use an "economic approach"	use an "engineering approach"
give pessimistic estimates on "best" performance	give optimistic estimates on "best" performance
can not explicitly represent technologies	allow for detailed description of technologies
reflect available technologies adopted by the market	reflect technical potential
the "most efficient" technologies are given by the production frontier (which is set by market behaviour)	efficient technologies can lie beyond the economic production frontier suggested by market behaviour
use aggregated data for predicting purposes	use disaggregated data for exploring purposes
are based on observed market behaviour	are independent of observed market behaviour
disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
endogenize behavioral relationships	assess costs of technological options directly

Hybrid models:

The hybrid models were developed to overcome the limitations of bottom-up and top-down energy system models. They incorporate the features of these two types of models. Bottom-up models are good in technological representation but do not capture the macro-economy-wide impacts whereas top-down models focus on macroeconomic environment and do not capture sectoral impacts adequately. Hybrid energy models combine elements of these two kinds of models. [23]. Example are: NEMS, MARKAL-MACRO, IPAC

Energy system models can further be classified based on time horizon, Geographical coverage, mathematical approach and sectoral coverage. These other classifications are well described in [7], [22],[28], [29] and [30].

4. SELECTION OF SUITABLE MODELS FOR SUB-SAHARAN AFRICA

In this section, the main aim of this study is addressed; which is to identify the class of energy system models that are best suited for SSA countries. In doing this, it is important to note that any model(s) that should be used for energy planning in SSA should able to project the future energy demand, the supply strategies, least cost options, the impacts of future policies - because of the uncertainties in SSA economies and also should be able to capture other features of the SSA energy sector and economy as earlier discussed.

4.1 Between Bottom-up and Top-down Energy System Models

In order to get realistic results in modeling technological choices for energy planning, a lot of data is required and a detailed description of the available energy technologies is also required. The level of information required is also high because specific techno-economic parameters like resources available, fuel extraction, capacity, operation and maintenance cost etc. must be modeled [31].

Technology leapfrogging has also been considered as an option for SSA countries most especially in this era of climate change. SSA countries have the option of deploying renewable energy technologies and other new emerging clean energy technologies to facilitate their socio-economic development; instead of making the same mistakes the developed countries made by burning coal and other fossil fuels. Modeling this technological quantum leap will require an energy system model that can characterize the available and new technologies in detail.

Further, many SSA economies are in transition and new energy policies will be developed subsequently. Hence there is a need for energy system models that can model the energy system impacts of these new policies. Bottom-up models contains detailed technology and energy system representation and as such, are very useful in predicting specific impacts of energy polices, since most of the parameters are exogeneous and they can easily be changed.

In view of these reasons as pertained to SSA countries, it is clear that the bottom-up category of models is the most suitable for energy system modeling in SSA countries.

4.2. Existing Bottom-up models (Search Strategy)

Here, literature was systematically surveyed to identify the existing stock of bottom up energy models in use and to understand if they effectively capture the features of SSA countries. The Scopus database search platform was used to select articles since 2010 up to February 2017, mentioning 'TITLE-ABS-KEY (energy system model Sub-Saharan Africa). The TITLE-ABS-KEY is the field code which refers to the section of the article to be searched. This code refers to the Title, Abstract and Keywords. The search was further refined by selecting energy as the subject area.

Selection Criteria

The identified studies were properly assessed and studies with no clear relation to energy system modeling in SSA were excluded. Energy system models found in the included studies were selected based on the following criteria:

- The model is an energy system model
- It is a bottom up energy model
- Its detailed documentation is available in literature
- The model has been previously used for energy system modeling in SSA countries

In doing this, care was taken to identify papers that didn't originate from SSA countries and also studies that produced multiple publications. Several studies identified used the same type of model for different purposes. The models were screened and the ones that didn't meet up with the set criteria were excluded.

Results of the Search

The results of this extensive search for energy system models suitable for SSA countries are given in Figure. 4.1.

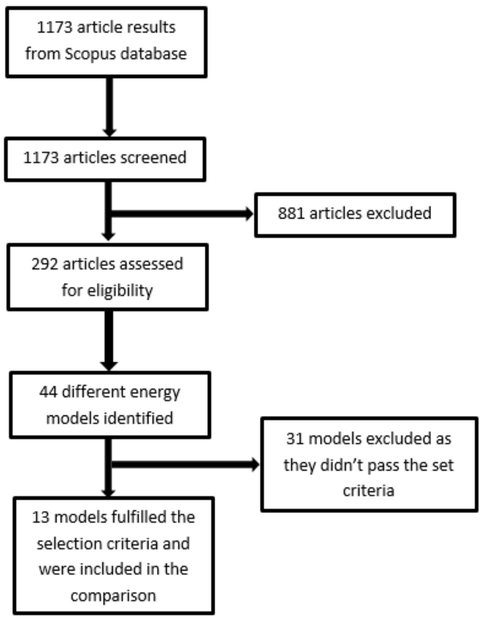

Figure. 4.1 Flow diagram of the search strategy

We identified 1173 articles through the Scopus database search facility. The articles titles, abstracts and keywords were screened. 881 articles were removed since they were neither concerning SSA nor energy system models. 292 articles were properly assessed for eligibility. The article contents vary considerably including policy impacts, implementation of a specific energy technology, overall energy system analysis of a country among others; and total number of 44 different energy models were identified. The identified models are enumerated in the appendices section. It is also worthwhile to state that some models were used repeatedly in different studies identified. 31 models were excluded out of the identified 44 models as they did not meet up with the set criteria for selection. The remaining 13 models that fulfilled the set criteria were further analyzed.

4.3. The Identified Bottom-Up Models

4.3.1. EFOM(Energy Flow Optimization model): This model was developed by Finon at Institut Economique et Juridique de l'Energie at Grenoble, France in 1974. The model belongs to the MARKAL family. It is technologically rich and covers both end-use and supply technologies. It uses an optimization approach to minimize the total discounted costs to meet a given energy demand of a state. The model is used in the analysis of the overall energy system of a country and can also be applied in the analysis of a single sector. The model has been modified to EFOM-ENV to carter for environmental issues involved in energy planning. It makes use of the Reference Energy System (RES) to represent the network of activities [16].

4.3.2. ENERGYPLAN: The EnergyPLAN model is a computer model for advance energy systems analysis. The model has been developed and maintained by the Sustainable Energy Planning Research Group of Aalborg University Denmark in 1999, and since then has been expanded continuously. The model is a deterministic type and it optimizes the operation of a given energy system based on the user's input. Analysis in ENERGYPLAN is done on hourly basis for one year and the results are analyzed based on different market-economic and simulation strategies. The model is designed for national and regional energy planning based on technical and economic analyses. The model runs 2 different types of analyses. The first is the technical analysis based on the demands and capacities and the second is based on economic optimization. EnergyPLAN is an open software and free of charge, it provides free online training and guides and it also facilitates third party developments by allowing additional help tools [32].

4.3.3. ENPEP (ENergy and Power Evaluation Program)**:** This model was developed by Argonne National Laboratory with support from the U.S. Department of Energy, the International Atomic Energy Agency, and the Hungarian Electric Board. It is a non-linear equilibrium model that matches the energy demand with the resources and technologies available. ENPEP is an integrated planning tool that analyses energy demands, corresponding resources requirements and the environmental implications. ENPEP is used to determine the response of various segments of the energy system to changes in energy demand and prices. It has a high degree of endogenization as well as describes all the sectors of the economy. The model also gives a detailed description of end-uses including renewable energy technologies. The main input parameter of ENPEP are: Energy system structures, base year energy statistics, energy demand projections and technical and policy constraints [33].

4.3.4. LEAP (Long Range Energy Alternative Planning):This model was developed by the Stockhom Environment Institute. It's a scenario based energy accounting model. It gives a detailed account of energy consumption, conversion, and production within the region under analysis. The model comprises of a technology and environmental database (TED). It models energy demands by sectors, sub-sectors, and equipment. The model is specifically used for energy demand, supply, and environmental impacts study. It can be used for energy and environmental policy analysis, biomass and land-use assessment, fuel cycle analysis, and integrated energy planning. LEAP is applicable to industrialized and developing countries [34].

4.3.5. MAED (Model for Analysis of Energy Demand): The methodology used in the MAED model came from the MEDEE model which was initially developed by B. Chateau and B. Lapillonne of the Institute Economique et Juridique de l 'Energie (IEJE) of the University of Grenoble, France. Ever since, MEDEE model has been further developed. For example, the MEDEE-2 model was developed for the needs of the International Institute for Applied Systems Analysis (IIASA), Austria. MEDEE-2 was adopted by the IAEA and some modifications were further made to it so that it can be applicable in developing countries after which it was now renamed MAED. MAED is a scenario-based simulation model and it is used for projecting energy and electricity demands on a long-term basis. The future energy demand is projected by using a bottom-up approach in which energy demand is disaggregated into several numbers of end-use categories such as services or production of certain goods. The aggregated energy consumption of the end-use activities is then used to project the total future energy demands for each sector. The model is basically designed to overcome the structural changes in energy demand [35].

4.3.6. MARKAL(MARKet ALlocation): This model was developed in the early 1980's by a consortium of members ofthe International Energy Agency (IEA)/ETSAP. The model is based on the General AlgebraicModeling System (GAMS) – which is a computer language that is designed to facilitate thedevelopment of algebraic models. The hosts for the program are the Kernforschungsanlage Jülich (KFA), Jülich, Germany and the Brookhaven National Laboratory (BNL), New York [36]. MARKAL is a technology-rich bottom-up model that is used for estimating energy supply with constraints over a multi-period of time. The objective of the model includes target oriented integrated energy analysis through a least cost approach. The model requires a low degree of endogenization, focuses only on the energy sector, detailed description of the end-use energy service (example: residential lighting and space conditioning) and energy technologies available. Many modifications have been incorporated into MARKAL of recent such as MARKAL-MACRO, MARKAL-MUSS and the window based ANSWER [36].

4.3.7. MESAP (Modular Energy System Analysis and Planning Environment): This model was developed by the Institute for Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart in 1997. The model is used for integrated energy system and environmental planning. It is used for making simulation and analyzing energy demand, supply, investment calculations, demand-side management among other uses. The planning tools include: PlaNet for demand analysis and supply simulation, INCA for comparative economic assessment of single technologies, WASP for electricity production based on least-cost approach, MESSAGE for integrated energy systems analysis [37]. MESAP also includes ENIS (the ENergy Information System), a link to databases from GIS and IKARUS.

4.3.8. MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact): This model was developed by the International Institute for Applied Systems Analysis (IIASA), Austria in the 1980s. A special agreement between IIASA and IAEA allowed the IAEA to use it and also to distribute it to its member states. MESSAGE is a dynamic linear programming model which calculates cost-minimal supply options under different constraints given by the user. The model uses an engineering optimization approach and it is used for developing medium to long term energy systems plan, also used for analyzing climate change policies and scenario analysis. It can be used for both regional and national studies [38].
The model can be used for simulating renewable energy, thermal generation, transport technologies among others. The inputs of the model are well detailed on the side of supply but more aggregated on the demand side[39].

4.3.9. POLES (Prospective Outlook on Long-term Energy Systems): This model was developed by Enerdata in collaboration with the European Commission's JRC IPTS and University of Grenoble-CNRS (EDDEN laboratory). It is a world partial equilibrium simulation model used for long-term energy supply-demand scenario analysis. It can simulate the energy sector until 2050. The model allows a detailed analysis and also computes GHG emission and its impacts. POLES can also forecast the effects of various energy issues such as energy policies, renewable energy penetration, energy efficiency etc. [40].

4.3.10. RETSCREEN: This is a clean energy model developed by Natural Resources Canada in 1996.The model is used for evaluating the energy production and savings, emission reductions, costs, financial feasibility of renewable energy projects as well as ongoing energy performance analysis. The model is available in multiple languages and also has a rich database of projects and climate data. The main purpose of RETScreen is a comparison between a "base case", usually the conventional technology and a "proposed case" i.e. the renewable energy technology. The model is not interested in the absolute costs but focus on the costs that would be incurred when the proposed case is implemented. Thus, one can check whether a project will be financially and technically viable. In RETScreen, the energy benefits are the same for both the base case and the proposed case [41].

4.3.11. TIMES (The Integrated MARKAL-EFOM System): The model is the successor of MARKAL. It is used for local, national and multi-national energy systems planning. TIMES has a rich based technology for assessing energy dynamics in a long-term. It can be used in designing least-cost pathways for sustainable energy systems. It can be applied in the analysis of the entire energy sector and can also be used in to study a single sector in detail. The Inputs of the model which is the reference case estimates of the end-use energy demand and the existing stock of technologies are given by the user. TIMES tries to provide energy services at a minimum global cost. The model can also be used in other energy-related issues like GHG emissions and energy policies. TIMES uses a scenario-based approach and is well suited for the exploration of energy futures. The complete scenario is made up of 4 inputs: energy service demands, primary resource potentials, a policy setting, and the descriptions of a set of technologies [42].

4.3.12. WASP (Wien Automatic System Planning): This model was initially developed by Tennessee Valley Authority (TVA) and Oak Ridge National Laboratory (ORNL) of USA to meet the needs of the International Atomic Energy Agency (IAEA). The model is commonly used in electricity investment planning. WASP is used to find the optimal expansion path for a power generating system within a long term. It does the analysis with the constraints given by the modeler. The model tries to minimize the discounted cost of power generation which is composed of the fuel cost, capital investment, salvage value of investment, fuel inventory cost, non-fuel operation maintenance cost and cost of energy not served. The complete simulation is done using 12 load duration curves to represent each year. The input in WASP requires the techno-economic characteristics of the existing energy systems. The model then provides the information on the capacity to be added to meet the future demand and the corresponding cost of the addition [43].

4.3.13. WEM (World Energy Model): This model is being used by the IEA for providing future energy projections as always reported in the World Energy Outlook (a publication of the IEA). WEM is a simulation model covering energy demand, energy conversion, and energy supply. The model consists of 3 main sections. The final energy consumption (agriculture, residential, transport, industry, services, and non-energy use), energy conversion (power generation, refinery and other energy conversion technologies) and energy supply. The outputs from WEM are energy flows, CO_2 emissions, and investments. The input data in WEM are very intensive and requires a lot of analysis. WEM can also be used in the analysis of individual countries. The model basically analyses Global and regional energy prospects, Environmental impact of energy use, Effects of policy actions and technological changes, Investment in the energy sector and Modern energy access prospects. The model is updated and recalibrated each year to keep it relevant. The latest version of the model covers an energy development up to 2040 in 25 regions [44].

5. SYNTHESIS AND CONCLUSION

The first thing observed from this review is that no existing energy system model is capable of capturing all the features of SSA countries. However, when considering the available stock of energy models, the MAED, LEAP, and MESSAGE appears to be the most suitable for SSA countries as they appear to capture large features of SSA countries. Other energy models like the MARKAL family of models tend to capture medium number of the features of SSA countries. However, it is worthwhile to note that all the above-mentioned models can be used for analysis. But to get more realistic results, energy models should be selected based on the purpose of study.

Energy system models can however be combined to achieve a particular purpose depending on what the modeler wants to do based on his/her research question. Some energy system models are designed for specific purposes and cannot capture every bit of the research question. For example, the MAED model can be combined with the WASP model for the purpose of electricity demand analysis and the least cost expansion pathways for the power system technologies.

For the purpose of energy demand analysis, the MAED and LEAP models are the most suitable for SSA countries. The models are able to capture the end-use technologies, power sector performance, and rural-urban divide. The LEAP model, however, will be better since it requires fewer skills and the input data are less intensive compared to MAED. The MAED model will be suitable for countries that have the set of data required and this is not usually the case in SSA countries.

For supply analysis, it also depends on what the modeler intends to do. For scenario based analysis the LEAP model will be the most suitable since it gives a direct result of the simulation. However, when policy, financial and technological constraints are involved, then, the MESSAGE model should be the most suitable.

In conclusion, owing to the fact that no existing energy model is able to cater for all the features of SSA countries as a result of the technical limitations of the models, it is therefore suggested that modular energy system packages should be used to address the different areas involved in modeling the energy system of SSA countries. Further, it is also suggested that further research should be done to improve the existing stock of energy system models and also develop new models that can adequately capture the features of SSA countries energy systems.

APPENDICES

Appendix A. List of the 44 Identified Energy Models

EFOM	ORCED	INFORSE	TRNSYS
ENERGYPLAN	LEAP	MESAP	E3MG
ENPEP	SIVAEL	WADE	BREDEM
MAED	2050 Calculator	PRIMES	EQUEST
MARKAL	IKARUS	MODEST	SAGE
PERSEUS	HOMER	PLEXOS	MEDEE
POLES	WEM	E4Cast	OSeMOSYS
RETSCREEN	MESSAGE	WASP	SAM
SimREN	TRACE 700	DECC	T*SOL
TIMES	TIMER	BALMOREL	PLANELEC
WILMAR	MiniCAM	RESGEN	NEMS

REFERENCES

[1] Amin M, Gellings C. The North American power delivery system: Balancing market restructuring and environmental economics with infrastructure security. Energy 2006;31:967–99. doi:10.1016/j.energy.2005.05.013.

[2] Laitner, J. A., Decanio, S.J., Coomey, J.G. and Sanstand AH (2003). Room for improvement: Increasing the value of energy modeling for policy analysis, Utilities Policy, 11, pp. 87-94. . 2003.

[3] Craig, P.P., Gadgil, A. and Koomey JG. What Can History Teach Us? A retrospective examination of long-term energy forecasts for the United States. Annu Rev Energy Environ 2002;27:83–118. doi:10.1146/annurev.energy.27.122001.083425.

[4] Energy Commission Ghana. Strategic National Energy Plan. Ghana. 2006.

[5] Institute of Energy. Master plan on power development stage V. Hanoi. 2000.

[6] Zongxin, W., DeLaquil, P., Larson E. D., Wennying, C., Pengfei G. Future. Implication of China's Energy-Technology Choices, [CIA]. CIA world fact book 2001.

[7] Van Beeck N. Classification of Energy Models. Tilburg University, Tilburg, Netherlands. 1999.

[8] IEA. Africa Energy Outlook: A Focus on Prospects in Sub-Saharan Africa 2014:1–242. https://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf (accessed July 6, 2017).

[9] IEA. World Energy Outlook. International Energy Agency. 2016.

[10] Legros, G., Bonjour, S., Bruce, N. and Havet I. The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa. Edited by Karen Holmes. UNDP and World Health Organization. 2009.

[11] NPBR. Nigeria Power Baseline Report 2015. http://www.nesistats.org/uploads/3/6/3/6/3636925/20150916_nigeria_energy_power_report_final.pdf (accessed October 12, 2017).

[12] Chambwera, M., Baker, A. and MacGregor J. The Informal Economy: A primer for development professionals on the importance of the informal economy. UK: International Institute for Environment and Development. 2011.

[13] Kwatiah N. Economics Discussion: Characteristics of an underdeveloped countries: Top 14 characteristics. Available at: http://www.economicsdiscussion.net/underdeveloped-countries/characteristics-of-an-underdeveloped-countries-top-14-characteristics/18971 (Accessed: 2016.

[14] Laura AA. Millenium development goals for Sub-Saharan Africa 2012. http://www.eoi.es/blogs/lauraambros/2012/01/17/millenium-development-goals-for-sub-saharan-africa/ (accessed May 26, 2017).

[15] Tester JW, Elisabeth M. Drake, Michael J. Driscoll, Michael W. Golay, William A. Peters. Sustainable energy□: choosing among options. MIT Press; 2012.

[16] Bhattacharyya SC, Timilsina GR. Modelling energy demand for developing countries: are specific features adequately captured. Energy Policy 2010;38:1979–90.

[17] Bruckner, T., Bashmakov, I.A. and Mulugetta Y. Energy Systems. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the 5th Assessment Report of the IPCC. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3ipcc_wg3_ar5_chapter7.pdf 2014.

[18] Herbst, A., Toro, F., Reitze, F. and Jochem E. Introduction to Energy Systems Modelling. Swiss J Econ Stat 2012;148:112.

[19] IPCC. Intergovernmental Panel on Climate Change: IPCC Second Assessment Synthesis of Scientific-Technical Information relevant to interpreting Article 2 of the UN Framework Convention on Climate Change 1995.

[20] Messner S. Endogenized technological learning in an energy systems model. vol. 7. Springer Verlag; 1997.

[21] Fleiter, T., Worrell, E. and Eichhammer W. Barriers to energy efficiency in industrial bottom-up energy demand models-A review. Renew Sustain Energy Rev 2011;15:3099–3111.

[22] Neshat, N., Amin-Naseri, M.R. and Danesh F. Energy models: Methods and characteristics. J Energy South Africa 2014;25:101–11.

[23] Heaps C. Integrated Energy-Environment Modeling and Leap. Available at: http://forums.seib.org/leap/Slides/LEAPSlides.ppt 5 (Accessed: 29 January 2017). 2002.

[24] Koch, M., Harnisch, J. and Blok K. A systematic analysis of the characteristics of energy models with regard to their suitability for practical policy recommendations for developing future strategies to mitigate climate change. Res Rep 299 97 311 2003:70. doi:Umweltbundesamt.

[25] UNFCCC. Module 5.1-Mitigation Methods and Tools in the Energy Sector. Presented by Charles Heaps. Seoul, Republic of Korea., 2005.

[26] Bhattacharyya SC, Timilsina GR. Energy demand models for policy formulation: a comparative study of energy demand models, World Bank Policy Research Working Paper No. 4866. Washington, DC.: World Bank. 2009.

[27] System Dynamics Society. System dynamics society (2012) 2012. http://www.systemdynamics.org/what-is-s/ (accessed February 10, 2017).

[28] Grubb M, Edmonds J, ten Brink P, Morrison M. The Costs of Limiting Fossil-Fuel CO2 Emissions: A Survey and Analysis. Annu Rev Energy Environ 1993;18:397–478. doi:10.1146/annurev.eg.18.110193.002145.

[29] Hall, L.M.H. and Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–628. doi:10.1016/j.apenergy.2016.02.044.

[30] Salas P. Literature Review of Energy-Economics Models, Regarding Technological Change and Uncertainty, 4CMR Working Paper Series 003, University of Cambridge, Department of Land Economy, Cambridge Centre for Climate Change Mitigation Research 2013.

[31] Alvarez DFM. Large Scale Integration of Renewable Energy Sources for Power Generation In Colombia: A Sensible Alternative To Conventional Energy Sources Scenario: 2010 - 2050. 2012.

[32] EnergyPLAN. EnergyPLAN Computer Model for Energy System Analysis. Available at: http://energy.plan.aau.dk/EnergyPLAN%20documentation.pdf (Accessed: 8 February 2017). 2003.

[33] Argonne National Laboratory. Energy systems - energy and power evaluation program (ENPEP-BALANCE). Available at: http://ceeesa.es.anl.gov/projects/Enpepwin.html (Accessed: 14 February 2017). 2015.

[34] SEI. LEAP: Long-range Energy Alternative Planning System, User Guide for LEAP 2005. Stockholm Environment Institute (SEI), Boston Center. 2005.

[35] IAEA. Model for Analysis of Energy Demand (MAED-2) User's Manual. Vienna: International Atomic Energy Agency. 2006.

[36] Fishbone, L.G., Giesen, G., Goldstein, G., Hymmen, H. A., Stock, K. J., Vos, H., Wilde, D., Zölcher, R., Balzer,C., Abilock H. User's guide for MARKAL (BNL/KFA Version 2) – a Multi-Period, linear-Programming model for energy system analysis, July 1st,

1983 1983.
[37] Schlenzig C. PlaNet – Ein entscheidungsunterstützendes System für die Energie- und Umweltplanung (PlaNet – a decision support system for energy and environmental planning). Germany: University of Stuttgart. 1998.
[38] Ryjkov S. MESSAGE. Available at: http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html (Accessed: 8 February 2017). 2012.
[39] Messner S, Strubegger. User's Guide for MESSAGE III. International Institute for Applied Systems Analysis. Available at: http://www.iiasa.ac.at/Admin/PUB/Documents/WP-95-069.pdf. (Accessed: 5 February 2017). 2005.
[40] Kitous A. POLES Model Prospective Outlook on Long-term Energy Systems. Enerdata services. 2006.
[41] RETScreen. RETScreen Software Online User Manual. Canada: Natural Resources Canada 2005.
[42] Loulou R, Remne U, Kanudia A, Lehtila A, Goldstein G. Documentation for the TIMES model: Part I 2005. http://iea-etsap.org/docs/TIMESDoc-Intro.pdf (accessed June 2, 2017).
[43] Aalborg University. EnergyPLAN | Advanced energy systems analysis computer model n.d. http://www.energyplan.eu/ (accessed May 26, 2017).
[44] IEA. World Energy Model Documentation. International Energy Agency. 2016.