sustainability

Article

A Study on Integrating SMRs into Uganda's Future Energy System

Niwagira Daniel and Juyoul Kim *

Department of NPP Engineering, KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Korea
* Correspondence: jykim@kings.ac.kr; Tel.: +82-52-712-7306

Abstract: Uganda is looking forward to diversifying its energy system to sustainably meet the present and future energy needs. To achieve this, the country is embarking on a nuclear power program to construct large nuclear reactors, although this would increase Uganda's electricity generation capacity, huge investments in construction and grid expansion required presents a big challenge considering the small size of Uganda's economy and grid. Luckily, emerging new nuclear technologies, such as small modular reactors (SMRs) can address these challenges due their enhanced features that are compatible with Uganda's energy system. SMRs having smaller capacities means that they would reduce the total investment costs in construction and also fit Uganda's small electric grid. In this study, the methodology followed two approaches to examine the best strategies to integrate SMRs into Uganda's future energy system, that is, the model for energy supply strategy alternatives and their general environmental impacts (MESSAGE) code and levelized cost of energy (LCOE) economic competitiveness analysis parameter. The results of analysis reveal that SMRs can play a key role in the future energy mix by contributing 13% to the total electricity generation. Additionally, the LCOE value of the SMRs was 78.01 $/MWh, which is competitive with large nuclear reactors with an LCOE value of 79.77 $/MWh and significantly lower than the LCOE of biomass, peat, and thermal energies. In conclusion, this study justified Uganda's need to invest in SMRs considering the country's energy security needs, future energy mix diversification goals, and national financial environment.

Keywords: small modular reactors; energy modeling; LCOE; MESSAGE; energy systems; nuclear power

Citation: Daniel, N.; Kim, J. A Study on Integrating SMRs into Uganda's Future Energy System. *Sustainability* **2022**, *14*, 10033. https://doi.org/10.3390/su141610033

Received: 19 July 2022
Accepted: 12 August 2022
Published: 13 August 2022

1. Introduction

Uganda is a country located in East Africa, with a total land area of about 241,559 km^2 of which 37,000 km^2 is covered by water [1]. It is endowed with a large number of natural resources such as abundant rainfall, fertile soils, gold, copper, cobalt, oil, and natural gas reserves [2]. Being a landlocked country, Uganda relies on neighboring countries Tanzania and Kenya, which have a coastline, to export and import goods [2]. The country's medium-sized economy has been growing at an average growth domestic product (GDP) rate of 7% per annum before 2016 and 4.5% after 2016 [3]. In addition, national electricity demand has been growing at an average rate of 10~12% per annum [4]. Uganda also has an abundance of energy resources, such as hydropower, biomass, solar, geothermal, and peat energies. The country has an estimated 2000 MWe potential of hydroelectric power along the Nile River, 450 MW of geothermal energy along the western rift valley, 1650 MWe of biomass cogeneration (often at sugar manufacturing plants), 460 million tons of biomass in stock with a sustainable annual output of 50 million tons, an average of 5.1 kWh/m^2/day of solar energy, and approximately 250 million tons of peat (800 MWe). The total renewable energy power generation potential is estimated to be 5300 MWe [2,5]. Nevertheless, the power generation potential from these sources, even if fully utilized, cannot meet the projected growth, including the national development goals set out in

Vision 2040 [6]. Uganda's total installed electricity capacity was 1237.49 MWe as of October 2020, generated by four sources as follows: 83% hydropower (1023.59 MWe), 8% thermal power (100 MWe), 5% cogeneration or biomass (63.9 MWe), and 5% grid-connected solar power (60 MWe) [7].

In 2007, the Ugandan government established "Vision 2040" to transform Uganda from a peasant to an industrialized and largely urban society. To achieve the goals of this vision, Uganda would develop and generate modern energy to drive the industrial and service sectors. It was estimated that Uganda would require 41,738 MWe by 2040, which would increase electricity consumption per capita to 3668 kWh. In addition, access to the national power grid would significantly increase to 80% [8].

Uganda Vision 2040 further states that the required capacity is to be generated from different energy sources, namely: hydropower (4500 MWe), thermal power (1500 MWe), nuclear power (24,000 MWe), solar power (5000 MWe), biomass (1700 MWe), peat (800 MWe), and geothermal power (4300 MWe) [8]. The energy sources and their contribution were to be determined after detailed feasibility studies on the energy mix. The vision also emphasizes the role of nuclear energy in overcoming the energy deficit. The role of nuclear energy was envisioned preferably based on the uranium resources available in the country and plans were made to invest in the development of the necessary nuclear infrastructure to support the early development and use of nuclear energy for electricity generation [8].

The Ugandan Energy Policy draft of 2019 is in effect, strategically directed towards energy security, sustainability, and economic competitiveness. Among the key issues facing Uganda's energy sector is vulnerability to climate change, as the country's energy balance is 88% biomass and electricity capacity mix is dominated by hydropower at 84% [9]. As in other Sub-Saharan African nations that largely depend on hydropower, weather changes, such as floods and dry spells, have jeopardized power supply for a long time, leading to frequent power outages [4]. These adverse climate changes could disrupt energy supply and raise the stakes of energy security. Therefore, Uganda's energy policy emphasizes the need to optimize the energy mix to ensure energy security and mitigate climate change [9]. In order to diversify its energy mix, Uganda has taken steps towards the introduction of nuclear power. Uganda Vision 2040 roadmap incorporates the development of significant nuclear capacity as part of the energy mix for Uganda's future energy needs [4]. An energy policy that includes nuclear power was drafted and a Nuclear Energy Program Implementing Organization (NEPIO) was established [9]. Uganda's NEPIO has completed several studies on different infrastructure issues and drafted a Nuclear Power Roadmap for Uganda that makes recommendations for key decisions on the development of the infrastructure for nuclear power in the short, medium, and long term [10]. Potential sites for nuclear power plant construction have been identified in the Kyoga, Kagera, and Aswa regions of Uganda [11]. The base scenario is for two 1000 MWe nuclear reactor units by 2031 [12]. In May 2018, Uganda signed a memorandum of understanding on cooperation in the peaceful uses of nuclear energy with China [11]. In June 2017, Uganda's Ministry of Energy and Mineral Development signed an agreement with Rosatom, Russia covering nuclear infrastructure and nuclear research centers with research reactors [11].

The Integrated Nuclear Infrastructure Review (INIR) team of the IAEA also visited Uganda in December 2021 and evaluated Uganda's nuclear power infrastructure development using Phase One of the IAEA's milestones approach [12]. The end of Phase one marks the readiness of a country to make a knowledgeable commitment to a nuclear power program [13]. The IAEA INIR team recommended that Uganda's Nuclear Power Roadmap needs to be updated and completed by conducting further studies that provide a basis for informed decisions and commitments for the nuclear power program. Other areas pointed out by the INIR team include preparedness of the electric grid, financing, radiation protection, environmental protection, etc. [10]. Globally, nuclear power projects have been facing major challenges, mainly due to construction delays caused by cost overruns. A notable example is Georgia's Vogtle Units 3 and 4 in the United States of America. The project involving two 1117 MWe Westinghouse AP1000 reactors was approved in 2009 and it was expected to cost approximately US $14 billion [14]. The project is now 5 years behind schedule and costs have surged to US $28.5 billion before completion [15]. Other projects, such as Flamanville Unit 3 in France, V.C. Summer 2 and 3 in the USA have faced similar challenges [16,17]. To overcome these challenges that have hampered the commercial nuclear industry for decades, cutting edge new nuclear technologies referred to as small modular reactors (SMRs) have been proposed. SMRs are advanced nuclear reactor units with a generating capacity up to 300 MWe per unit, about one-third of that of conventional nuclear power plants. SMRs being modular makes it possible to manufacture the systems and components and ship them as a unit to the installation site [18]. SMRs have been designed as an option to provide flexible power generation for a wide range of consumers and applications [19]. In addition, they offer better upfront capital cost affordability, are suitable for cogeneration and non-electrical applications, and are capable of operating in remote regions with less developed infrastructure [19]. All of these features are suitable for Uganda's energy system because one of the challenges in accelerating access to energy is the cost of infrastructure and grid connectivity for rural electrification. A single power plant should not exceed 10 percent of the total grid capacity installed [18]. Yet, using this analogy, Uganda's grid of 1237 MWe would not be capable of handling its proposed 2000 MWe large nuclear power. Therefore, based on Uganda's grid infrastructure, where sufficient transmission lines and grid capacity are lacking, SMRs can be installed on-grid or off-grid, providing low carbon power to industries and the population [18]. Compared to existing reactors, the proposed SMR designs are generally simple, and SMR safety concepts often rely on passive systems and the reactor's unique safety features, such as low power and operating pressure. There over 70 designs of SMRs undergoing different stages of development in many countries around the world. Below is Table 1 showing a brief summary of some SMR designs at advanced stages of development.

Table 1. SMR design types and their stage of development [20].

SMR Type	Design	Output (MWe)	Country	Status
Water cooled reactors	CAREM	30	Argentina	Under construction
	CAP200	150/200	China	Conceptual Design
	SMART	100	Republic of Korea	Certified design
	NuScale	50×12	United States of America	Under Regulatory Review
High temperature gas cooled reactor	HTR-PM	210	China	Under construction
	MHR-T	205×4	Russian Federation	Conceptual design
	A-HTR-100	50	South Africa	Conceptual design
Fast Neutron spectrum SMR	4S	10	Japan	Detailed design
	BREST-OD-300	300	Russian Federation	Detailed design
Molten salt SMR	IMSR	190	Canada	Conceptual design
	CMSR	100~115	Denmark	Conceptual design

The water-cooled reactor represents a major SMR design using integrated light water reactor (LWR) technology. It represents the most mature technology as it operates like most large power plants today. The gas-cooled high-temperature SMR provides information on modular HTGRs under development and construction [21]. HTGR provides high temperature heat ($\geq$ 750 °C) that can be used for more efficient power generation, various industrial applications, and cogeneration. The fast neutron spectrum SMR provides a fast neutron spectrum with all the different coolant options. These coolants include sodium-cooled fast reactors (SFRs), heavy metal-cooled fast reactors (HLMCs, or lead or lead-bismuth), gas-cooled fast reactors (GFRs), and molten salt fast reactors (MSFRs). A molten salt SMR refers to an SMR using advanced reactor technology for molten salt fuel (and cooling) [21]. This study focused on integral pressurized water small modular reactors, represented as i-PWR (SMR), because of much experience with operating light water reactors throughout the world on a large scale, unlike other SMR designs that use moderators and coolants that have not operated before.

Previous studies have used the MESSAGE (model for energy supply strategy options and their general environmental consequences) code to construct long-term energy strategies for optimization. Egypt employed the MESSAGE code to optimize electrical generation technologies in order to reduce carbon emissions over a 45-year time frame. Findings of that study were that nuclear power is the best choice of electricity-generating technology for satisfying Egypt's future electricity demand while also lowering CO_2 emissions. In Nigeria, another study was conducted utilizing the MESSAGE code to find the optimum energy supply method to meet a future energy demand [22]. The study was based on two scenarios, one modeling the electricity generation mix without carbon emission constraints and the second scenario imposing carbon emission constraints. The results showed that both nuclear and fossil fuel power plants are optimal power generation technologies that meet Nigeria's future energy needs, with nuclear power causing the least environmental damage [22]. The adoption of nuclear power was identified as the best long-term power generation strategy for Saudi Arabia [23]. The MESSAGE code was used to model the optimal strategy for the introduction of nuclear energy in Saudi Arabia. The results of the study showed that renewable and nuclear energy technologies will be the most competitive future strategies for power supply in Saudi Arabia until 2050. Michealson and Jiang in their paper reviewed the integration of SMRs in renewable energy microgrids; key issues and approaches were examined to show how SMRs can be effectively integrated into microgrids as a clean and sustainable energy supply. Issues related to unit sizing, operation, and control were identified; however, the paper did not dig deeper into the existing literature of this subject [24]. Budnitz and his colleagues' study reviewed the expansion of nuclear power technology to new countries; they analyzed the technical attributes of SMRs, their pros and cons in regards to economics, grid compatibility, and safety. In their major conclusions, the need for a strong national and international regulatory regime was emphasized [25].

The main objective of comprehensive energy system analysis is to formulate medium- and long-term supply strategies that meet a projected demand and requirements of sustainable development in all its social, economic, and environmental dimensions, thereby ensuring secure energy supply [26]. This study aimed to evaluate the potential role of SMRs if they were integrated into Uganda's future energy system. This was performed by modeling the entire electricity-generating mix from available energy resources, including SMRs, to obtain an optimal long-term energy supply strategy. This was modeled in the MESSAGE code using three scenarios; the first scenario was based on Uganda's existing energy sources, the second scenario was based on Uganda Vision 2040, which aims to use new energy sources including large nuclear reactors to diversify its future energy mix, and the last scenario represents our proposal to Uganda to consider integrating SMRs into the future energy mix. To validate the results from MESSAGE modeling, an economic analysis was performed using levelized cost of energy (LCOE) analysis. This was conducted by calculating the LCOE of different electricity-generating technologies and compared them with that of nuclear technologies.

2. Materials and Methods

The study employed two approaches to carry out analysis; the first approach used the MESSAGE code to optimize the future electricity generation mix of Uganda, and in the second approach, an economic analysis through LCOE calculation was performed to determine the economic competitiveness of small modular reactors with alternative technologies.

2.1. The MESSAGE Code

The MESSAGE is a model developed for optimizing the energy system (i.e., energy supply and use). The model was originally developed at the International Institute for Applied Systems Analysis (IIASA), and the International Atomic Energy Agency (IAEA) added a user interface to facilitate its use [27]. The underlying principle of the MESSAGE model is the optimization of an objective function under a set of constraints that define the feasible range containing all possible solutions to the problem. The value of the objective function helps to select the solution that is the most suitable according to the defined criteria [27]. This objective function minimizes total discounted systems costs, which include the investment cost, the operating cost, and any additional penalty cost defined for the limits, bounds, and constraints on the relationships (such as the gas emission limits). The equation for this objective function is expressed by the following mathematical formula:

$$Total\ system\ cost = \sum_{t=1}^{T} \beta \times \sum_{i=1}^{n} C_{it} \times X_{it} \tag{1}$$

where $\sum_{i=1}^{n} C_{it} \times X_{it}$ is the sum of all costs incurred in period t and $\beta = \frac{1}{1+r}$, where r is the discount rate [28].

The present value is calculated by discounting all costs incurred at later dates from the base year of the case study, and the sum of the discounted costs is used to find the optimal solution. Discounting makes the costs incurred at different points in time comparable; the discount rate determines the weighting of the different time periods in the optimization. In principle, it should be equal to the long-term real interest rate, without taking into account inflation or other opportunity costs [27]. The modeling method is based on the construction of a network of energy flows describing the entire energy system, starting from domestic energy resources (oil and gas, uranium, coal mines, etc.), through the primary and secondary levels, to the given demand at the end-use level, divided by consumption types such as heat, fuel, electricity, and so on. This method compares the performance of a given technology with its alternatives based on a life cycle analysis under different national or local conditions. When an energy resource or consumption can be met by different options, such as meeting heat demand by oil, NG, electricity, or solar energy, the optimal solution selects the most appropriate option in terms of the calculated discounted cost of the unit of energy delivered, taking into account the total technology cost of investment, operation and maintenance (O&M), and the fuel cost at constant base year prices. This approach provides a realistic assessment of the long-term role of an energy supply option under competitive conditions. Environmental aspects can be analyzed by considering and, if necessary, limiting the amounts of air pollutants emitted by different technologies at different stages of the energy supply chain. This helps in evaluating the impact of environmental regulations on the development of the energy system, which may give advantages to the use of some clean technologies, such as nuclear power and renewable energy.

The MESSAGE was used because it is one of the most suitable models for assessing the potential role and competitiveness of SMRs [29]. Other software tools for energy planning include LEAP, WASP, FINPLAN, and POWERWORLD [30]. The main advantages of the MESSAGE code are:

(i) Ability to consider technical, economic, environmental, regulatory, and policy constraints on power generation technology.
(ii) Ability to find the optimal mix of energy supply assets to be built or expanded over time to meet the expected future energy demands while minimizing overall system costs.

2.2. Model Description of Ugandan Energy System

Uganda's national energy mix was modeled considering the available data and public information on the technologies participating in national electricity generation (resources, capacities, activities, and economic parameters (costs, efficiency, load factors, etc.)), according to the existing legal framework. To compensate for the lack of data, internationally agreed upon data from studies in the domain have been used. The study defined the base year as 2015, with the national energy mix keeping its dominant hydropower characteristic and other producers of electricity, namely biomass, thermal, and solar power plants, and the time horizon for the performed analysis was assumed to be 2050. For electricity demand evolution, two scenarios were considered. The first scenario is from an energy demand forecast from 2015~2040 completed by AF-Consult Switzerland Ltd. contracted by the government of Uganda [6]. The demand forecast was obtained through the addition of the total energy consumption of the on-grid customers in each of the years of the forecast period. On top of this, the suppressed demand, the losses, and the export load were added. The results of the study reported a 9.8% annual average growth rate in gross energy consumption being 5963 GWh demand in the year 2015 and 27,771 GWh demand in 2040. The second scenario was based on Uganda's historical data from 1980~2019 for total electricity consumption and total carbon emissions and adopted the constant growth method to predict future values for the entire time horizon until 2050. The average annual growth rate (AAGR) of electricity consumption was 7.0%, which was calculated using the data obtained from the US Energy Information Administration (EIA) from 1980 to 2019 [31], while the AAGR in carbon emissions was 5.5%. The results were plotted and are shown in Figure 1 below. The first scenario, which reports AAGR of 9.8%, was selected for Uganda's electricity demand evolution in MESSAGE modeling for conservativeness.

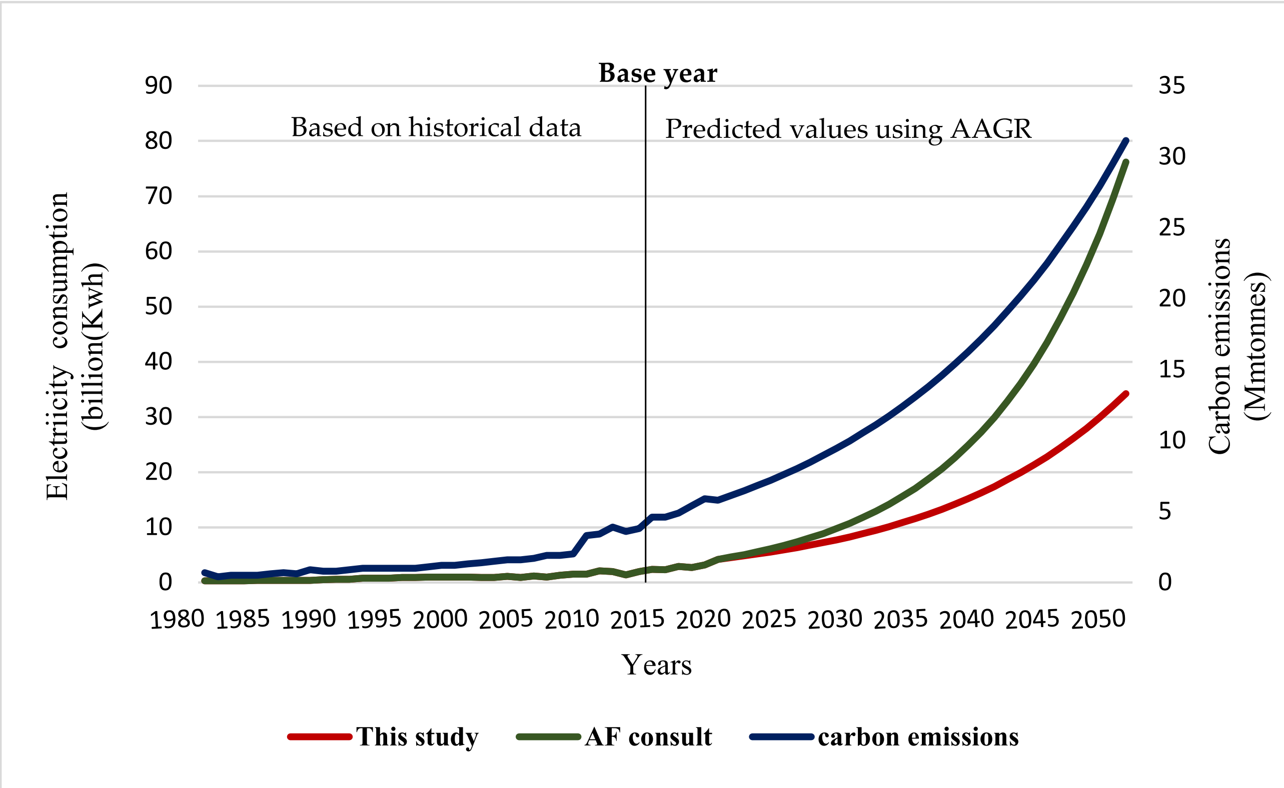

Figure 1. Prediction of Uganda's electricity consumption and carbon emission.

To meet the projected demand in energy sustainably and counter the rising carbon emissions in Uganda's energy system, a system analysis was performed based on available resources and information. Uganda's energy system is divided into a supply network that includes final, secondary, and primary energy levels, as well as domestic energy resources (oil, gas, uranium, biomass, peat, etc.). Technologies are defined by activity and capacity. Activity indicates input and output energy, efficiency, variable operation and maintenance costs, and user-imposed limits and constraints on the activity. Capacity describes the installed capacity, investment cost, fixed operation and maintenance cost, plant factor, construction time, and economic life, as well as the imposed limits on installed capacity, investment cost, and penetration factor. According to the modeling framework of the MESSAGE, the power system representation consists of time frame, load region, electric load curve, energy levels, energy forms, technologies, resources, demand, and constraints. These elements are briefly introduced below.

2.2.1. Time Frame

The study period covers the time horizon from 2015 to 2050, with a time step of 5 years. The year 2015 represents the base year, while the year 2020 is the start year in the optimization process (first model year).

2.2.2. Load Regions and Load Curves

Fluctuations in electricity demand, is represented by annual load profiles, usually termed as load regions and load curves. According to the variability characteristics of the Ugandan load curve, a day is divided into three time zones, the load peaks from the 19th to the 23rd hour in the evening, then off-peaks from 24 to 6 h at night and the load demand becomes modest between 7 h to 18 h during day time [31]. The load profile was assumed to be the same for all modeling years. Due to the nature of electricity as a non-storage form of energy, implicit coupling between power production and consumption must be considered when power production is to follow the required time-varying demand. Therefore, the modeling of the power grid requires specifying an annual hourly load curve. In this analysis, the time-load curve of future power demand was adopted from a previous study dealing with forecasting peak demand in Uganda [31]. With the Ugandan grid being dominated by hydropower and a portion of a solar power, which face production fluctuations due to seasonal changes, stable sources such as SMRs could help to load follow when integrated with renewables in those circumstances where hydropower and solar PV are unavailable given that the grid size characteristics are similar.

2.2.3. Hydro System Modeling

There are three types of hydropower facilities that can be modeled in the MESSAGE: run of river hydro, hydro with the rivers system and storage, and hydro cascade with pumped storage. The type that was modeled in this study is the hydro with rivers system and storage because it is the most common hydro system in Uganda along the Nile River. For modeling in the MESSAGE, a technology was introduced with two rivers and a water storage system. River 1 brings water from natural sources and provides in flow to the storage; the hydropower plant takes water from the storage and generates electricity by discharging water in downstream River 2. The storage system has a maximum capacity and allows an overflow of excess water down the course of River 2.

2.2.4. Energy Levels

The introduction of energy levels is essential for the construction of the physical flow model of the national energy system. Energy levels classify the different stages of the conversion processes to produce and supply a particular form of energy along the energy chain. This helps illustrate how a form of energy is delivered. Four energy levels are considered in this analysis, consisting of resources, primary energy, secondary energy, and final energy. The final energy level is identical to the energy demand. The energy levels are interconnected by energy conversion technologies, such as extraction, treatment, generation, transportation, and distribution, as shown in Figure 2. Import and export of energy forms are modeled at either the primary or secondary level, reflecting the real situation of each fuel type.

- Resources

Resources represent the first stage in the structured energy chain and refer to available finite domestic energy resources, such as fossil (oil, gas, and coal), nuclear (uranium and thorium), and traditional (wood) resources. In modeling energy resources, the MESSAGE provides the ability to define up to three different grades (or cost categories) of a resource, i.e., a categorization of the product from the same resource. Uganda's fossil resources are limited to oil and natural gas (NG). Proven geological oil reserves are estimated at nearly 6.5 billion barrels of oil of which 1.4 billion barrels are recoverable [32]. With the East African oil pipeline project recently getting the go-ahead, Uganda is set to produce its first oil yield as early as 2025 and production in the next five years is expected to jump to

230,000 barrels per day from zero in 2021 [33]. Proven geological reserves of natural gas in Uganda are estimated at 500 billion cubic feet [34]; however, no information regarding resource utilization or development for electricity generation has been available; thus, NG was excluded from technology modeling. Uganda's Ministry of Energy and Minerals has previously stated that the country has significant uranium deposits but estimates of the reserves are unknown as the minerals have not been commercially investigated [35]. The first nuclear fuel supplies for Uganda's planned power plants are expected to come from imports [6].

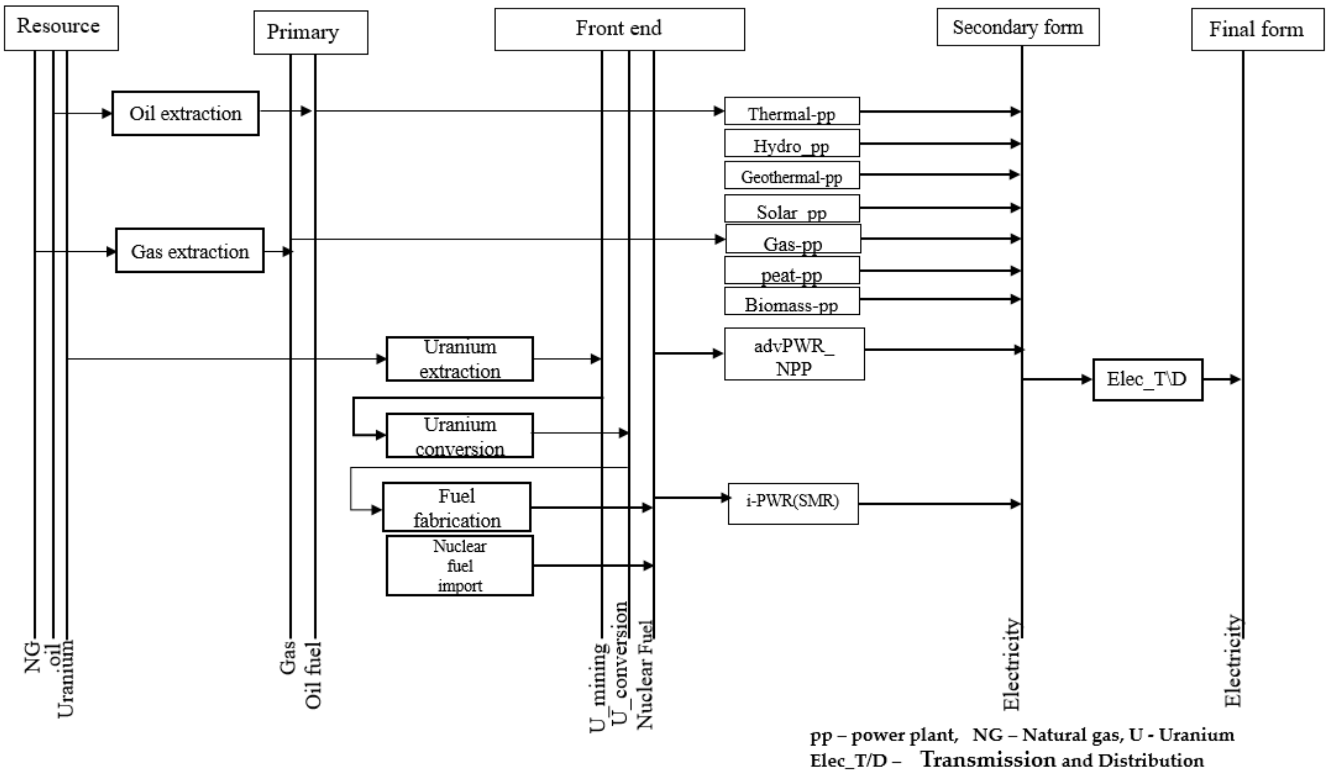

Figure 2. Ugandan energy system including energy chains, technologies, levels, and energy forms.

- Primary energy level

Extracted fuel oil was defined at this energy level. This is directly used as fuel for thermal power plants.

- Secondary energy level

Many forms of energy can be recovered from primary sources, namely NG after processing at gas factories, liquefied petroleum gas (produced at gas factories, oil refineries, and by direct import), gasoline and kerosene, diesel, and electricity. Electricity is the only energy form that has been defined at this level.

- Final energy level

Only electricity has been included as the main form of energy to represent electricity supply in all consumption sectors (industry, domestic, and residential).

2.3. Scenarios Formulation

Three scenarios for optimizing the future electricity-generating mix were devised and chosen for analysis. These include;

(i) The business as usual (BAU) scenario

This scenario looked at the situation where Uganda continues to rely on the existing energy mix as of 2020, which is comprised of hydropower, solar power, thermal power, and biomass, to analyze its future satisfaction of demand. Constraints were imposed on maximum capacity development for each technology according to the potential of each national resource. That is, 4500 MWe for hydropower, 1700 MWe for biomass, 5000 MWe for solar power, and 4300 MWe for thermal power [8]. The purpose of this scenario was to evaluate the worst scenario for Uganda if it only develops current technologies to their full potential.

(ii) The reference scenario

This scenario is based on Uganda's plans for development of new electricity-generating technologies; these include geothermal, large nuclear reactor, and peat [8,9]. Uganda is looking forward to the construction of two large nuclear reactor units, each with a capacity of 1000 MWe, with a predicted start-up date of 2032 [36]. However, until now the exact reactor type has not been decided. Due to much experience with the operation of light water-cooled reactors in the nuclear industry, this scenario assumed that the reactor type to be constructed by Uganda is an advanced pressurized water reactor, represented in this study as advanced PWR. The modeling for geothermal and peat was also completed by imposing constraints on total installed capacities based on the potential of these resources described in Uganda Vision 2040 [8]. This scenario analyzed the role of new electricity-generating technologies in expanding Uganda's future electricity-generating system in scenario (i).

(iii) The optimistic scenario

In this scenario, this study proposed SMRs to be integrated in Uganda's future energy system, which would look like the reference scenario above to factor in Uganda's financial and infrastructure environment. With respect to the nature of the current SMR development, the majority of the designs are based on light water reactor technology due to mature experience with the operation of large light water nuclear reactors. Therefore, this study proposed an integral pressurized water reactor type of SMRs, represented as i-PWR (SMR), with a projected starting capacity of 100 MWe in 2035. A constraint of 100 MWe maximum annual capacity addition was imposed on the growth rate of SMRs in the model. All other assumptions of this scenario are similar to the reference scenario.

2.4. The Levelized Cost of Energy (LCOE)

The study also performed an economic analysis based on the levelized cost of energy (LCOE). The levelized cost of energy is the principal tool for comparing plant-level unit costs for different baseload technologies over their operating lifetimes [37]. The LCOE corresponds to the average price that consumers have to pay for the electricity supplied to offset all costs incurred by the plant owner or operator, such as the cost of capital (including expected remodeling, operation and maintenance costs, decommissioning, and fuel cost capital [38,39]. The main objective of the economic analysis was to assess the future nuclear energy generation cost competitiveness compared to other competing technologies for electricity generation in Uganda, namely hydropower, solar, solar hybrid, peat, geothermal, biomass, and thermal power plants. The economic analysis was performed by calculating the LCOE for each technology using the equation given below [40].

$$\mathrm{LCOE} = \left\{ \frac{OCC \times CRF + Fixed\ O\&M}{8760 \times CF} \right\} + (FC \times HR) + variable\ O\&M \tag{2}$$

where OCC is the overnight capital cost in USD \$/kW, CRF is the capital recovery factor, CF is the capacity factor in percentage, $Fixed\ O\&M$ is the fixed operation and maintenance cost in US \$/kW-year, $Variable\ O\&M$ is the variable operation and maintenance cost in US \$/MWh, FC is the fuel cost in US \$/MWh, and HR is heat rate in BTU/kWh.

The units for the LCOE are US \$/MWh; therefore, all variables in the equation were converted to similar units before the calculation. Capital recovery factor (CRF) is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time [25]. It is calculated using the number of periods (n) and the discount rate per period i, in the following equation:

$$\text{CRF} = \left\{i(1+i)^n\right\}/\left\{\left[(1+i)^n\right] - 1\right\} \quad (3)$$

LCOE analysis has been used widely by academia, national organizations, and intergovernmental organizations to compare the competitiveness of different electricity technologies, for example, to make policy decisions between fossil fuel sources and renewable energy sources [38,41–43]. Limitations to the LCOE approach have been addressed in many studies, including uncertainty of future costs, treatment of discount rates and inflation rate based on assumptions, and inability to deal with wider system costs [43–46]. Studies providing alternative approaches to the LCOE have been completed; these are based on analyzing the total systems cost rather than plant level costs to account for intermittence and variability [47–50].

Sensitivity analysis was performed, highlighting the effect of various perturbations on the LCOE (e.g., discount rate, fixed O&M costs, and overnight capital costs). To confirm the validity of the economic analysis, the LCOE's robustness index (RI) was calculated, taking into account the simultaneous fluctuations of several input parameters of nuclear and alternative power plants. The robustness index (RI) can be defined as the ratio of the costs associated with alternative sources divided by the costs of nuclear sources. This relationship is commonly referred to as the relative cost-competitive ratio between nuclear energy and alternative technologies. When tolerance limits are defined, the higher the RI value, the better the performance. A given nuclear technology is "more robust" when the indicator value is far from the acceptable limit and "less robust" when the indicator value is close to the acceptable limit. Current competitive analysis assumes a tolerance of 1.0. If the RI ratio is greater than 1.0, nuclear technology is cost competitive with alternative technologies [51]. Tables 2 and 3 below show input data used for MESSAGE code simulation and LCOE calculations. Figure 3 shows the approach followed by the study for analysis.

Table 2. Input data for MESSAGE code for three scenarios using a base year of 2015 and modeling period of 35 years.

Parameter	Input
Base year	2015
Modeling period	2015 to 2050
Discount rate	5%, 8%, 10%
Energy chain	Resources, primary, secondary, final
AAGR of electricity demand	9.8% [6]

Table 3. Technology input parameters required for simulation in MESSAGE code and LCOE calculation. Costs are given using the 2020 US dollar [52].

Technology	Technology Capacity Factor (%) [53]	Plant Life (Years)	Overnight Capital Cost ($/kW)	Variable Cost ($/MWh)	Fixed O&M ($/kW-year)	Fuel Cost ($/MWh) [54]	Heat Rate (Btu/kWh)
Elec_TD	N/A	60	1000	10	50	N/A	N/A
Thermal [22]	30	35	1563	4.7	35.34	62.85	11,259
Hydro	54	80	2769	1.4	42.01	N/A	N/A
Biomass	83	30	4078	4.85	126.36	68	13,500
Adv-PWR	90	60	6034	2.38	122.26	7	10,455
i-PWR (SMR)	90	60	6183	3.02	95.48	7	10,455
Solar (PV) [a]	29	25	1248	0	15.33	N/A	N/A
Solar Hybrid [b]	28	25	1612	0	32.33	N/A	N/A
Peat	70	30	4375 [c]	0	110	22.25	10,339
Geothermal	90	30	2772	1.17	137.5	N/A	8946

[a] Solar (PV) is a photovoltaic solar power plant. [b] Solar hybrid is a solar (PV) plant paired with battery storage system. [c] Due to absence of capital cost on peat power plants, overnight capital cost was calculated by dividing total investment cost in US dollars by plant capacity in kWe for a peat project in the neighboring country of Rwanda [55].

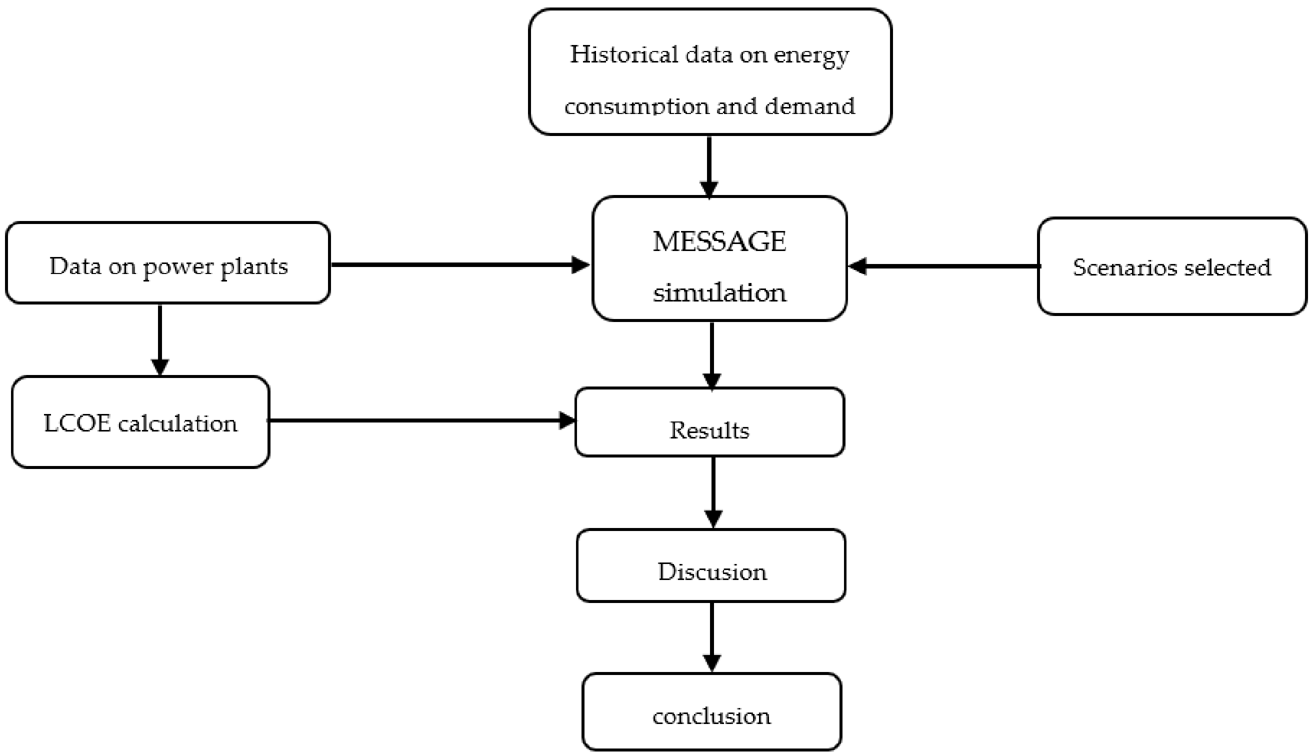

Figure 3. Data flow diagram used for MESSAGE code analysis and LCOE calculation.

3. Results

The results presented here are for the three scenarios formulated for analysis in the MESSAGE code of possible situations for Uganda's future electricity demands. Using the national electricity demand projections [6], the peak demand will grow at an average annual rate of 9.8%, from 489 MW in 2015 to 12,309 MW in 2050. The evolution of peak demand throughout the modeling period is shown by the solid line with nodes on the figures illustrating electricity production capacity for the three scenarios as described in the following sections.

3.1. The BAU Scenario (Scenario I)

This scenario was derived based on the electricity generation mix of 2020, which had four major electricity-generating technologies, that is, hydro, solar, biomass, and thermal power plants. The simulation in the MESSAGE code was completed starting from the base year of 2015 for the entire time horizon until 2050. This scenario predicts a total installed capacity of 10,200 Mwe in the last year (2050). Moreover, hydropower continues to dominate the energy mix throughout the entire time horizon, the most significant being between 2015 and 2035, where it contributes 78% and 91%, respectively, until 2040 when solar power upgrades to about 2969.8 MWe (52%) for the total installed capacity. The modeling period ends in 2050 with only three technologies generating electricity, that is, hydro (44%), solar (39%), and biomass (17%). There is a noticeable energy deficit of 156 MWe in 2035, which expands to 2109 MWe in 2050 due to a mismatch between generation and demand. Figure 4 below illustrates the BAU scenario results.

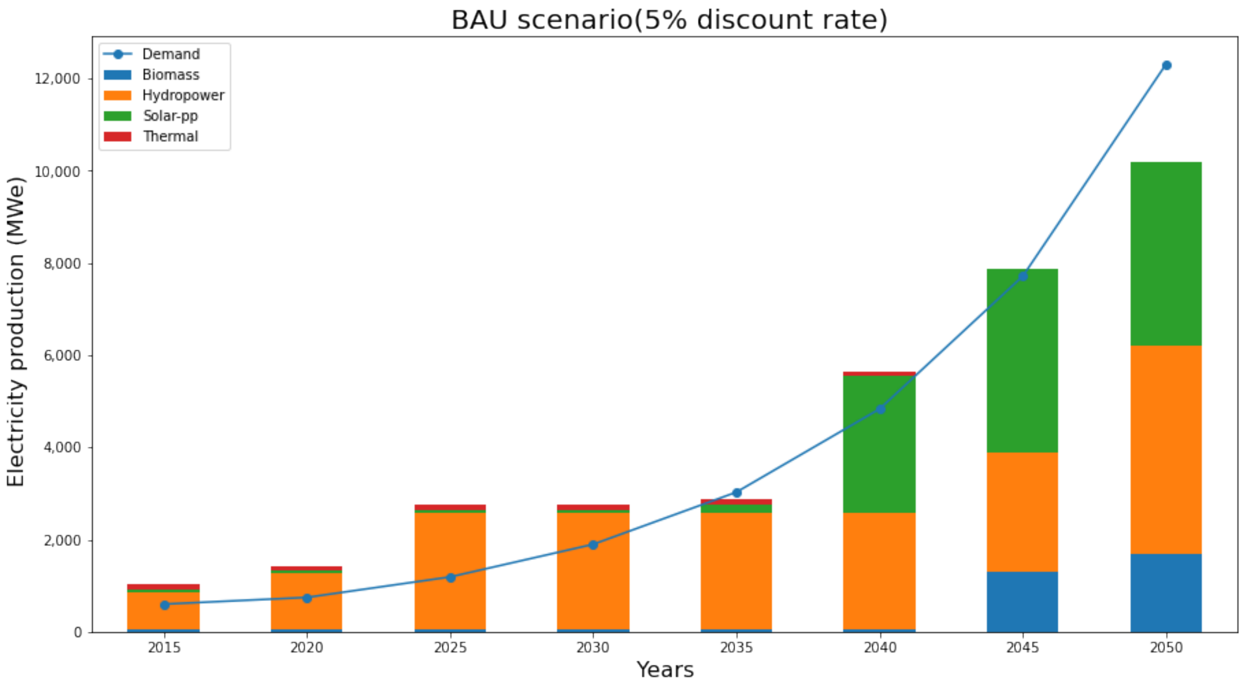

Figure 4. Total installed capacity of each electricity-generating technology in the BAU scenario.

3.2. The Reference Scenario (Scenario II)

This scenario considers the addition of new electricity-generating sources to the existing energy mix that Uganda is considering to include in its future electricity generation mix, according to Uganda Vision 2040. These include nuclear power (represented by Adv-PWR), peat, and geothermal. In this scenario, hydropower dominates the electricity generation mix for the first 20 years of the modeling period through 2035, contributing 69% of the total electricity mix in that year. Solar and peat become significant in 2040, contributing 46% and 12%, respectively. Although nuclear was added in 2035, it becomes competitive with other electricity-generating sources in 2045, where it contributes 2000 MWe (21%) and 3000 MWe (22%) in the last year of modeling. Geothermal is added to the energy mix in 2050 to balance the expanding energy demand, representing 10% of the total energy mix. The maximum electricity generation capacity for this scenario in the final year of modeling is 13,716 MWe. Biomass and thermal contribute the least with contributions of 0.4% and 0%, respectively, in the last year. The addition of new electricity-generating technologies of geothermal, peat, and nuclear increases electricity generation capacity from 10,200 MWe as seen in the BAU scenario to 13,716 MWe, for an increase of 3516 MWe. This addition helps to offset the electricity deficit that was observed in the BAU scenario. The results are shown in Figure 5 below.

3.3. The Optimistic Scenario (Scenario III)

This assumed scenario is similar to the reference scenario but includes the proposal for Uganda to include SMRs in the energy mix, using i-PWR (SMR) as a representative model of SMRs. The electricity generation mix for this scenario also has a major share of hydropower; however, in 2040, Adv-PWR and solar contribute a significant share: 23% and 35%, respectively. Modeling shows that i-PWR (SMR) contributes 13% of the total generating capacity in 2050. The total percentage of nuclear energy at the end of the modeling period is 30% of the remaining 17% coming from Adv-PWR. Other new non-nuclear technologies that were introduced also significantly contributed, increasing the total electricity generation capacity to 16,868.4 MWe from 10,200 MWe in the BAU scenario. This increased the electricity generation capacity by 6668.4 MWe, helping to overcome energy shortages observed in the BAU scenario. The new non-nuclear technologies include geothermal and peat, contributing 20% and 5%, respectively, in 2050. However, the existing technologies, such as hydropower and solar continue to have a significant share of the electricity generation mix in the last year, representing 30% and 27%, respectively. These results are shown in Figure 6, and advantages and disadvantages of each scenario are described in Table 4.

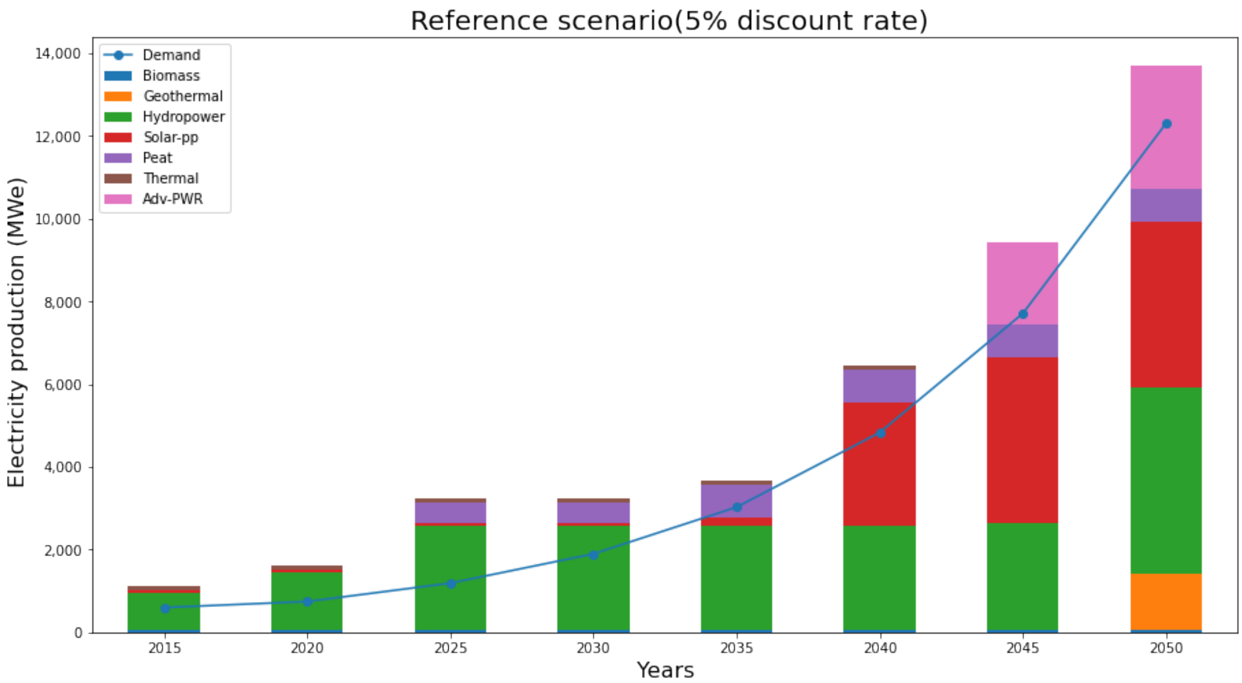

Figure 5. Total installed capacity of each electricity-generating technology in the reference scenario.

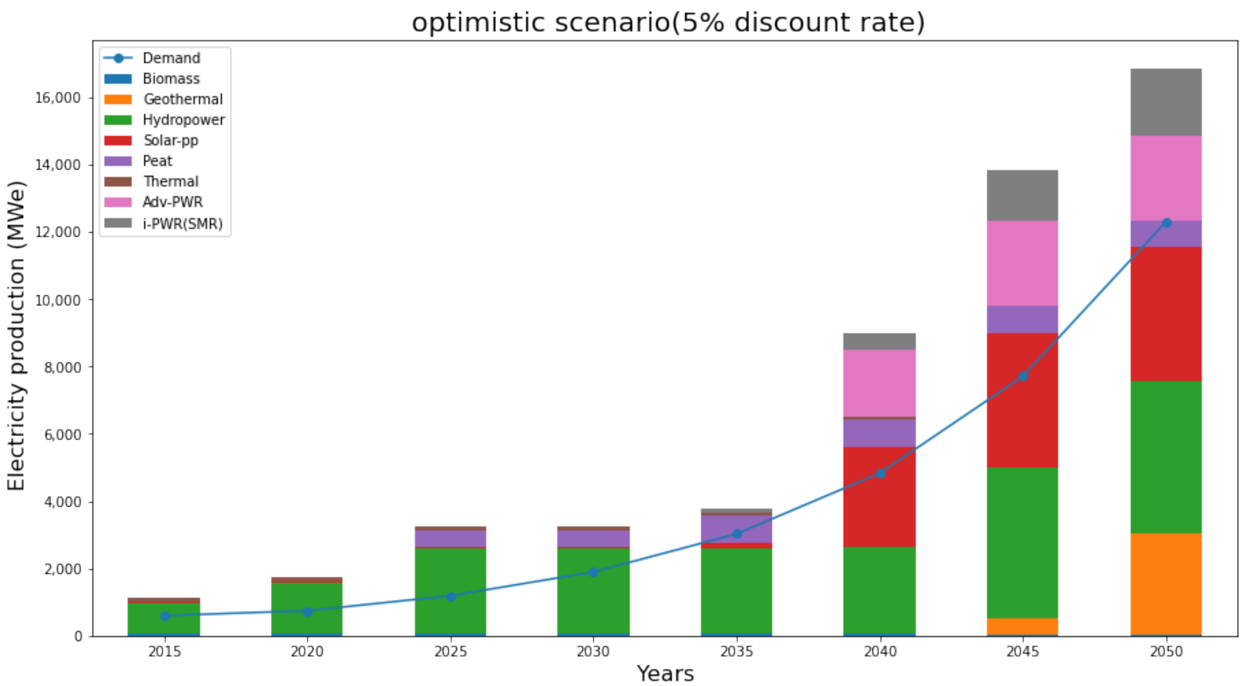

Figure 6. Total installed capacity of each electricity-generating technology in the optimistic scenario.

Table 4. Advantages and disadvantages of each scenario.

Scenario	Advantages	Disadvantages
BAU	- Little capital expenditure is required	- No energy mix diversification - Electricity shortages - Inefficient utilization of national resources
Reference	- Some degree of electricity mix diversification - Electricity generation matches demand	- Capital intensive
Optimistic	- Diversified electricity generation mix - Efficient utilization of national resources - Efficient satisfaction of demand	- Huge capital expenditures required

3.4. Sensitivity Analysis on Discount Rates

Sensitivity analysis was also performed for the optimistic scenario by increasing discount rates from 5% to 8% and 10%, to measure the effect of the discount rate on energy system development. For the discount rate of 5%, the total share of nuclear power, both Adv-PWR and i-PWR (SMR) reached 30% in the last year. The nuclear share reduced to 24% and 15% for discount rates of 8% and 10%, respectively. The share of nuclear power for the discount rate of 10% only came from i-PWR (SMR). These results are represented in Figure 7. The analysis showed that high discount rates favor generating technologies with lower investment costs, which reduce the competitiveness of nuclear energy. Therefore, the construction of nuclear power plants would be attractive at a lower discount rate.

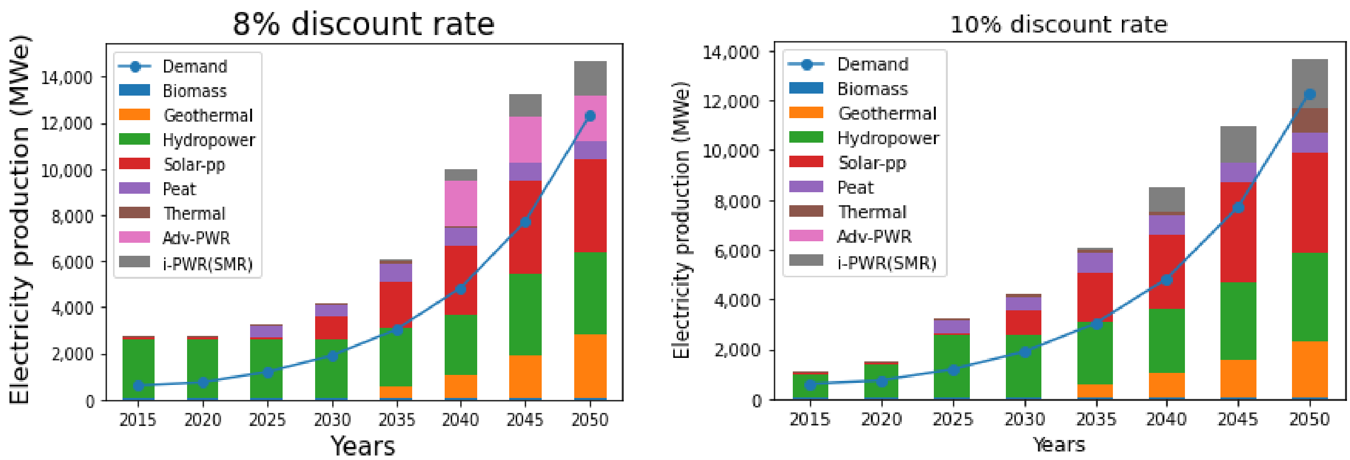

Figure 7. Total electricity production in the optimistic scenario for each technology, for 8% and 10 % discount rates.

3.5. LCOE Calculation Results

The LCOE for all technologies was calculated using Equation (2) and the input data in Table 3. An assumed discounted rate of 5% was used for LCOE calculation. This was conducted to compare the economic competitiveness of nuclear technologies compared to other competing technologies. The analysis was performed for large and small modular reactor and other technologies considered for Uganda's future electricity generation mix, i.e., hydropower, solar power (PV), solar hybrid, biomass, peat, geothermal, and thermal. The results are presented in Table 5.

Table 5. Calculated LCOE values for each technology.

Technology	Hydropower	Adv-PWR	i-PWR (SMR)	Solar (PV)	Solar Hybrid	Geothermal	Biomass	Peat	Thermal
LCOE ($/MWh)	36.28	79.77	78.01	39.53	59.81	43.33	343.74	131.77	261.86

The calculated results show that LCOE values for large nuclear reactors and small modular reactors deviated by a LCOE value of 1.76 $/MWh, with Adv-PWR (79.77 $/MWh) being slightly higher than the LCOE for i-PWR (SMR) (78.01 $/MWh). Nuclear technologies had significantly lower LCOE values compared to other competing technologies, such as peat (131.77 $/MWh), thermal (261.83 $/MWh), and biomass (343.74 $/MWh), showing that SMRs are more attractive for investment than large reactors, peat, thermal, and biomass. However, nuclear technologies had higher LCOE values than hydropower (36.28 $/MWh), solar PV (39.53 $/MWh), hybrid solar (59.81 $/MWh), and geothermal (43.33 $/MWh), as shown in Table 6.

Table 6. Robustness indices of nuclear technologies.

Robustness Index (RI) of Nuclear Technologies							
Technology	LCOE ($/MWh)	$\frac{LCOE_{hydro}}{LCOE_{nulcear}}$	$\frac{LCOE_{solar(PV)}}{LCOE_{nuclear}}$	$\frac{LCOE_{Geothermal}}{LCOE_{nuclear}}$	$\frac{LCOE_{peat}}{LCOE_{nuclear}}$	$\frac{LCOE_{thermal}}{LCOE_{nuclear}}$	$\frac{LCOE_{Biomass}}{LCOE_{nuclear}}$
Adv-PWR	79.77	0.45	0.50	0.54	1.65	3.28	4.31
i-PWR (SMR)	78.01	0.47	0.51	0.56	1.69	3.36	4.41
Alternative technology		Hydro	Solar (PV)	Geothermal	Peat	Thermal	Biomass
LCOE ($/MWh)		39.54	343.74	43.33	131.77	261.86	343.74

Consider that nuclear energy is considered more robust (competitive) when the RI value is higher than the tolerable limit (1.0). In this case, i-PWR (SMR) is slightly more competitive than Adv-PWR, considering that all of the associated RI values are higher. The results in the table reveal that nuclear energy technologies are more attractive than biomass, thermal, and peat, and less attractive than hydro and solar. Three critical input parameters were selected to estimate the RI for deviation from the data used to calculate the LCOE, namely discount rate, overnight capital costs, plant lifetime, and capacity factor. Each input parameter was perturbed separately, keeping other input parameters at their values used in the reference scenario. The LCOE corresponding to these values was calculated and the RI, $\frac{LCOE_{alternative}}{LCOE_{nuclear}}$, was calculated accordingly. The variation of the perturbed robustness index (RI_{pert}) from the reference robustness index (RI_{Ref}) was then calculated as a percentage and tabulated as shown in Table 7.

The differences in the levelized cost of energy and robustness index values, corresponding to perturbed parameter values are shown above. Based on the variation of the ratio $\frac{LCOE_{Alternative}}{LCOE_{Nuclear}}$ for the three perturbed input parameters, it can be noticed that the most critical parameter that affected the competitiveness of nuclear energy is the discount rate; the LCOE for nuclear technologies raised by 27% for a 3% increase in the discount rate. The perturbed robustness index (RI_{per}) varied the reference robustness index (RI_{Ref}) between 6–13% (for hydro), 0–2% (for solar), 12% (for peat), 18–20% (for thermal), and 17–18% (for biomass). It can be seen that increasing the discount rate has the least effect on nuclear energy competitiveness against solar while the highest impacts are observed in thermal and biomass plants. Increasing capital costs by 20% also affected the robustness of nuclear energy to some degree with the highest variability noticed for solar power, followed by biomass, while the least variability was observed in peat, geothermal, and hydro power. Decreasing plant life by 20% had the least effect on the robustness of nuclear energy where percentage variation in nuclear technologies varied between 0–8% for all technologies.

Table 7. Robustness indices of various nuclear technologies for the considered data perturbations.

Perturbed parameter/ power plant	Parameter variation	LCOE ($/MWh)	$\frac{LCOE_{hydro}}{LCOE_{nuclear}}$	$\frac{LCOE_{solar(PV)}}{LCOE_{nuclear}}$	$\frac{LCOE_{Geothermal}}{LCOE_{nuclear}}$	$\frac{LCOE_{peat}}{LCOE_{nuclear}}$	$\frac{LCOE_{thermal}}{LCOE_{nulcear}}$	$\frac{LCOE_{Biomass}}{LCOE_{nuclear}}$
			Variation of RI_{per} from RI_{Ref} (%)					
***Overnight Capital Cost* +20%**								
Adv-PWR		87.85	0.47 (4%)	0.79 (37%)	0.52 (4%)	1.61 (2%)	3.06 (7%)	4.02 (7%)
i-PWR (SMR)		83.28	0.50 (6%)	0.83 (38%)	0.55 (2%)	1.69 (0%)	3.23 (13%)	4.24 (17%)
Alternative technology			Hydro	Solar (PV)	Geothermal	Peat	Thermal	Biomass
LCOE values ($/MWh)			41.65	69.40	46.06	141.06	269.13	353.21
***Discount rate* +3%**								
Adv-PWR		101.18	0.5 (13%)	0.50 (0%)	0.51 (6%)	1.47 (12%)	2.73 (20%)	3.57 (17%)
i-PWR (SMR)		99.9	0.52 (6%)	0.50 (2%)	0.52 (7%)	1.49 (12%)	2.77 (18%)	3.61 (18%)
Alternative technology			Hydro	Solar (PV)	Geothermal	Peat	Thermal	Biomass
LCOE ($/MWh)			51.63	50.32	51.69	148.74	276.57	361.03
***Lifetime* −20%**								
Adv-PWR		81.67	0.45 (0%)	0.54 (8%)	0.56 (3.7%)	1.68 (2%)	3.25 (1%)	4.28 (1%)
i-PWR (SMR)		79.96	0.46 (2%)	0.55 (8%)	0.57 (2%)	1.71 (2%)	3.32 (1%)	4.37 (1%)
Alternative technology			Hydro	Solar (PV)	Geothermal	Peat	Thermal	Biomass
LCOE ($/MWh)			36.95	43.94	45.94	137.07	265.46	349.14

4. Discussion

In the BAU scenario, the electricity generation mix is limited to the existing technologies as of 2020, that is, hydro, solar, biomass, and thermal power plants. An electricity shortage of 156 MWe begins in 2035 and the deficit expands to 2109 MWe in the last year due to inadequate generation capabilities of the energy mix. This scenario shows that even if the existing electricity-generating technologies are utilized to their full potential, they cannot meet the future electricity demand as shown by the results in this scenario. For example, if fully utilized, the full potential of hydro resources add up to a total of 4500 MWe [8]; moreover, some of the existing hydro power plants, such as Nalubaale Hydroelectric Power Station with a capacity of 180 MWe, is about to reach the end of its design life after operating for 68 years. In addition, this scenario predicts an energy mix that is dominated by renewables (100% contribution) at the end of the modeling period, which makes the Ugandan electricity generation systems vulnerable to changes in climate conditions such as floods, which could devastate the country's generation capacity. This scenario shows that the existing electricity generation mix is insufficient to meet Uganda's electricity demand in the future, which calls for energy mix diversification to bring in new technologies that are more efficient and do not depend on climate conditions, such as nuclear and geothermal power.

The reference scenario was formulated based on Uganda Vision 2040 and Uganda's energy policy draft of 2019 [9] to diversify the energy mix by adding new electricity technologies, such as peat, geothermal, and nuclear energy, to increase generation capacity, and by reducing the impact of climate changes on the electricity generation supply. The results show that the total electricity generation capacity increased by 34% at the end of the modeling period and the electricity capacity grew beyond peak demand, which offset the electricity deficit that was seen in the BAU scenario. The optimistic scenario shows that for nuclear power to play a significant role in the future energy system, SMRs should be adopted as the total share of nuclear, increased from 21% in the reference scenario to 30%. This scenario shows that SMRs are competitive with other electricity technologies, which justifies the need for Uganda to consider SMRs in its future energy mix, helping to provide a stable and clean source of energy to compliment the intermittent hydroelectric power and solar power plants. A high discount rate gives more weight or importance to present expenditures than to future ones, while a low discount rate reduces these differences, favoring technologies that have high investment costs but low operating costs, which means that capital-intensive technologies such as nuclear power plants should come in at low discount rates. The results obtained for the LCOE were compared to those obtained in the surveyed literature. LCOE values from a study conducted by the US Energy Information Administration [52] for geothermal, biomass, solar hybrid, solar (PV), Adv-PWR, and hydropower technologies were compared with the calculated values from this study, while LCOE comparison for SMRs and thermal power was performed with different studies, respectively [56,57]. No literature was available for LCOE comparison with peat power plants. LCOE values for geothermal, solar hybrid, solar (PV), Adv-PWR, and i-PWR (SMR) deviated by smaller margins, while significant differences were reported for thermal and biomass plants, as shown in Figure 8. The disparity in LCOE values for thermal power plants is majorly due the fact the literature study used the 2003 US dollar for calculating costs while this study used the 2020 US dollar. Meanwhile, the disparity in LCOE values for biomass is due to differences in costs assumed in either studies. For example, this study used United States generic costs due to the absence of data for Uganda; this can lead to discrepancies in calculated values. For example, LCOE values for biomass are likely to be far less in Uganda due to an abundance of fuel for this resource, significantly cutting fuel costs. For SMRs, actual LCOE values in Uganda are likely to be higher than those calculated in this study or used as a reference in other studies due to high costs that will be incurred in developing infrastructure for SMRs, considering that the country has little nuclear infrastructure. However, these costs are expected to be higher for the first SMRs and relatively lower for the one of a kind SMRs due technology learning and sufficient infrastructure development in the future. The calculated LCOE values for solar hybrid are higher than those of solar (PV) due to additional costs required for the installation of the battery storage for a hybrid solar PV plant; however, a hybrid solar plant comes with the advantages of better efficiency due to its ability to store power and provide it whenever required.

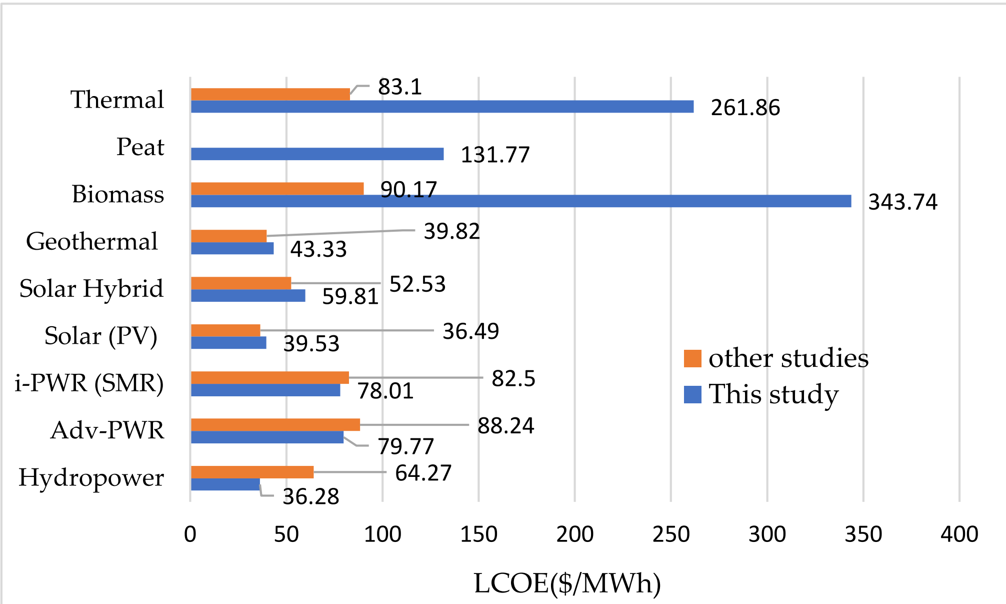

Figure 8. Comparison between LCOE values for this study and other studies.

5. Conclusions

The electricity peak demand for Uganda was projected to expand to 12309 MWe in 2050 from 489 MWe in the base year. To meet this demand, an optimal future energy mix for Uganda was modeled by formulating three scenarios, namely the BAU scenario, reference scenario, and optimistic scenario. The findings reveal that Uganda cannot rely on the existing energy mix to meet the future energy demand as there would be energy gaps as shown in the BAU scenario. Moreover Uganda would depend primarily on solar and hydro power plants to meet this demand, and these plants rely on weather conditions. The addition of other electricity-generating technologies, such as nuclear, geothermal, and peat power plants, to the energy mix shows that Uganda can counter electricity shortages and have a sustainable energy mix throughout the study modeling period, with peat adding 500 MWe by 2025, nuclear energy contributing 2000 MWe by 2045, and geothermal energy contributing 1365 MWe by 2050. In this scenario, the major electricity-generating technologies in the descending order of total installed capacity contribution would be hydro, solar, nuclear, geothermal, and peat power plants. However, the optimistic scenario (the proposed scenario for the introduction of SMRs) showed an increase in nuclear power generation from 21% to 30% contribution to a more stable and diversified energy system, meeting Uganda's future energy needs. According to the study findings, nuclear energy can be an important candidate for domestic electricity production in terms of cost competitiveness and security of supply. The findings show that nuclear power can contribute up to 21% in 2050 if only a large reactor design (Adv-PWR) is installed; however, this nuclear share can increase to 30% if SMRs are added to the nuclear energy portfolio to secure the projected national electricity demand. The MESSAGE model depicts the entire nuclear energy system with time-dependent parameters for medium- and long-term planning. The MESSAGE is capable of performing energy system optimization and selecting the best alternative for energy generation while taking into account various types of objective functions (cost, uranium use, waste generated, etc.).

Author Contributions: Conceptualization, N.D.; methodology, N.D.; software, N.D.; validation, J.K.; formal analysis, N.D. and J.K.; investigation, N.D. and J.K.; resources, N.D. and J.K.; data curation, N.D.; writing-original draft preparation, N.D.; writing-review and editing, N.D.; visualization, N.D.; supervision, J.K.; project administration, J.K.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2003015). This research was also supported by the 2022 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request from the corresponding author.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Uganda G of Executive Summary Energy Efficiency Roadmap for Uganda Making Energy Efficiency Count [Internet]. Available online: https://escholarship.org/uc/item/7wb7r4dr (accessed on 15 July 2022).
2. GIZ. Sector Brief Uganda: Renewable Energy. GIZ [Internet]. 2022. Available online: https://www.giz.de/en/downloads/giz2022-en-sectorbrief-uganda-renewable-energy.pdf (accessed on 14 July 2022).
3. World Bank. Uganda Overview: Development News, Research, Data World Bank [Internet]. 2022. Available online: https://www.worldbank.org/en/country/uganda/overview (accessed on 14 July 2022).
4. Enterprise Agency. *Final Energy Report Uganda Commissioned by the Netherlands Enterprise Agency*; Natural Resource Governance Institute: New York, NY, USA, 2018.
5. ERA. Electricity Regulatory Authority—Homepage [Internet]. 2017. Available online: https://www.era.go.ug/index.php?option=com_content&view=article&id=214:renewable-energy-opportunities&catid=100:renewable-energy-investment-guide (accessed on 15 July 2022).

6. Ministry of Energy and Mineral Development. *Study on Integrating Nuclear Power in Generation Capacity Plan 2015–2040 Final Report*; Ministry of Energy and Mineral Development: Kampala, Uganda, 2015.
7. Uganda Electricity Sector [Internet]. Available online: https://www.era.go.ug/index.php/sector-overview/uganda-electricity-sector (accessed on 13 June 2022).
8. Uganda Vision 2040. *Annu. Meet Midwest Polit. Sci.* **2007**, *12*, 1–7. Available online: chrome-https://www.greengrowthknowledge.org/sites/default/files/downloads/policy-database/UGANDA%29%20Vision%202040.pdf (accessed on 16 June 2022).
9. Ministry of Energy and Mineral Development. *Draft National Energy Policy*; Ministry of Energy and Mineral Development: Kampala, Uganda, 2019.
10. WNA. IAEA Completes Ugandan Nuclear Infrastructure Review: New Nuclear—World Nuclear News [Internet]. 2022. Available online: https://www.world-nuclear-news.org/Articles/IAEA-completes-Ugandan-nuclear-infrastructure-revi (accessed on 15 July 2022).
11. WNA. Emerging Nuclear Energy Countries [Internet]. Nuclear Safety. 2022, pp. 1–27. Available online: https://world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx (accessed on 15 July 2022).
12. IAEA. IAEA Reviews Sri Lanka's Nuclear Power Infrastructure Development IAEA [Internet]. 2022. Available online: https://www.iaea.org/newscenter/pressreleases/iaea-reviews-ugandas-nuclear-power-infrastructure-development (accessed on 12 June 2022).
13. International Atomic Energy Agency IAEA. Milestones Approach IAEA [Internet]. Available online: https://www.iaea.org/topics/infrastructure-development/milestones-approach (accessed on 15 July 2022).
14. Reuters. Southern Sticks to Cost, Startup Estimates for Vogtle Nuclear Reactors in Georgia Reuters [Internet]. 2022. Available online: https://www.reuters.com/business/energy/southern-sticks-cost-startup-estimates-vogtle-nuclear-reactors-georgia-2022-04-28/ (accessed on 13 July 2022).
15. Augustachronicle. Plant Vogtle Cost Doubles to $28.5 Billion as Other Owners Balk [Internet]. 2021. Available online: https://www.augustachronicle.com/story/news/2021/11/04/georgia-power-nuclear-reactors-plant-vogtle-cost-doubles-energy-costs/6286729001/ (accessed on 13 July 2022).
16. WNN. US Governor Releases Report on VC Summer Flaws [Internet]. World Nuclear Association. 2017. Available online: https://www.world-nuclear-news.org/C-US-governor-releases-report-on-VC-Summer-flaws-06091701.html (accessed on 13 July 2022).
17. World Nuclear News. Fresh Delay to Flamanville 3 Blamed on Pandemic: New Nuclear—World Nuclear News [Internet]. 2022. Available online: https://www.world-nuclear-news.org/Articles/Fresh-delay-to-Flamanville-blamed-on-impact-of-pan (accessed on 13 July 2022).
18. Liou, J. What are Small Modular Reactors (SMRs)? [Internet]. International Atomic Energy Agency. 2021. Available online: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs (accessed on 15 July 2022).
19. IAEA. Small modular reactors. *Mater. World* **2014**, *22*, 44–47. Available online: https://www.iaea.org/topics/small-modular-reactors (accessed on 15 July 2022).
20. Reitsma, F.; Subki, M.H.; Luque-Gutierrez, J.C. Advances In Small Modular Reactor Technology Developments 2020 Edition A Supplement to: IAEA Advanced Reactors Information System (ARIS). 2020. Available online: http://aris.iaea.org (accessed on 17 July 2022).
21. International Atomic Energy Association. *Advances in Small Modular Reactor Technology Developments*; International Atomic Energy Agency: Vienna, Austria, 2014.
22. Kim, J.; Abdel-Hameed, A.; Joseph, S.R.; Ramadhan, H.H.; Nandutu, M.; Hyun, J.H. Modeling long-term electricity generation planning to reduce carbon dioxide emissions in Nigeria. *Energies* **2021**, *14*, 6258. [CrossRef]
23. Esmail, S.M.M.; Cheong, J.H. Studies on Optimal Strategy to Adopt Nuclear Power Plants into Saudi Arabian Energy System Using Message Tool. *Sci. Technol. Nucl. Install.* **2021**, *2021*, 8818479. [CrossRef]
24. Michaelson, D.; Jiang, J. Review of integration of small modular reactors in renewable energy microgrids. *Renew Sustain. Energy Rev.* **2021**, *152*, 111638. [CrossRef]
25. Budnitz, R.J.; Rogner, H.H.; Shihab-Eldin, A. Expansion of nuclear power technology to new countries—SMRs, safety culture issues, and the need for an improved international safety regime. *Energy Policy* **2018**, *119*, 535–544. [CrossRef]
26. Kinley, D.; Fao, I.; Piel, J.Y. Photos on the Cover. Available online: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1222_web.pdf (accessed on 13 July 2022).
27. IAEA. IAEA Nuclear Energy Series @ Modelling Nuclear Energy Systems with MESSAGE: A User's Guide Modelling Nuclear Energy Systems with MESSAGE: A User's Guide. Available online: https://www.iaea.org/publications/10861/modelling-nuclear-energy-systems-with-message-a-users-guide (accessed on 13 June 2022).
28. Abdel-Hameed, A.; Kim, J.Y.; Hyun, J.H.; Ramadhan, H.H.; Joseph, S.R.; Nandutu, M. Optimization of electricity generation technologies to reduce carbon dioxide emissions in Egypt. *Appl. Sci.* **2021**, *11*, 8788. [CrossRef]
29. IAEA. *Approaches to Assess Competitiveness of Small and Medium Sized Reactors*; International Atomic Energy Agency: Vienna, Austria, 2009; pp. 27–30.
30. Connolly, D.; Lund, H.; Mathiesen, B.V.; Leahy, M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl. Energy* **2010**, *87*, 1059–1082. [CrossRef]

31. EIA. International-U.S. Energy Information Administration (EIA) [Internet]. 2020. Available online: https://www.eia.gov/international/data/country/UGA/electricity/electricity-consumption?pd=2&p=0000002&u=0&f=A&v=mapbubble&a=-&i=none&vo=value&&t=C&g=none&l=249--234&s=315532800000&e=1577836800000 (accessed on 8 August 2022).
32. Okoboi, G.; Mawejje, J. Electricity Peak Demand in Uganda: Insights and Foresight. *Energy Sustain. Soc.* **2016**, *9*, 26. [CrossRef]
33. Proven Oils Reserves for Uganda Search [Internet]. Available online: https://www.bing.com/search?q=proven+oils+reserves+for+Uganda&qs=n&form=QBRE&sp=-1&pq=proven+oils+reserves+for+uganda&sc=8-31&sk=&cvid=38BAF08F8AD64AADB7E3AAED53380261 (accessed on 13 June 2022).
34. Worldoil. Uganda Stands to Be One of Sub-Saharan Africa's Top Five Oil Producers by 2025 [Internet]. Available online: https://www.worldoil.com/news/2021/6/9/uganda-stands-to-be-one-of-sub-saharan-africa-s-top-five-oil-producers-by-2025 (accessed on 13 June 2022).
35. Worldometer. Uganda Natural Gas Reserves, Production and Consumption Statistics—Worldometer [Internet]. Available online: https://www.worldometers.info/gas/uganda-natural-gas/ (accessed on 13 June 2022).
36. Uganda Says Russia to Help It Develop Nuclear Energy Reuters [Internet]. Available online: https://www.reuters.com/article/us-uganda-russia-idUSKBN1W328N (accessed on 18 July 2022).
37. Bloomberg. Uganda Acquires Land for East Africa's First Nuclear Power Plant—Bloomberg [Internet]. 2022. Available online: https://www.bloomberg.com/news/articles/2022-05-10/uganda-acquires-land-for-east-africa-s-first-nuclear-power-plant#xj4y7vzkg (accessed on 30 June 2022).
38. (NCDC) NC for DC. 2020 Edition. National Guidelines on Infection Prevention and Control for Viral Hemorrhagic Fevers (VHF) [Internet]. 2020. Available online: https://ncdc.gov.ng/themes/common/docs/protocols/111_1579986179.pdf (accessed on 12 July 2022).
39. IAEA. Basic Principles Objectives IAEA Nuclear Energy Series. Available online: https://www.iaea.org/publications/10604/inpro-methodology-for-sustainability-assessment-of-nuclear-energy-systems-economics (accessed on 20 June 2022).
40. NREL. Simple Levelized Cost of Energy (LCOE) Calculator Documentation Energy Analysis NREL [Internet]. Available online: https://www.nrel.gov/analysis/tech-lcoe-documentation.html (accessed on 30 June 2022).
41. Allan, G.; Gilmartin, M.; McGregor, P.; Swales, K. Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of "banded" renewables obligation certificates. *Energy Policy* **2011**, *39*, 23–39. [CrossRef]
42. Aquila, G.; Pamplona, E.O.; Queiroz, A.R.; Rotela, J.P.; Fonseca, M.N. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. *Renew Sustain. Energy Rev.* **2017**, *70*, 1090–1098. [CrossRef]
43. Lazard. Levelized Cost Of Energy, Levelized Cost of Storage, and Levelized Cost Of Hydrogen [Internet]. 2021, pp. 1–5. Available online: https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/ (accessed on 5 August 2022).
44. Aldersey-Williams, J.; Rubert, T. Levelised cost of energy—A theoretical justification and critical assessment. *Energy Policy* **2019**, *124*, 169–179. [CrossRef]
45. Larsson, S.; Fantazzini, D.; Davidsson, S.; Kullander, S.; Höök, M. Reviewing electricity production cost assessments. *Renew Sustain. Energy Rev.* **2014**, *30*, 170–183. [CrossRef]
46. Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies on JSTOR [Internet]. Available online: https://www.jstor.org/stable/29783746 (accessed on 5 August 2022).
47. Gross, R.; Blyth, W.; Heptonstall, P. Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. *Energy Econ.* **2010**, *32*, 796–804. [CrossRef]
48. Hansen, K. Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs. *Energy Strateg. Rev.* **2019**, *24*, 68–82. [CrossRef]
49. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renew Sustain. Energy Rev.* **2014**, *33*, 74–86. [CrossRef]
50. Ringkjøb, H.K.; Haugan, P.M.; Solbrekke, I.M. A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renew Sustain. Energy Rev.* **2018**, *96*, 440–459. [CrossRef]
51. IAEA. Experience in Modelling Nuclear Systems with Message: Country Case Studies. Iaea-Tecdoc-1837 [Internet]. 2018. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1837web.pdf (accessed on 10 June 2022).
52. EIA. *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*; U.S. Energy Information Administration: Washington, DC, USA, 2020; p. 212.
53. EIA. *Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013*; U.S. Energy Information Administration: Washington, DC, USA, 2022; pp. 1–5.
54. NREL. Data Electricity 2022 ATB NREL [Internet]. 2022. Available online: https://atb.nrel.gov/electricity/2022/data (accessed on 4 August 2022).
55. Reuters. Group Building Rwandan Peat-Fired Power Plant Signs Financing Deal | Reuters [Internet]. 2016. Available online: https://www.reuters.com/article/ozabs-uk-rwanda-electricity-idAFKBN13I0RN (accessed on 4 August 2022).

56. Weimar, M.R.; Zbib, A.; Todd, D.; Buongiorno, J.; Shirvan, K. Techno-Economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest April 2021. Available online: https://www.ntis.gov/about (accessed on 4 August 2022).
57. OECD. *Projected Costs of Generating Electricity*; OECD: Paris, France, 2005.