Scenario Analysis of the Low Carbon Power System in Zambia by Using an Integrated Energy Demand-Supply Modeling Approach

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Scenario analysis of the low carbon power system in Zambia by using an integrated energy demand-supply modeling approach

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Abstract

Zambia has recently integrated solar and wind into its power system. Yet, to date, it is still struggling to reach an optimal energy-environment-economic nexus. The lack of planned investment in the energy sector has made the country's economy vulnerable. Zambia has a growing population that relies on energy to meet their needs. However, the development of more power grids is still be undertaken. In the meantime, the country continues to import energy resources such as oil and electricity to meet the demand. The consumption rate of the final electricity in Zambia is yet to be fully matched by the actual generation produced. The increase in demand has led to continuous power cuts, a factor in the gradual development of the country's economy. The power shortfall in the country has also led to the continuous use of fossil-based energy supply options for heating and electricity production. This has led to a predominance of emissions, indicating that, government and institutional structures should integrate climate change policies across all sectors. This study focuses on developing a bottom-up interlinked energy demand-supply modeling framework that considers energy supply options in meeting Zambia's energy demand. The model's objective is to choose a combination of resources and technologies, subject to satisfying techno-economic and environmental constraints. To help assist in policymaking, this model analyzes the effects of different scenarios compared to a baseline (2019) scenario on energy demand and supply. For the case of the demand side, past data on electricity demand were analyzed to predict the future electricity demand under the current policies. The baseline scenario results revealed the power outages in Zambia, especially at peak times, which have been attributed to reliance on imported fuel for power generation, slow-paced integration of renewable resources, and not fully utilizing resource potential for the supply side. To overcome the power outages and meet the electricity demand in 2035, a comprehensive scenario analysis was conducted, including the main scenarios of 30% integration of renewable energy, no coal power generation, and low emission targets (10%, 20%, 30%, 40%, and 50% reduction from the baseline) in 2035. The expected CO_2 reductions from the renewable energy scenario, No coal scenario, and 50% low emission target are estimated at 5222 kilotons in 2035, respectively. The rationing of power in Zambia is a significant issue that needs policy diversification and integration of other energy sources. Therefore, the electricity supply must be explored to its full potential for Zambia's economic growth forecast to increase.

Keywords: Zambia, Integrated energy system modeling; cost-minimization approach, GHG emissions, Seasonal Autoregressive Integrated Moving Average

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Chapter 1

Introduction

1.1. Background.

Zambia has experienced a severe electricity supply shortage since 2016.[1] Zambia is in Sub-Saharan Africa, where the average population has limited access to electricity. The World Bank indicators show 44.52% of the people in Zambia have access to electricity [2]. Looking at economic indicators and past historical data of the country, the country is showing slight progress in utilizing its wide range of energy resources to supply electricity. However, there is an urgent need to improve the capacity factor of the power sector to reduce the chronic energy deficit in Zambia.

Energy-related policy and investing decisions are critical and should consider all possible power supply and demand side options. The energy sector, through its CO_2 emissions, transforming resources into electricity, seems to be the leading contributor to greenhouse gases. Zambia's Intended Nationally Determined Contribution (INDC) commits to reducing GHG emissions by 25 percent by 2030.[3] The country commits to achieving this reduction through domestic efforts and the possibility of international support.

Electricity generation and consumption in the country contribute approximately 40% of global CO2 emissions [4]. In Zambia, fuel combustion activities and energy industries present a major environmental hazardous challenge. Figure 1.1 represents the historical contribution of the fossil fuel source to total GHG emissions in Zambia. Annual CO_2 emissions per capita for fossil fuels, specifically oil and coal in Zambia, have sharply increased from 1630 kilotons in 2000 to 6340 kilotons in 2018.[5] The limited enforcement of sustainable energy transition technologies makes the country vulnerable to the effects of climate change. Zambia is ranked 26 out of 182 countries in the 2018 Global Climate Risk Index and is classified as having high to extreme risk in the 2018 Climate Change Vulnerability Index[6]. In addition, in Zambia's envisioned future economic activities and population increase, there would be increased electricity demand. Since, most investments are allocated to social development projects, particularly health, education, institutional housing, and water supply, the renewable energy projects deployment has not been effectively hailed yet, as one of the prerequisites for fostering green growth and achieving sustainable development in this country. Increasing the penetration of variable renewable technologies is one important approach to climate mitigation.

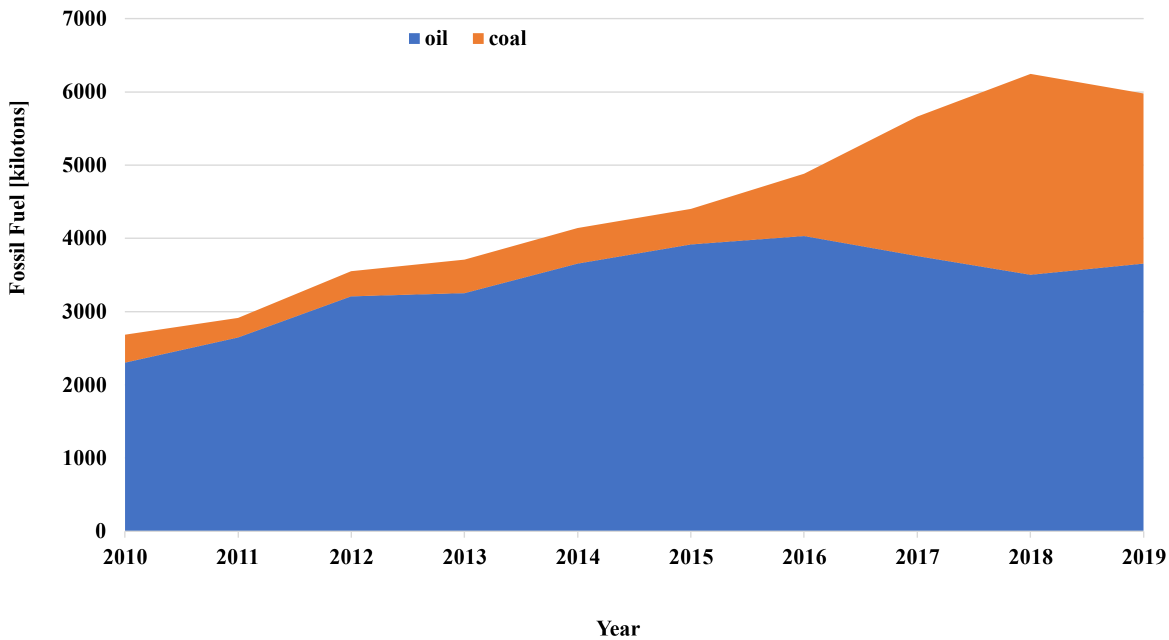

Figure 1.1. Trends of CO_2 emissions from different fossil fuels (adapted from [5]).

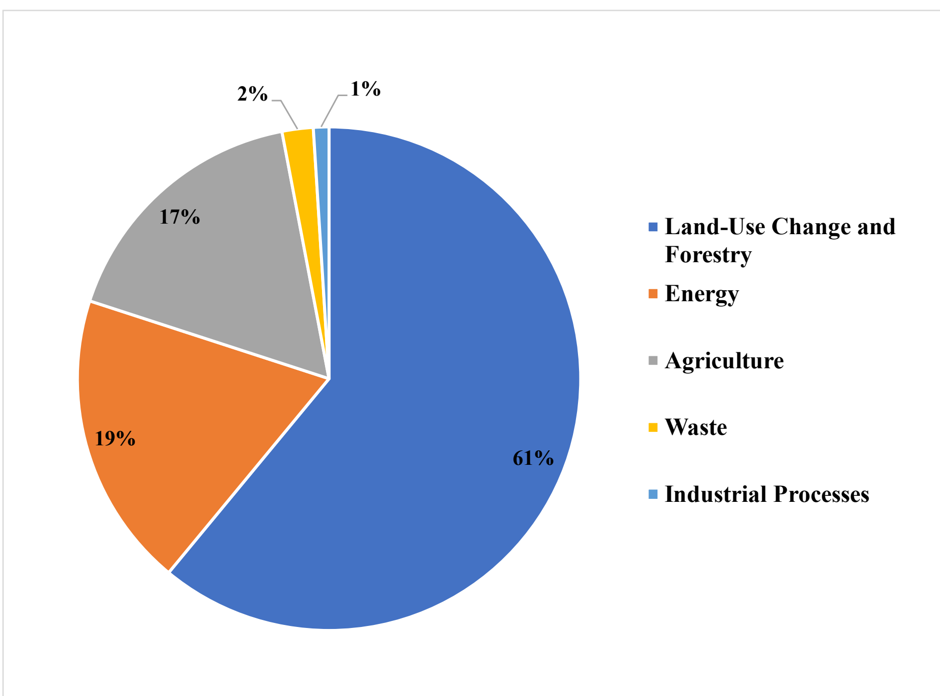

Figure 1.2. Contribution of sectors of the energy system(adapted from[7]).

Figure 1.2 shows the five different sectors contributing to the country's emissions. Notably, a huge demand for energy leads to emissions due to conversion processes. Several greenhouse gases, such as methane and nitrous oxide, have contributed to global climate change. Zambia showed commitment by complying with the SDG 13 measures set by the United Nations. Zambia signed the treaty with the United Nations Framework on Climate change (UNFCCC) to reduce their GHG emissions through employing low carbon-based energy generation and efficient consumption.[5] To justify the efforts of the clean energy transition, feasibility studies on potential sites to install renewable energy sources that can increase the installed National Electricity Capacity of Zambia. The proliferation of wind and solar energy in Zambia will help lessen the emissions from industrial processes in the energy sector. The country is subject to adverse impacts of climate change due to its location, social-economic stresses, and its low adaptive capacity[8]. As a country dependent on hydropower generation, climate change significantly impacts droughts and disaster-related infrastructure damage, such as dams.

The yearly Energy Sector Report, which gives an overview of the Energy Sector in Zambia, has affirmed the power deficits that have been occurring in the country. Figure 1.3 shows the steady national electricity generation compared to the recorded power deficit in electricity. According to the 2019 Energy sector Report, one of the reasons for the power deficit was the generation constraints from hydropower stations is low water levels.[9]

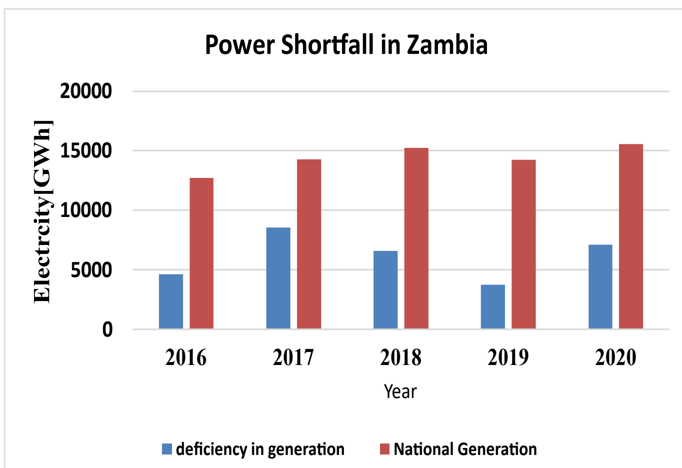

Figure 1.3. Trend of electricity deficiency in Zambia.

Figure 1.4 shows the 2019 energy mix of the country.

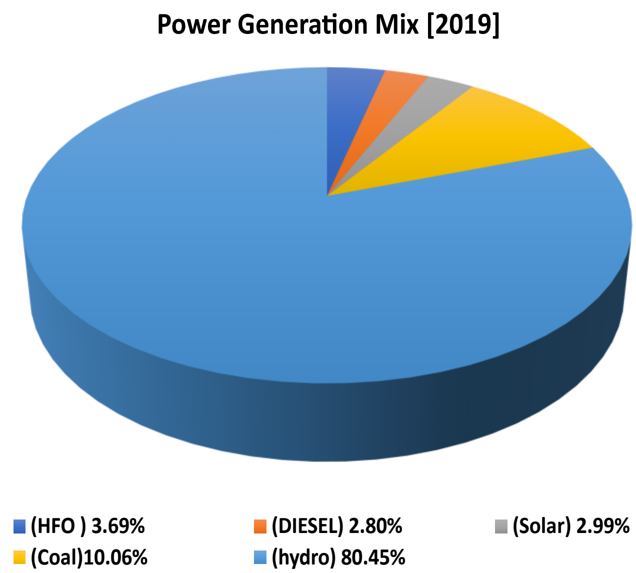

Figure 1.4. The power generation mix for the base year.

The concern of climate change and energy security is crucially shown in the energy supply of the Hydropower plant, which accounts for 80.45 percent of installed capacity and use of fossil fuels. Another alarming concern is the low capacity of solar, which is a variable renewable energy resource in the mix.

1.2. Literature Review.

There are few studies focused on the context of Zambia's energy system and implementing energy policies that would promote different scenarios in this system. In recent years, distinct methodological techniques and toolkits have been applied to forecast energy demand and supply. The demand side has mainly consisted of models considering the overall correlation of peak demand and energy consumption with economic factors to evaluate each demand factor separately. The Peak demand forecast in Zambia has proven to be important to ensure that future supply security does not exceed the maximum system load.

Supply-side models have mainly focused on the existence and future availability of energy supply technologies, considering each technology using optimization or simulation. Prudenzi et al. projected the outlook of energy demand and supply in the national electric system in Zambia, taking into account the optimal integration of renewable energy sources such as wind and solar energy, addressing the technical and economic constraints with a special focus on the different demand load patterns in the region for the years 2025 and 2030 [10]. The methodological approach considered the reference scenario of the country, statistical analysis, and a hybrid approach combining probabilistic and deterministic methods have been developed for the dynamic sizing of the operating reserve. To select the cost-effective mix, the simulation of the variable renewable energy sources (solar and wind) and the hydro-thermal dispatching of the system operation was done hourly. As a result, the different technologies were optimally coordinated, finally considering the analysis of the grid constraints (Zambia transmission network, grid load ability, and security of supply). Their results revealed that, an installed capacity of 1,176MW from solar and 1,200 MW from wind would be needed up to 2025. Although, despite this renewable energy integration, the energy supply would still be insufficient to meet the electricity demand in 2025. Therefore, the installed capacity needed to increase by 36% in 2030, even with the additional installed capacity from renewable resources. The Zambia Electricity cost of service study further described the necessary steps for long-term reliability of the transmission network to meet higher peak demand despite network constraints in the horizon 2020-2040. In addition, the need to develop the electricity supply system, by adding more hydroelectric capacity and increasing the installed capacity of solar and wind energy [11].

Zambia's electricity system would be affected by droughts, and how the system's adaptative capacity could be improved. Bernard Tembo et al. projected the energy demand of Zambia, using the Long-range Energy Alternative Planning system, and showed an increasing demand. Their results revealed that there is a need for Zambia to have additional policies to diversify the electricity system. In addition, a dry year can limit hydropower and increase generating costs either by importing electricity or capital investments for oil and coal power plants. in this study, the demand projections were made using the Long-Range Alternative Planning system (LEAP). LEAP was chosen because of its adequacy in modeling the demand side of the Zambian system. It tracks energy consumption and production in all sectors of an economy. In this model, the energy is a function of activity multiplied by the energy intensity of the activity. It also considers the economic sectors, residential, electricity intensity, base year intensity, and growth in GDP, the elasticity between electricity intensity and income. Their results also stated that there is a need for Zambia to have additional policies to diversify the electricity system. In addition, a dry year can limit hydropower and increase generating costs either by importing electricity or capital investments for oil and coal power plants[12]. Lucy Allington et al. assessed the implications of different scenarios (fossil future, least cost, and Net Zero 2050) to improve energy sector policy-making for 2020-2050[13]. The model selected in this study was the Open-Source Energy Modelling System (OSeMOSYS), which uses techno-economic data for power transmission, refineries, and electricity generation technologies to provide a projection for estimated costs of renewable energy technologies up to 2050. Their studies concluded the future reduction of these technologies from base year 2020.

Zambia has no known petroleum deposits; therefore, it is a country that is highly impacted by the dynamic conditions of importing oil for energy use. The correlation between the cost of oil and the amount imported is a huge disparity. The cost of imports continues to increase regardless of the state of the economy. In addition, the unfavorable climate risks aversions associated with fossil fuel use. Most of the energy modeling tool show details of the end-use sectors and representation of their electricity consumption. This has led to increased modeling tools to show the spatial scale and market penetration of technologies as a function of price and relevant policy interventions.

Some of the recent studies in Zambia energy system modeling are presented in Table 1.1.

The similarities with all the mentioned models are factoring in the relationships of energy demand, supply, emissions, electricity transmission, and capacity expansion and costing to ensure energy supply security, reduce greenhouse gas emissions, and develop and integrate clean energy technologies.

Table 1.1. Related works on energy modeling in Zambia-Africa.

Purpose	Focus sector	Horizon	Methodological Approach	Tool/Techniques Employed	Reference
Modeling energy requirements for a biogas-supported decentralized water treatment systems for communities Chambishi (Zambia) and diepsloot (South Africa) townships.	Supply	-	Optimization	Buswell mathematical model	[14]
Modeling of the wind energy potential in Zambia.	Supply	2031-2050	Simulation and dynamical downscaling approaches	High CORDEX-Africa models	[15]
Assessment of solar energy Distribution and Potential in Zambia.	Supply	-	Simulation	ArcGIS and array model (excel)	[16]
Scenario analysis of the sustainable development of Zambia's electricity sector.	Demand and Supply	2008-2030	Simulating/accounting/ optimization	LEAP/ MESSAGE	[12]
Modeling sustainable long-term electricity supply-demand in Africa.	Demand and Supply	-	Accounting/Simulation	LEAP	[17]

1.3. Modeling approach used in energy system analysis.

Optimization models:

These models are used to determine the best possible solution considering decision-making variables, parameters describing the system, and constraints. The objective function is matched with suitable least-cost solutions of technology choices for energy systems based on subjective constraints. In addition to the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), Market Allocation (MARKAL) and PRIMES Energy System Model are considered in this category [18]. Modeling tools such as MARKAL and MESSAGE can also be coupled with general equilibrium models to calculate quadratic demand curves of energy prices[18]. The MARKAL program aims to integrate energy analysis and planning by minimizing long-term costs [19].

Hybrid Models:

These models merge different methodological components considering endogenous relationships between the economy and the energy system. This means there is no essential necessity for determining economic factors such as employment, income effects, economic growth rates, and competitiveness). In this category, LEAP, PAMS, and BUENAS models combine elements of simulation and accounting models[18]. Long-Range Energy Alternatives Planning System is a general-purpose energy accounting model in which the model developer inputs all data to project end-use activity and intensity [20]. The main objective of the development of BUENAS is to provide the most accurate and comprehensive assessment possible of energy savings and greenhouse gas emissions reductions from the energy efficiency program. It is designed as a policy analysis tool to create scenarios with the goal of higher energy efficiency [21]. It provides a comprehensive assessment of possible energy savings and greenhouse gases. It calculates the carbon dioxide mitigation from final energy savings by integrating a carbon conversion factor each year for the specified time.

In general, the bottom-up models try to find ways of searching for alternate energy sources for energy security. The top-down models use accounting procedures to factor in energy as an input to the economy and quantify the impact on the economy, considering the constraints of the available energy supplies.

Table 1.2 summarizes the different modeling approaches used in energy systems analysis.

Table 1.2. The summary of different energy models [22].

Model	Developer	Purpose	Modelling Paradigm	Methodological Approach
BUENAS (Bottom-Up Energy Analysis System)	USA(Lawrence Berkeley National Laboratory)	Energy demand	User-defined (Hybrid)	Simulation/Accounting
LEAP	USA(SEI)	Integrated	User-defined (Hybrid)	Simulation/Accounting
MAED	Austria(IAEA)	Energy demand	Bottom-up	Simulation/Accounting
MARKAL-MACRO	Brookhaven National Laboratory USA	Integrated	Hybrid	Macro-economic/Optimization
MARKAL	OECD-IEA	Energy Supply	Bottom-up	Optimization/Equilibrium
MESSAGE (I,II,III)	Austria(IIASA)	Energy Supply	Bottom-up	Optimization/Equilibrium
NEMS	USA(DOE-EIA)	Energy Demand	Least-Cost(Top-Down)	Simulation/Optimization/Equilibrium
NIA	USA(DOE-EIA)	Energy Demand	User-defined/shipment elastic model	Accounting
MESSAGE-MACRO	IIASA Austria	Integrated (Energy Supply Linked to Macroeconomics)	Hybrid	Simulation/Accounting
PRIMES	Greece(NTUA)	Integrated	Least-Cost(Hybrid)	Optimization/Equilibrium
REEPS	USA(EPRI)		Ownership efficiency, use &equipment size sub-models	Simulation
OSeMOSYS	Open-Source research community, UCL USA	Energy Demand	Bottom-up	Optimization

1.4. Research Gap and Originality Highlights

Despite the diversity of studies highlighted in Table 1.1, very few studies discussed the future sustainable energy system, capturing the linkage between both energy supply and demand sides and other aspects of low-emission policies in Zambia. The lack of integration between demand and supply vectors in the Zambian energy system requires a feedback loop linking the demand, supply, and environmental constraints. The integration of demand and supply models allows overall reductions or increase in specified energy source to be observed. Another challenge observed is the undetailed analytical framework that encompasses the specification of the future model horizon and effective policy actions on climate change in the methodological approach. This prevents better analysis of the direct and indirect effects of policies.

Comprehensively, this paper applies an integrated energy supply-demand modeling framework designed to develop reliable and policy-sensitive forecasts by retaining the link between both the demand and supply sectors in the energy system and utilizing cost-effective future energy planning policies in Zambia. On the demand side, the research uses time series analysis to forecast future electricity demand in Zambia. To this aim, the Seasonal Autoregressive Integrated Moving Average (SARIMA) model is used to predict electricity demand trained on 15 years of Zambia's monthly electricity demand from 2019 to 2035. The supply energy model identifies the optimal combination of resources and technologies needed to satisfy exogenously specified electricity demand levels, using the cost minimization approach, considering technical, institutional, environmental, and economic constraints. The proposed integrated model is applied to analyze the effects of different scenarios on the integration of renewable energy sources and emission reduction targets in Zambia. The scenarios considered are the baseline, No Coal, Carbon Emission targets, and renewable energy share. The baseline depicts the energy mix of the country in 2019. A 30 percent share of the renewable scenario is also considered. Furthermore, the emission reduction targets (10%, 20%, 30%, 40%, and 50%) were analyzed on the supply side. The overall modeling framework developed in this study is represented in Figure 1.5.

The upcoming chapters of the thesis consider the demand and supply modeling framework. Chapter 2 consists of a suitable model to forecast energy demand for Zambia and integrate it into an optimal supply model. Chapter 3 covers the details of the data settings. Chapter 4 included the detailed scenarios as stated above. It covers the baseline results, factoring in the electricity supply deficiency each year in the total supply and a high reduction in CO_2 emission from the current energy mix in the baseline scenario. Chapter 5 covers the results and discussions. The final chapter concludes the paper with policy recommendations.

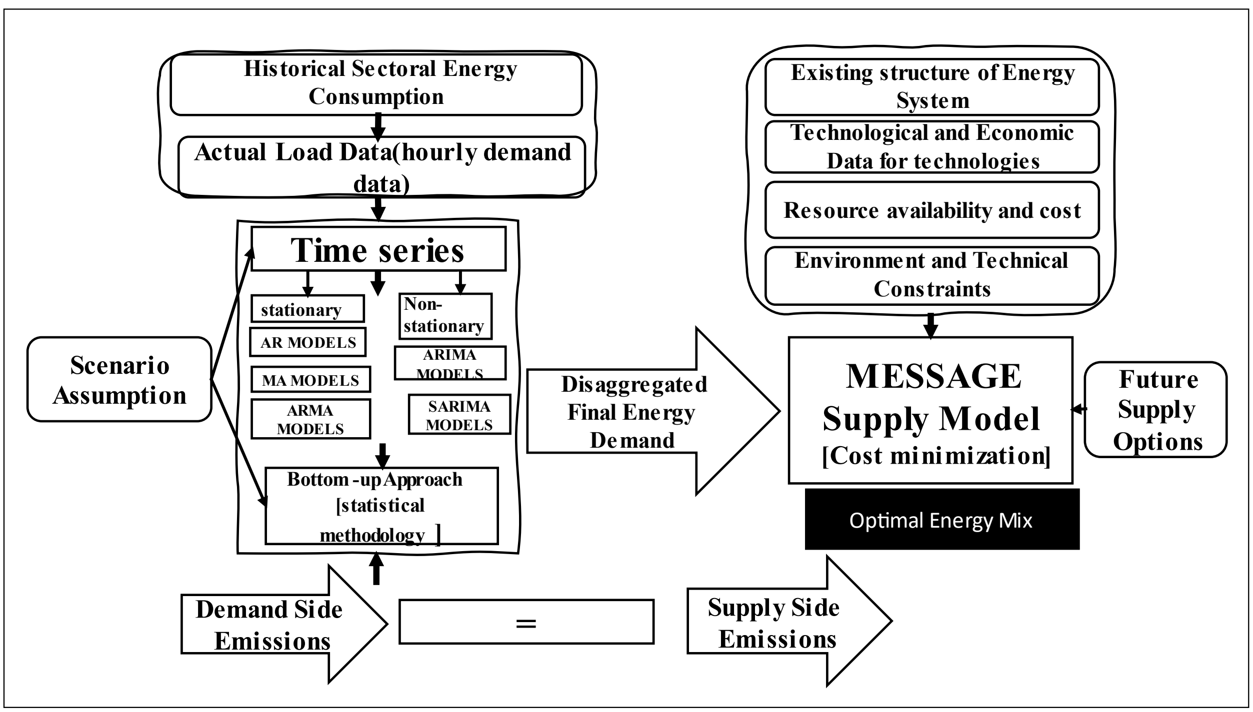

Figure 1.5. The Overall concept of an integrated energy model for Zambia.

Chapter 2

Integrated energy demand-supply modeling framework

The research process comprised the development of an integrated energy demand-supply model that can accurately forecast Zambia's future demand and energy supply mix, which is explained in the following sections.

2.1. Energy demand model:

2.1.1. Time series analysis:

The Time series modeling approach provides the energy demand projection over the model horizon (2019-2035). The time series data here is sampled based on a time-based dimension(years). Therefore, the time series data have time-series components that must be extracted (Seasonal and Trend Decomposition). Figure 2.1 represents some of the different forecasting methods that can be considered.

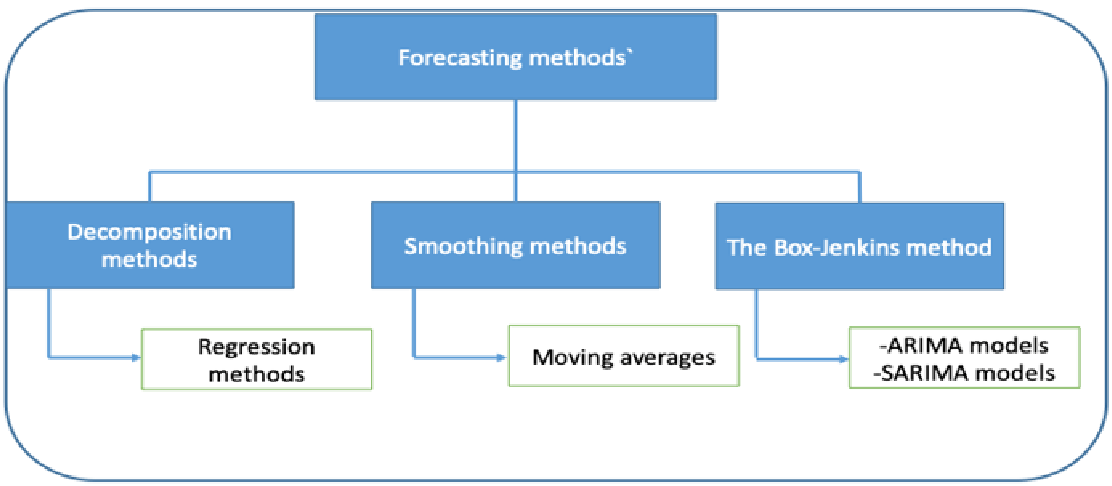

Figure 2.1. Different forecasting methods applicable to data sets [adapted from [23]].

The data pattern is important for further statistical analytical methods that consider the association between current and past series values when predicting future time series data. In addition, the time series approach helps ensure that past data fits the model to forecast closely related values by identifying outliers in the data. It requires modeling approaches that connect the correlation factor with the time and past data. This then gives a good forecast by looking at past behavior and then extending the patterns to the future forecast. Regression methods sometimes can imply that the energy demand for any year is a function of variables of only that year and have no effect from the past data.

Generally, a forecasting model can be introduced as follows [24]:

Let $A_0, A_1, A_2, A_3, A_4 \ldots\ldots A_k$ be the time series data for k factors with a response variable

$y_0, y_1, y_2, y_3, y_{4,} y_5$

The expected next single prediction is

$$y_{n+1} = f(A_0, A_1, \dots \dots A_k : y_0, y_1, \dots, y_n) \quad (2\text{-}1)$$

2.1.1.1. Decomposition:

A basic approach to the decomposition of a time series is representing the function of variables and the observed value at the time, t.[23]

$$Y_t = f(A_t, B_t, C_t) \quad (2\text{-}2)$$

- **Trend:** the data can show a trend in which its value variably changes with time; an increasing value shows a positive trend, and decreasing, a negative trend. B_t is the trend component at time, t.
- **Seasonality**: the data can display periodical patterns repeating at a constant frequency. The frequency of the seasonal components can have a period pattern, such as occurring every 12 months. A_t is the seasonal component at time t
- **Cycle:** Here we observe if trends have no set repetitions or seasonality. Data having this characteristic is cyclical time series data.B_t is also the cycle component at time t.
- **Remainder:** This data is obtained after extracting the data's trend and seasonality. This helps in detecting irregularities in time-series.R_t
- **Stationarity:** Time series data with statistical features that do not change over time. (Constant mean, standard deviation, and covariance are independent of time. The properties of a stationary time series are having no trend/no seasonality. No systematic change in variation. No periodic fluctuations. Suppose a series is found to have one of these properties. In that case, a Box-Jenkins method is used to transform the non-stationary time series into a stationary one, using a detrending or differencing method. The white noise causes unpredictability in a forecast with a zero mean.

Another useful way to transform the series is through a logarithmic transform:

$$X_t = \log_e(Y_t) \quad (2\text{-}3)$$

It is easier to evaluate the time series when the data values are greater than 0, $Y_t > 0$, as the logarithm. This method allows a complete analysis of the actual data by back transforming the results into the original sequence. This gives us a better estimate.

2.1.1.2. Autoregression AR(a)models:

This method uses the value of the previous values of the same time series to predict the value at the next step. It uses an order a to determine how many previous time steps were inputted. The AR process of an order can be written as

$$Y_t = c + \emptyset_1 y_{t-1} + \emptyset_2 y_{t-w} + \cdots + \emptyset_a y_{t-a} + \varepsilon_t \quad (2\text{-}4)$$

Where c is white noise and y_{t-1} and y_{t-w} are the lags. Order a is the lag value. Where c is a constant, $\emptyset_j$ are parameters to be determined and e_t is the error term. Constraints are applied to the value of $\emptyset_j$:

For $a = 1, -1 < \emptyset_1 < 1$.

For $a = 2, -1 < \emptyset_2 < 1, \emptyset_2 + \emptyset_1 < 1$ and $\emptyset_2 - \emptyset_1 < 1$

For $a \geq 3$, for advanced conditions

And ε_t is normally distributed with a mean of 0 and a variance of 1.

2.1.1.3. Moving Average MA(b) models:

This is a process where the present value of a series is defined as a linear combination of past errors. The errors are independently distributed with the normal distribution. The MA process of order q is defined as:

$$Y_t = c + \varepsilon_t - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2} - \cdots - \theta_b \varepsilon_{t-b}, \quad (2.5)$$

ε_t is white noise. A white noise process is a sequence of independent and identically distributed random variables. The sequences tend to be uncorrelated, have zero mean and have a constant variance. $\emptyset_j$ are parameters to be determined and e_t is the error term. Constraints are applied to the value of $\emptyset_j$:

For $b = 1, -1 < \theta_1 < 1$.

For $b = 2, -1 < \theta_2 < 1, \theta_2 + \theta_1 < 1$ and $\theta_2 - \theta_1 < 1$

For $b \geq 3$, for advanced conditions

And ε_t is normally distributed with a mean of 0 and a variance of 1.

Let's consider the order 1 MA process

$$y_t = c + \varepsilon_t + \theta_1 \varepsilon_{t-1} \quad (2\text{-}6)$$

2.1.1.4. Tests for stationarity:

The two main tests considered for the time series stationarity are the Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin Test (KPSS test).

Dickey-Fuller Test (Unit Root Test).

The unit root is a nonstationary feature of stochastic processes and can cause data interference. These tests are used to give a statistical approximation to which the null hypothesis can be rejected.

$$y_t = c + \beta t + \alpha y_{t-1} + \varphi_1 \Delta Y_{t-1} + \varphi_2 \Delta Y_{t-2} .. + \varphi_p \Delta Y_{t-p} + e_t \quad (2\text{-}7)$$

This equation above provides enough differencing terms for the equation (y_t.). The differencing terms are written as $\Delta y = y_t - y_{t-1}$ .The test has the following assumptions:

- Null Hypothesis (H_o); the series is non-stationary (unit root)
- Alternate Hypothesis (H_A); the series is stationary (no unit root)

The null hypothesis assumes the presence of the unit root. The null hypothesis is rejected when the test statistic (ADF statistic) is less than the critical value, and the p-value is less than the significance level of 0.05. This means the time series does not have a unit root.

Kwiatkowski-Phillips-Schmidt-Shin (KPSS) Test:

This unit root test tests for the stationarity of a series around a deterministic trend. The null hypothesis for the KPSS test is that the data are stationary. This null hypothesis is different from the stationary test. For this test, we do not want to reject the null hypothesis. In other words, we want the p-value to be greater than 0.05, not less than 0.05. Conditions to reject the Null Hypothesis (H_O); If the KPSS statistic is less than the critical values and the p-value is less than 0.05. This means the time series does not have a unit root.

2.1.1.5. ARIMA (Autoregressive Integrated Moving Average) Model:

The objective of the demand methodological approach used in this paper is the ARIMA modeling for forecasting energy demand. The ARIMA model focuses on the autocorrelations of the data, unlike decomposition models, which look at the description of the trend and seasonality in the data. Determining the stationarity of these models is a crucial factor, and the performance of the ARIMA model is subject to evaluation under the four criteria: Akaike criterion (AIC), Schwarz Bayesian criterion (SBC), maximum likelihood, and standard error. It will be observed that the ARIMA models are linear because future values are confined to linear functions of past data. The past data is also evaluated against the fitted data in the same range to observe the correlation between the two to validate our forecast.

An ARIMA model is labeled as an ARIMA model (p, d, q), wherein.

- p is the number of autoregressive terms (lags of the stationarized series)
- d is the number of differences between the stationaries of the series
- q is the number of moving averages (lags of forecast errors)

The behavior of time series may be affected by the differences from one observation to the next. The stationarity of the series is a crucial factor. Hence, we consider seasonal (P, D, Q) [25]

$$\mathrm{ARIMA}(p, d, q) \quad (P, D, Q)_m \tag{2-7}$$

Non-seasonal part Seasonal part of the model

- where m = seasonal length in the data.
- The data are plotted.

The following equations show the standard representation of the ARIMA model. Autoregressive models assume that Y_t is a linear function of the preceding values and is given by [26]

$$Y_t = \alpha_1 Y_{t-1} + \varepsilon_t \tag{2-8}$$

Each observation consists of a random component (random shock, e) and a linear combination in this combination of previous combinations. α_1 in this equation is the self-regression coefficient. The behavior of time series may be affected by the differences from one observation to the next.

$$Y_t = Y_{t-1} + \varepsilon_t \tag{2-9}$$

A differentiation of order 1 assumes the difference between two successive Y values is constant. ε_t is white noise. This shows that all residuals from the ARIMA (p, d, q) are within the threshold limits.

$$Y_t = \varepsilon_t - \theta_1 \varepsilon_{t-1} \tag{2-10}$$

The current value of a moving average process is a linear combination of the current disturbance with one or more previous perturbations.

The general non-seasonal model ARIMA p, d, q:

$$\Phi(L) \quad (1 - L)^{d(yt-c)} = \Theta(L)\ \mathcal{E}t \tag{2-11}$$

AR part of order p — lag-1 Differencing of order d — MA part of order q

A stationary time series is necessary to find the required ARIMA model. This model uses the forecasting stages with a Box-Jenkins time series approach [27] Identification, estimation, diagnostic checking, and forecasting to find a suitable ARIMA model. The mean and autocorrelation structure are constant over time. Log transformations help decrease the variance of the model. A differentiation of order 1 is taken for the seasonal part and the non-seasonal part of the model.

The overall process for forecasting using an ARIMA model is depicted in Figure 2.2.

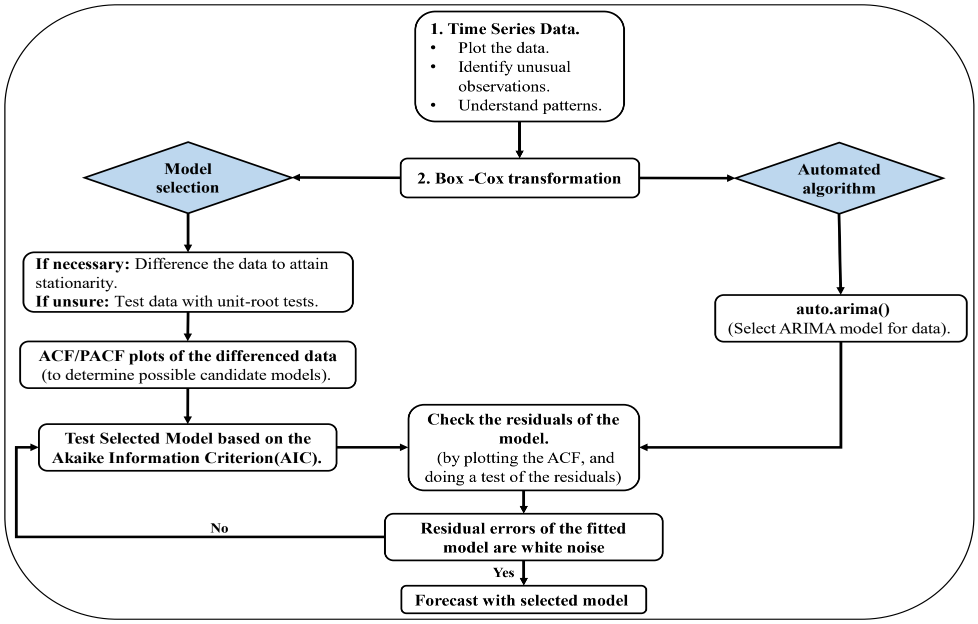

Figure 2.2. Overall process for forecasting using an ARIMA model [adapted from[25]].

2.1.2. Energy demand forecasting using the SARIMA model:

2.1.2.1. Identification:

This study uses the time-series decomposition technique to forecast the monthly short-term electricity demand in Zambia. The proposed forecasting model is based on the Seasonal Auto-Regressive Integrated Moving Average (SARIMA) time series method. The seasonal ARIMA model consists of modeling the number of yearly observations while considering both the non-seasonal part of the model and the seasonal part of the model. As stated, it has additional seasonal terms which are often multiplied by the non-seasonal terms. It relies on differences and seasonal lags to fit the seasonal patterns, which can be expressed using the following operator polynomials as follows [28]:

$$\left(1-\phi_1 A-\cdots-\phi_p A^p\right)\left(1-\Phi_1 A^s-\cdots-\Phi_P A^{sP}\right)(1-A)^c\left(1-A^s\right)^C D_t^0 = \left(1-\theta_1 A-\cdots-\theta_q A^q\right)\left(1-\Theta_1 A^n-\cdots-\Theta_Q A^{nQ}\right)d_t \quad (2\text{-}12)$$

In the equation above, the D_t^0 represents the fitted historical monthly electricity demand at time t. In addition, the non-seasonal autoregressive and moving average elements are represented by polynomials $\phi_p(A)$ and $\theta_q(A)$ of trend orders p and q. The parameters $\Phi_P(A)$ and $\Theta_Q(A)$ refer to seasonal autoregressive and moving average elements of trend orders P and Q. c and C represent the corresponding non-seasonal and seasonal difference components. A represents the backward shift operator. d_t refers to the error term, with a significance of mean 0 and variance 1. n is the number of periods per season. ϕ and Θ are the model coefficients.

2.1.2.2. Residual Analysis:

Following the steps shown in Figure 2.2, the historical energy demand data seems non-stationary with some seasonality. Therefore, the Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of the seasonally differenced should be plotted, and the spikes should be analyzed. To find the appropriate SARIMA model based on the ACF and PACF, the seasonality of the significant spikes at specific lags of both seasonal and non-seasonal terms should be determined. Using the Box-Jenkins methodology, the residuals (forecast errors) are checked to be white noise, by plotting its sample ACF. The series may show significant autocorrelation at certain lags; they seem to correspond to a stationary process.

2.1.2.3. Model Accuracy:

Mean absolute percentage error:

$$\mathrm{MAPE} = \left(\frac{1}{n}\right) * \sum \left(\frac{|\mathrm{actual} - \mathrm{forecast}|}{|\mathrm{actual}|}\right) * 100 \qquad (2\text{-}13)$$

The MAPE value obtained for the model means the average difference between the predicted value and the actual value. The lower the value for MAPE, the better a model can forecast the values.

R squared (Coefficient of determination):

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \qquad (2\text{-}14)$$

It specifies the number of data points that are within the results. A value of 1 or 0 would indicate the regression line represents all or none of the data. A negative model represents a model of a poor fit.

The Mean Square Error:

$$\mathrm{MSE} = 1/n \sum_{t=1}^{n} e_t^2 \qquad (2\text{-}15)$$

The squared quantity of the residual error relates the set of data points with the regression line to find the squared error difference. The lesser the MSE, the better the model.

Chapter 3

Energy Supply Model

3.1. Energy supply model:

In this study, the Model for Energy Supply Systems, and their General Environmental Impact (MESSAGE) is used as the energy supply model, which is founded on the dynamic linear mathematical programming method to find the optimal plausible combination of the energy supply technologies to satisfy the forecasted electricity demand (optimization of energy supply and utilization. The optimal solution is based on the least costs, availability of technologies, constraints, and bounds set on technologies over the horizon. The model also finds an optimal timing for adding new energy supply technologies based on future needs. It is a modeling framework used for medium to long-term planning of an energy system and uses a bottom-up perspective approach.

It also considers the greenhouse gasses (GHG) emitting sectors. Specifically, the energy and industrial processes emit carbon dioxide and other radioactive gasses. The MESSAGE-ix Integrated Assessment Model and the ix-modeling platform are central energy environment economy systems analysis tools. The message-ix integrates data sources and models at specific levels over time. There are different types of horizons, such as perfect foresight, myopic or rolling horizon[29]. The model allows flexibility on upper and lower bounds on both the generation and capacity of the technologies. This allows for ease of shift in considering more investment in variable renewable energy sources and future costs in the market.

3.2. The history of the MESSAGE model:

The model for energy supply systems and their General Environmental Impact (MESSAGE) is a process-based integrated assessment model; it allows for a detailed representation of the technical engineering, socio-economic, and several combining processes in energy and land-use systems. The model has been developed at IIASA[30].The first version focused on the supply side of fossil resources such as oil and gas; however, the global version of the MESSAGE model is now extended to an integrated model focusing on energy demand, supply, and specific emitted gases.

The MESSAGE model has the flexibility of parameters by “the user-defined relations”[30]. These can allow the implementation of constraints or bounds on aggregate activities across technologies. Furthermore, the different models use various scales with different temporal and spatial resolutions. The ix-modeling platform consists of a numerical solver that can transform modeled data into output to get processed results. The extended use of the energy systems model considers the reference energy system data, which considers the commodity transformations, fossil reserves estimated, and time series demand data. Then processed results from any specific model. The baseline is modeled first, then we develop and calibrate a new scenario by modifying the model structure while considering the baseline.

3.3. Main object classes of the ix modeling platform[29];

There are three different class names listed below.

Platform

The platform is the first step in inputting data into the model, which can continuously be edited.

Timeseries

The input data(sets/parameters) and flexible model output are based on a scenario.

Scenario

The model is solved by exporting the scenario to a numerical solver, such as by using General Algebraic Modeling System (GAMS) to solve the model. The ix-modeling platform includes an interface to GAMS. After running the program, the numerical solution is imported to the platform instance. The objective function is the major step in combining all the costs across all modules detailed below. These include investment, operational costs for technologies such as variable costs for exhaustible resource extraction and additional integrated forms of renewable energy sources, and, if specified, emissions taxes.

3.4. Mathematical Formulation of Supply Model:

The objective function of the model denotes the discounted cost of the energy system through the model horizon. The discounted cost is employed to consider the present value of all future cash flows through the discount rate. Discounting ensures that the costs incurred at different points in the time slice are comparable in the optimization. The discount rate equals the long-term real interest rate (excluding inflation and other opportunity costs)[31]. A low discount rate reduces differences in the present and future costs, thereby advocating for reduced investment costs of technology. A high discount rate is more inclined to reduce present costs than future ones.

Thus, the cost variable represents the total cost of the resource, investment for new technology, operation and maintenance, and emissions, as follows [32]. The principle of the MESSAGE-ix model is to compute the objective function under a set of constraints technical, environmental, and economic constraints, as expressed by the following system of equations:

$$\text{Min } C = \sum_{x} df_{x} * c_{\mathbf{x}} \tag{3-1}$$

Subject to:

Economic constraint:

$$c_{\mathbf{x}} = \sum_{s,h} Ia_{v,h}.Fx_{v,h} + \sum_{tec} Hd_{tec} * AddCap_{tec} + \sum_{tec} Md_{tec} * Cap_{tec} + \sum_{tec} Td_{tec} * D_{tec} + \sum_{tec,e} Fs_{tec,e} * Fn_{tec,e} \tag{3-2}$$

$$df_x = \frac{1}{(1+DR)^x} \tag{3-3}$$

Demand constraint:

$$\sum_x \sum_t \sum_{tec} D_{tec,y,t} \geq \sum_x \sum_t E^0_{y,t} \tag{3-4}$$

This constrains demand that can be set for a particular load region at the end-use of a technology.

Capacity constraint:

$$\sum_m D_{tec,m,x,t} \leq DUR_t \times kf_{tec,x,m,t} \times K_{tec,x,m,t} \tag{3-5}$$

This constraint bounds the capacity over a period of years and relates to the capacity factor for all the conversion technologies.

Resource constraint:

$$FY_{t,x} \leq R_{u,h,z} * (ST_{u,h} - \sum_{x'<y} DUR_{x'} * \ Fy_{d,h,x'} \tag{3-6}$$

It limits the resource extracted in a specific year by also considering the extraction rate for any year.

Emission Constraints:

$$\sum\nolimits_{tec} \mathbf{FS_{tec,e,x}} = \mathbf{FN\_bound_{e,x}} \tag{3-7}$$

Where in the above equations, C is the total cost; df is the capital recovery factor computed based on the discount rate over the model horizon; DR is the discount rate; x is the year; t: is the load region (i.e., different months of the year) ; c_x is the total cost for year y. $Ia_{v,h}$ and $Fx_{v,h}$ are cost and extracted resources of each type v and grade h. Hd_{tec}, Md_{tec}, and Td_{tec} represent the investment, fixed, and variable costs for each technology tec, whereas $Addcap_{tec}$, k_{tec}, and D_{tec} are the added, maintained capacities and the generation (energy outflow) of each conversion technology. $FS_{tec,e}$ and $FN_{tec,e}$ are the emission tax and emission amount for each technology tec and emission category e. $E^0_{y,t}$ is the electricity demand predicted by the SARIMA model; DUR_t its e duration of the load region t; $Cf_{tec,y,m,t}$ is the capacity factor; $cap_{tec,y,m,t}$ is the maintained capacity during the year; $FT_{s,z}$ is the extraction of resource r during a specified year y, assuming the value is lower than the resource volume $ST_{u,h}$ and extracted during the previous year x' using the constant rate of extraction of the remaining resource $R_{u,h,z}$. $FS_{tec,e,y}$ represents the emissions of the technology after applying specific bounds on emissions($FN\_bound_{e,y}$).

3.5. Reference Energy System in Zambia:

The Zambia Reference Energy System (RES) Figure 3.1 used in the energy supply model in this study which reflects the change in the activity of each technology, $\sum_{m} D_{tec,m,y,t}$, at the specified levels of the energy supply chain. In the Reference energy system, the energy demand is defined at the useful energy level and is obtained using time series analysis. There are limits on new investment, fuel availability and trade, environmental regulations and policies, and the pace at which new technologies are accepted and integrated into the current energy supply model, assuming full temporal and spatial flexibility[30]. The figure below defines a full set of available conversion technologies in Zambia. The conversion process specified below typically begins with resource extraction to transformation, the flow and distribution of the energy carriers, and finally, the end-use technologies. Resources are not easily converted into useful energy; therefore, the reference energy system has different energy levels. The conversion process defines each technologies process of taking energy commodities.

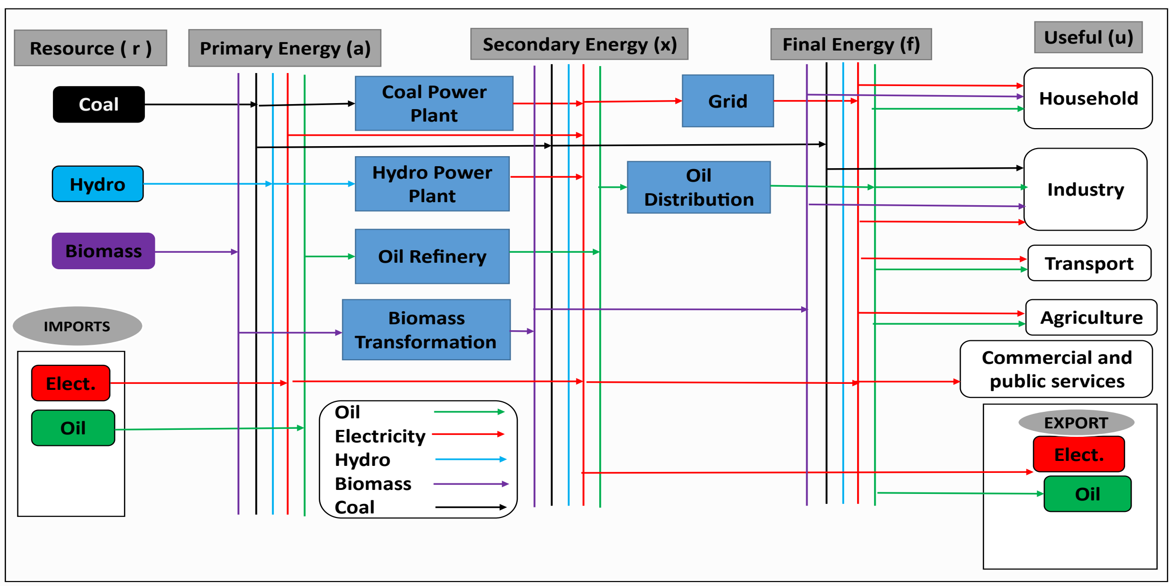

Figure 3.1. Reference Energy System (RES) for Zambia.

3.5.1. Resource level:

The resources are the starting point of the electricity chain output. The resources produced by the extraction technologies such as non-fossil based (hydro, etc.) and fossil fuel-based (coal, HFO, Diesel). These include any raw resources such as coal, oil in the ground, or biomass on the field. This consists of the various energy resources that are available in various forms. Others include wind, solar, natural gas, geothermal, biogas, and hydro.

The resources produced can come from different cost categories, also called grades. This shows the costs that must be incurred upon obtaining the resources. The annual resource extraction, the cost category(grade), g, and the elasticity of the technology in a period are considered here. The resource level also takes into consideration the available resources and future reserves based on trends and policies. In the case of Zambia, there are local coal reserves. This helps in future planning in case of unintended disturbance in the flow of energy commodities during the extracting, conversion, and generation processes. These include any raw resources such as coal, oil in the ground, or biomass on the field. There is an estimated coal-proven reserve of 49.6 million short tons[33]. There are several indicators of renewable source potential. Solar PV: the highest annual generation per unit of installed PV capacity at 1.6-1.8 (MWh/kWp) has a proportion of land area about 94% in comparison to the world at 20%.The wind power density at the height of 100m at a level of (<260W/m^2) has a proportion of the land area of 100% in comparison to the world at 60%[34].

3.5.2. Renewable Energy Level:

Hydro is the renewable energy resource that is available as the other renewable energy sources are either integrated or still under consideration (feasibility studies on geothermal etc.) in Zambia. Several sites, especially in Eastern Province, have a planned capacity and actual operating capacity of solar and wind technologies, which has increased the generation. The capacity factor of renewable technologies and flexibility of integration are considered at this level. More renewable capacity should be integrated as it's unlimited in nature and has zero resource cost despite having constraints on availability. For example, the wind has natural airflows to turn turbines, which can produce electricity. This is also the same for solar PVs.

3.5.3. Primary Energy Level:

This level consists of the extracted and pre-processed resources that are at a generation site. (i.e., crude oil as an input to the refinery. In Zambia, the petroleum feedstock is imported in the form of spiked crude oil and finished products, mainly from the Middle East.

3.5.4. Secondary Energy Level:

This level represents the processed form of energy transmitted or transported to the last structured energy system flow stage. Technologies can take energy commodities from one level and put them out at another level (i.e., the refineries that produce refined oil products from crude oil at the primary level. In our case, fine oil products such as diesel oil products. Flexibility is also modeled at this level.

3.5.5. Final Energy Level:

At this level, the final demand for energy commodities is modeled. Depending upon the electricity carrier, here, a transmission, distribution, and transport network links the secondary level with the primary level. The interlinked network chain from the commodity to the primary level than the final product. The finalized product should satisfy demand. In our case, we consider the final level commodity as electricity which can be used for (heating, lighting, or transportation).

3.5.6. Technologies:

The technologies are linked to their specific capacities after construction. The reference year the technology was built is also important as its duration of existence. This is needed for future projects when additional capacity is required. The model considers energy forms in the direction from the resource to the next level. There exist conversion and transfer technologies. This study considers the conversion technologies that convert one commodity to the other, especially electricity. Technologies are the key building blocks of a model instance.

The MESSAGEix implementation supports a detailed vintage representation of installed capacity for each technology. Decreasing efficiency, Increased operation and maintenance costs towards the end of a plant's technical lifetime[29].The mathematical formulation of MESSAGEix is centered on technologies that use and produce/generate commodities. These commodities can be modeled at different levels to depict a reference energy system from primary extraction to final or useful energy consumption.

3.5.7. Structure and modules:

The mathematical formulation of MESSAGEix is centered on technologies that use and produce/generate commodities. These commodities can be modeled at different levels to depict a reference energy system from primary extraction to final or useful energy consumption.[29]The model considers the region(country), and it further considers the available resources and the levels of the reference energy system of the country. In addition, for the grade of resource quality in the extraction and mining sector. To develop the complete model, the technical costs of the technologies from the input commodities to the output. Based on certain linear constraints, the emission produced is reduced or increased. The specificity of the temporal hierarchy levels is also defined. This model considers the time in months for a specified time horizon. Table 3.1 summarizes the technologies considered in this study.

Table 3.1. Details of technologies involved in the MESSAGE Model for Zambia

Technology Category	**Sub-Category**	**Detailed Technologies**
Conversion	Electric (Fossil Fuel Based)	Coal (Local) Power Plant
Conversion	Non-Electric (Import Crude Oil) Electric (Fossil Fuel Based)	Oil Refinery Oil(FO) Power Plant
Conversion	Non-Electric (Import Crude Oil) Electric (Fossil Fuel Based)	Oil Refinery Oil (HSD) Power Plant
Conversion	Electric (Renewable Based)	Hydro Power Plant
Conversion	Electric (Renewable Based)	Wind Power Plant
Conversion	Electric (Renewable-Based)	Solar Power Plant

Figure 3.2 describes the techno-economic and environmental constraints and links between the resource input and the final level. This figure gives an overview of the costs of each resource (i.e., fossil fuels), their availability, and the output obtained. The costs here include the cost of extracting the resource, also the cost at which it can be used to provide energy services(electricity). In addition, it shows the model inputs describing their economic (investment costs, fixed and variable operation and maintenance costs), technical (e.g., conversion efficiencies), and environmental parameters (GHG emissions). The base year for the model is 2019, and it is considered that the already existing capacity is up until 2019.

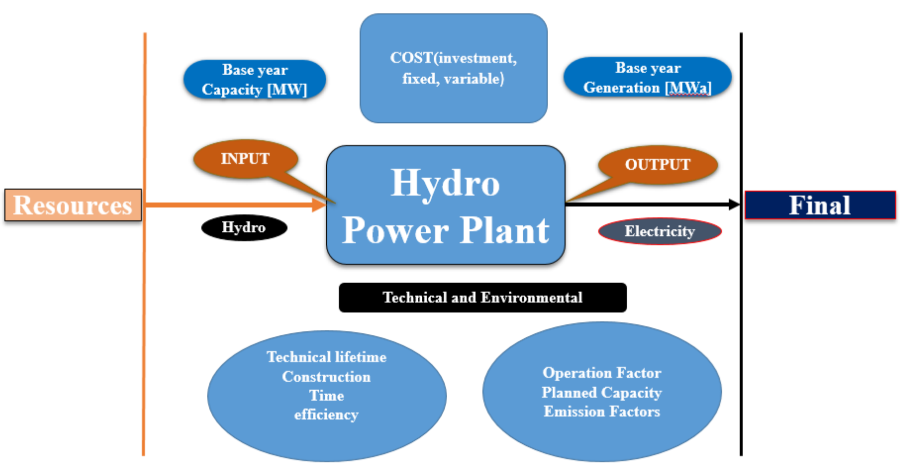

Figure 3.2. Basic parameters required for the definition of technology in the energy supply Model

These techno-economic and environmental constraints are all connected to capacity. In this study, the factors considered are:

- Total investment costs of the conversion technologies (e.g., per kilowatt), as well as the distribution of capital costs throughout the construction time.
- The number of years for construction of each conversion technology.
- Fixed operating and maintenance costs (per unit of capacity, e.g., per kW).
- Variable operating costs (per output unit, e.g., per kilowatt-hour, kWh, excluding fuel costs).
- The technical lifetime of the conversion technology is in years.
- Year of first commercial availability and last year of commercial availability of the technology.
- Emissions in a specified unit of $CO_{2\ are}$ due to the consumption of fossil fuels.
- Generation based on the installed capacity of technology.
- Constraints such as capacity factor annually for newly installed capacity and the growth or decrease of the generation of technology.
- Technical application constraints, such as integrated amounts of shares of wind or solar power
- The Lag time between the input and output of the technology. (Considered for short time steps and longer time steps).

The model also considers the energy inputs and outputs conversion efficiencies, respectively. It is known that most conversion technologies are associated with one energy input and one output. This is how the efficiency of each technology is calculated:

$$\text{Efficiency} = \text{Output}/\text{Input} \tag{3-8}$$

The model allows the different technologies to utilize different fuels subject to their shares. The activity variables of technologies are provided by the units of the main input consumed by technology and for sources such as solar, which do not have a direct main input. For the case of a Hydro power plant, the unit of output(hydro) is the electricity which is measured in MWa (MWa=8760MWh). Zambia's local reserves have an input unit of million short tonnes for coal, and the output electricity is measured in Mega Watt Anum. In this study, the oil refinery has the same input, and output units for the technology with a technology conversion efficiency is calibrated with the input, which in turn provides outputs such as diesel and oil (HFO) in their proportion.

$$\text{Input}_{\text{value}} = \frac{\pi}{(\sigma * \beta)} \tag{3-9}$$

$$\text{Output}_{\text{value}} = 1 - £ \tag{4-0}$$

Where the conversion efficiency is denoted as (β), the input commodity calorific value (σ), percentage auxiliary consumption £, and unit conversion factor π

Electric-sector flexibility in the model is represented as follows: each generating technology is assigned a coefficient between -1 and 1, representing (if positive) the fraction of generation from that technology that is flexible or (if negative) the additional flexible generation required for each unit of generation from that technology. Load also has a parameter (a negative one) representing the amount of flexible energy the system requires solely to meet changes and uncertainty in load. The table below shows the standard flexibility parameters of technologies.

Table 3.2. Flexibility Parameters of technologies from[30].

Technology	Flexibility Parameter
Load	-0.1
Wind	-0.08
Solar PV	-0.05
Coal	0.15
Gas CC	0.5
Hydropower	0.5
Oil/Gas Steam	1
Gas CT	1

Figure 3.3 represents the flow chart describing the process of MESSAGE modeling.

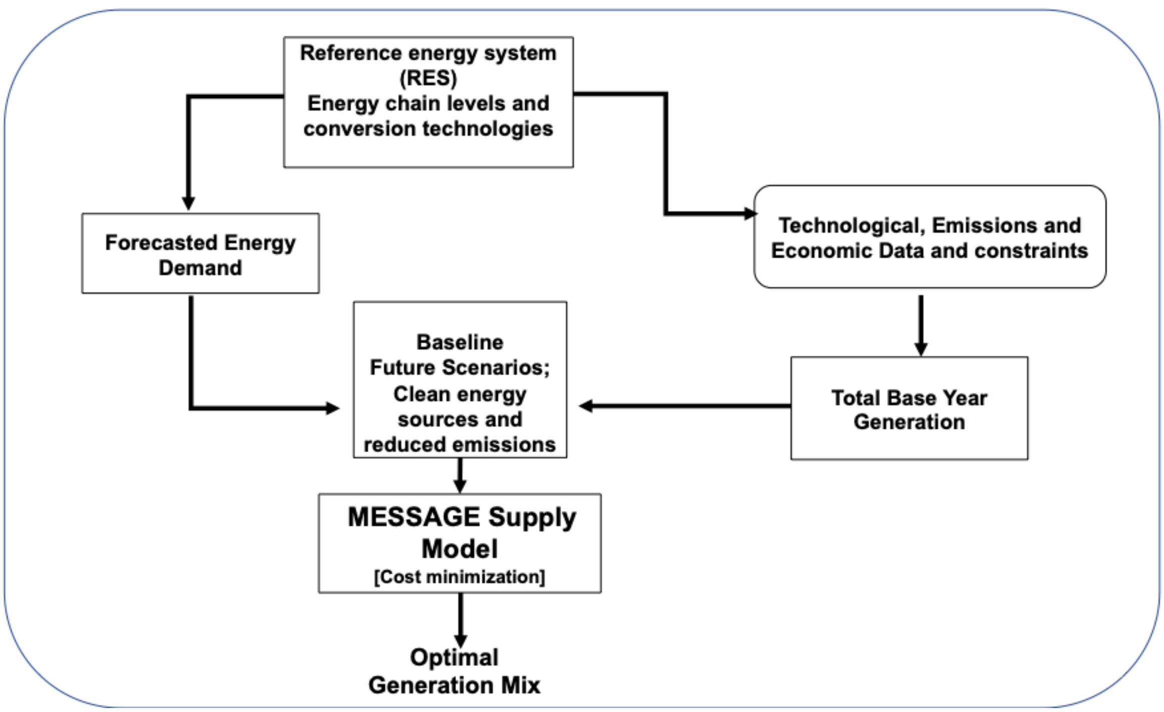

Figure 3.3. Framework of the MESSAGE energy model.

Chapter 4

Data Inventory

This study relied primarily on published public domain documents collected from publicly available sources, including the Energy Sector reports for Zambia [9] produced annually for the years 2016-2021, Historical generation and load data for the years 2006-2018 from Zambia Electricity Supply Corporation Limited (ZESCO) [35].Ministry of Energy[36], International Energy Agency(IEA)[37] and National Renewable Energy Laboratory(NREL) [38]. The dataset includes the techno-economic parameters of supply-side technologies, installed capacities, emission factors and final electricity demands.

4.1 Energy Demand Data and Energy Supply Data:

The Energy demand data will be observed with the forecasted data (2006-2035). The baseline scenario considered the installed power capacities in 2019, as the base year, where the hydropower plant accounts for 80.45 percent of installed capacity. The remaining technologies with corresponding installed capacity fraction include coal powerplant (10.06%), Heavy Fuel Oil powerplant (3.69%), diesel (2.80%), and solar PV (2.99%) [9]. The inconsistent imports of petroleum feedstock (crude oil) directly impact the generation from the power plant. Zambia currently uses local coal for the generation of electricity. The Maamba Collieries coal-fired thermal power plant and the integration of other thermal power plants are essential to meet the base load requirements of the country. There is a future for expanding coal power generation: increasing the resource capacity at Maamba Collieries, Dangote Power Plant also contributes to the national grid. Maximizing the utilization of abundant resources is imperative to resolve “the constant power supply shortage” in Zambia. According to the 7 National Development plan 2017-2021, Zambia’s energy sector has had a consistent deficit because of limited investment over the years, the effects of climate change on water availability, and other cost-reflective tariffs on resources[39] Table 4.1 summarizes the techno-economic characteristics of each generation of technologies used in the supply energy model.

Table 4.1. Summary of technical and economic characteristics of conversion technologies([40]).

	Hydro_PP	**Solar_PP**	**OIL(FO)_PP**	**Wind_PP**	**Coal_PP**	**OIL(HSD)_PP**
Investment Costs ($/kW)	2,227	1,146	800	2,438	1,900	924
Variable O&M costs($/kW)	4.5	-	105.4	85.5	52.7	85.5
Fixed Costs ($/kW)	8.5	40	20	40	50	20
Plant Factor (share)	0.95	0	0.75	0.9	0.95	0.75
Efficiency(%)	85	33	38	35	40	33
Operation Factor(%)	97	99	70	97	85	70
Fuel	-	-	HFO	-	Coal	Diesel
Capacity Factor(%)	42	25	80	35	40	80
Base Year Generation[MWa]	1307.4	48.6	60	0	163.5	45.6
Base Year Capacity[MW]	3500	48.6	59.97	0	600	45.5
Historical Capacity [MW]	2400	89.14	150	0	330	84

The baseline scenario considers the volatile changing price of oil based on the average growth rate of the fluctuating oil price of HFO in Zambia and diesel for 2010-2021. Figure 4.1 shows the variation of the variable costs with a change in oil price for the horizon 2019-2035. The Oil (HFO) and Diesel prices at which Zambia imports a gallon of oil are, respectively, $2.25 and $2.49 for the base year of the model, considering the exchange rate of the Zambian Kwacha to the USD, sharp increases in international oil prices, and the average cost of previous years.

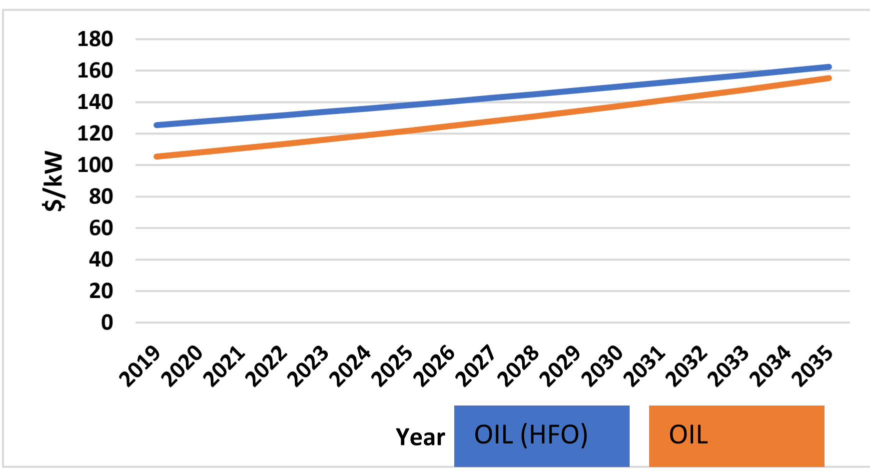

Figure 4.1. Variation of the variable costs with a change in oil price.

Figure 4.2 and Figure 4.3 show the feasible sites for wind and solar power plants in Zambia. Detailed information on costs and resource availability are given in Tables (4.2-4.4)

4.2. Main Assumptions for the integrated Demand-Supply Model:

The horizon considered in MESSAGE-ix spans from 2019-2035, with 2019 being the base year. The currency used in the model for fuel prices and technologies estimations is US Dollar based on the 2019 exchange rate. Although, the discounting rate of 10% is consistently used for the costs occurring at different points in time comparable, the discount rate chosen defines the weights different periods get in the optimization. Other assumptions used in the model are as follows:

- Investment costs over the horizon are constant, with fluctuating operation and maintenance costs for each fuel for the horizon calculated in USD.
- All model scenarios have a fixed interval (horizon from the base year to 2035 the end of the horizon.

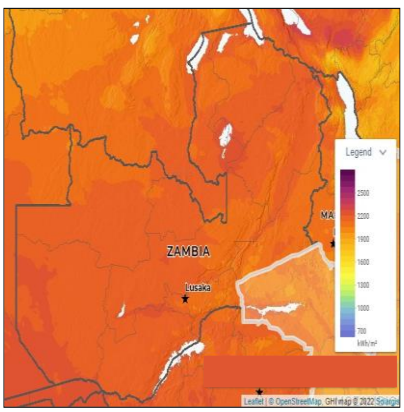

Figure 4.2. Shows the renewable energy potential in Zambia-Solar potential[41].

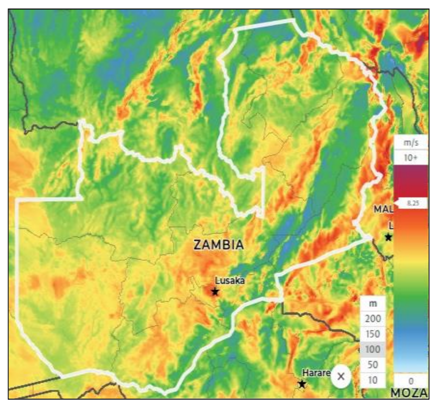

Figure 4.3. Shows the renewable energy potential in the Zambia wind speed map[42].

Table 4.2 to Table 4.4 show the techno-economic input data for the Zambia energy supply system model. It includes components such as resources, conversion technologies, the efficiency of energy use, and the distinct costs for all resources. Table 4.2 shows the existing reserves of fossil fuels and renewable energy extracted for power generation. Table 4.3 shows the average amount of crude oil imported into Zambia.

Table 4.2. Resource cost and availability data[43] [44][45].

Category	Resource	Reserve	Cost	Base Year Extraction
Fossil Fuel	Coal	49.6[Mt]	170[$/Mt]	5087[Mt/Year]
	Crude Oil	-	-	-
Renewable	Hydro	6000[MW]	-	-
	Wind	150[MW]	-	-
	Solar	600[MW]	-	-

Table 4.3. Cost and environmental parameters of power technologies[40].

Parameters	Hydro_PP	Solar_PP	OIL(FO)_PP	Wind_PP	Coal_PP	OIL(HSD)_PP
Plant Life	50	25	40	25	30	30
Construction Time	5	0.83	4	2	4	4
Investment Cost[$/kW]	2227	1146	800	2438	1900	924
Fixed Cost[$/kW-Year]	8.5	40	20	40	50	20
Var.Cost[$/kWa]	4.5	0	105.398	4.5	52.619	85.422
Emission Factor [kt CO_2/MWa]	0	0	5.96	0	6.31	6.68

Table 4.4. Cost and quantity of Imports[46].

Commodity	Imports		Cost	
	Unit	Value	Unit	Value
Crude Oil	[MT]	700,277	[$/T]	75.6

Chapter 5

Results and Discussion

5.1. Prediction of the monthly electricity demand in Zambia:

Figure 5.1 shows the time series of electricity demand for the period of 2006-2019, indicating clear seasonality in the dataset. First, the log transformation was performed to stabilize the slight increase in the variance with the level. The fifteen-year month electricity demand data was split into 2006 to 2019 training data to train the model and 2019 to 2020 for testing validation of the predicted data. The Box Jenkins time series procedure explained in Figure 2.2 was applied to the time series data to find the best SARIMA model, considering four criteria of Akaike criterion, Box-L Jung statistics(Qc), maximum likelihood, and standard error. The SARIMA model was first fitted to the first N-12 values after the appropriate transformation of the raw data. As can be observed from Figure 5.2, both seasonal and non-seasonal differenced data have significant spikes at lags 12, 24, and 36 in the partial autocorrelation function (PACF), which suggest suggests a seasonal order of 3 and non-seasonal order of 2 (the value of p and P in Eq (1)). Similarly, the Autocorrelation Function (ACF) analysis reveals one spike at lag 12 for seasonal and 2 spikes at the same lag for non-seasonal.

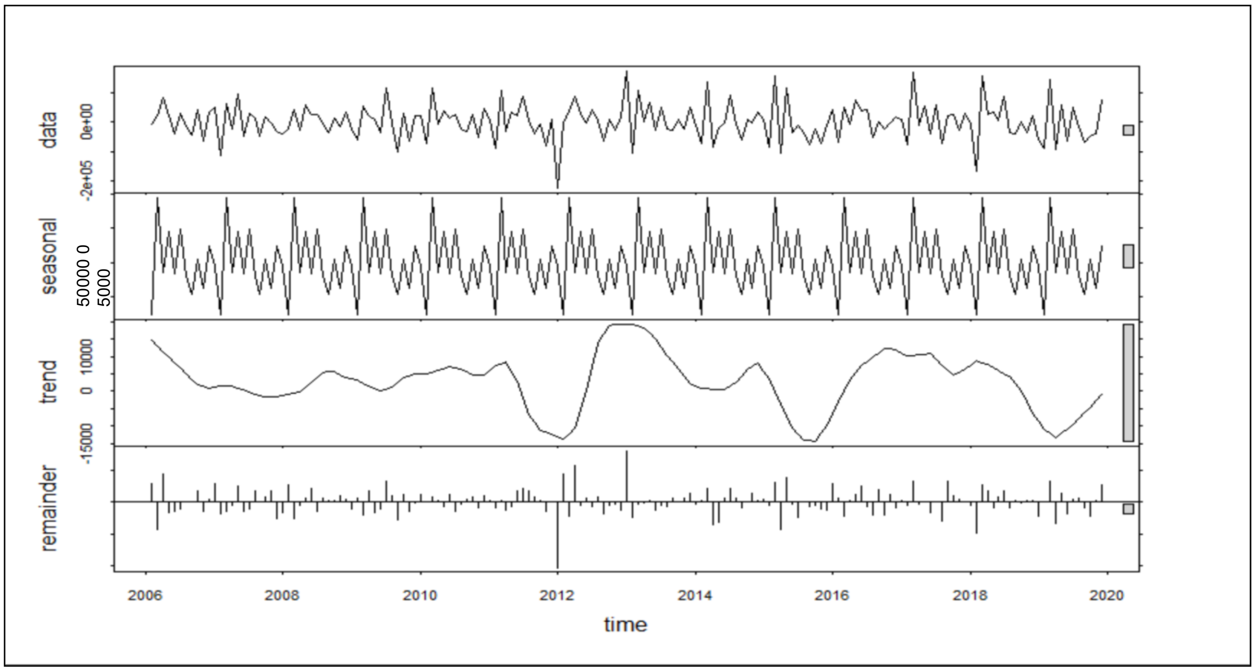

Figure 5.1. Monthly electricity demand time series decomposition.

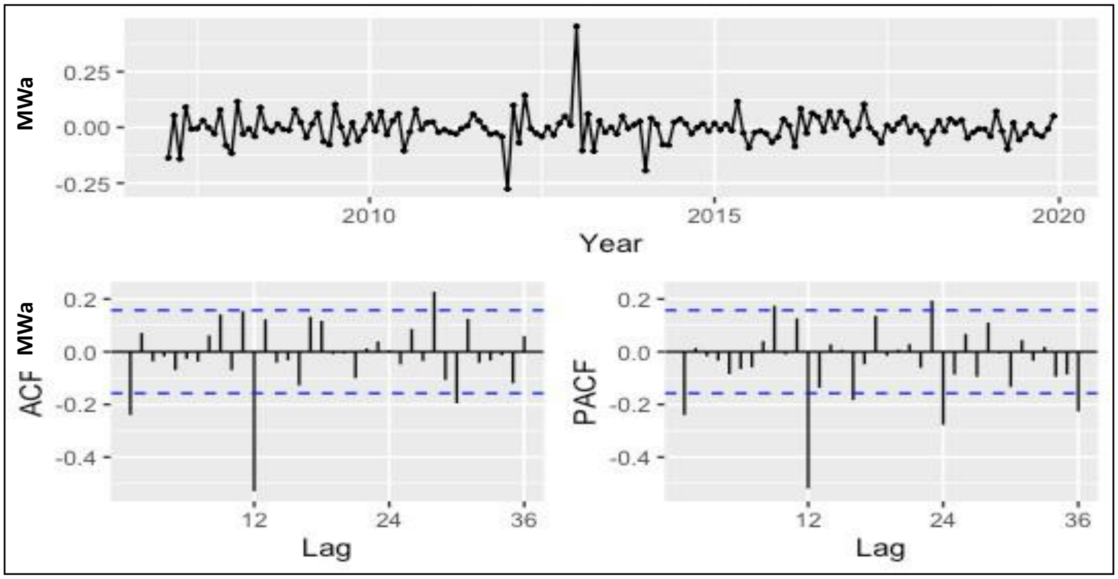

Figure 5.2. ACF AND PACF plots of seasoned and non-seasonal differenced Demand.

Based on the above discussion, The suggested best SARIMA models are given in Table 5.1

Table 5.1. Selection of ARIMA model for Zambia's Electricity demand.

MODEL	AIC	BIC	LOG-LIKELIHOOD	RMSE	MAPE	MAE	AICc
ARIMA (2,1,2)(3,1,1)	-459.04	-432.38	238.52	38187.99	2.751	26963.92	-457.69

The developed SARIMA model was used to predict the future electricity demand in Zambia, which is shown in Figure 5.4. To validate the model, the ACF, and PACF of the residual portmanteau test and the distribution of errors were checked using Box-Ljung. The spikes should be within the significant limits, so they appear as white noise (as shown in Figure 5.3). The distribution of the residuals in the selected SARIMA model rejected a null hypothesis on the independent distribution of errors. The p-value was greater than 0.05(p-value=0.66). The Mean absolute percentage error (MAPE) for the test data achieved a 2.75 %, with an R^2 at 0.95, indicating the high accuracy of the predicted model.

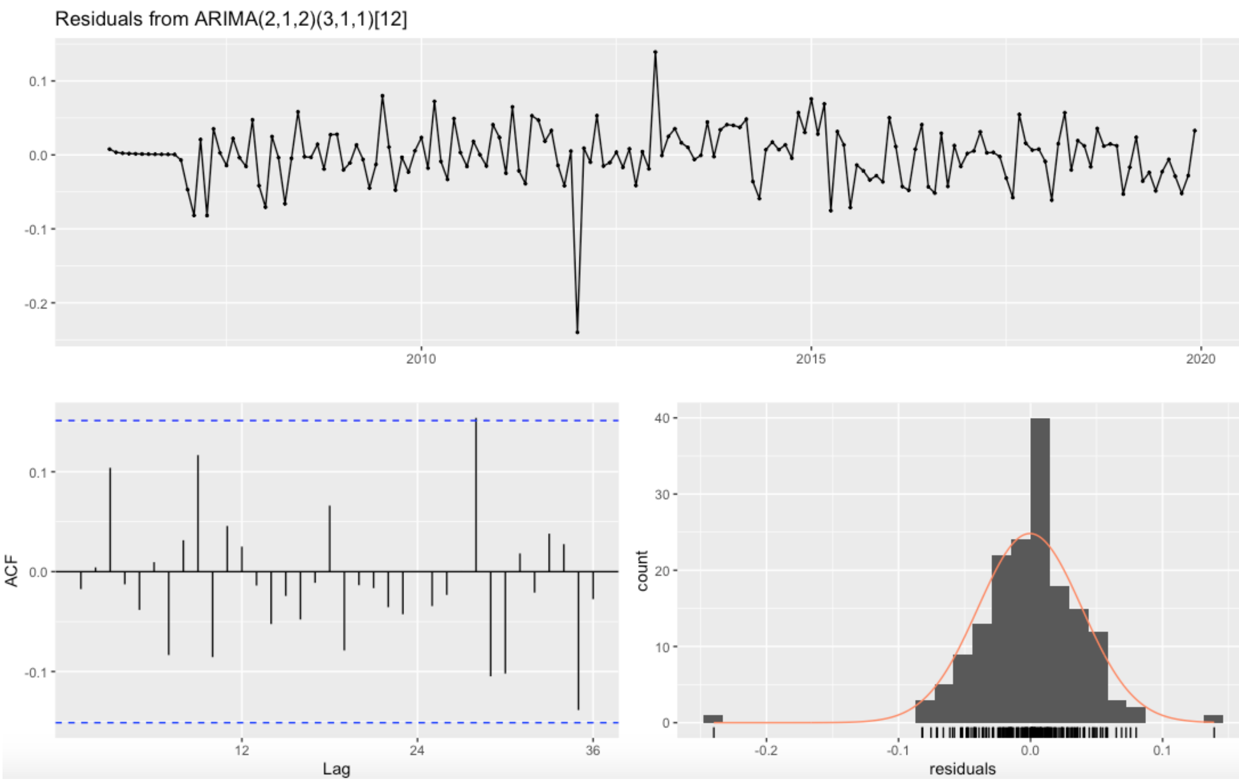

Figure 5.3. ACF and PACF of the residual.

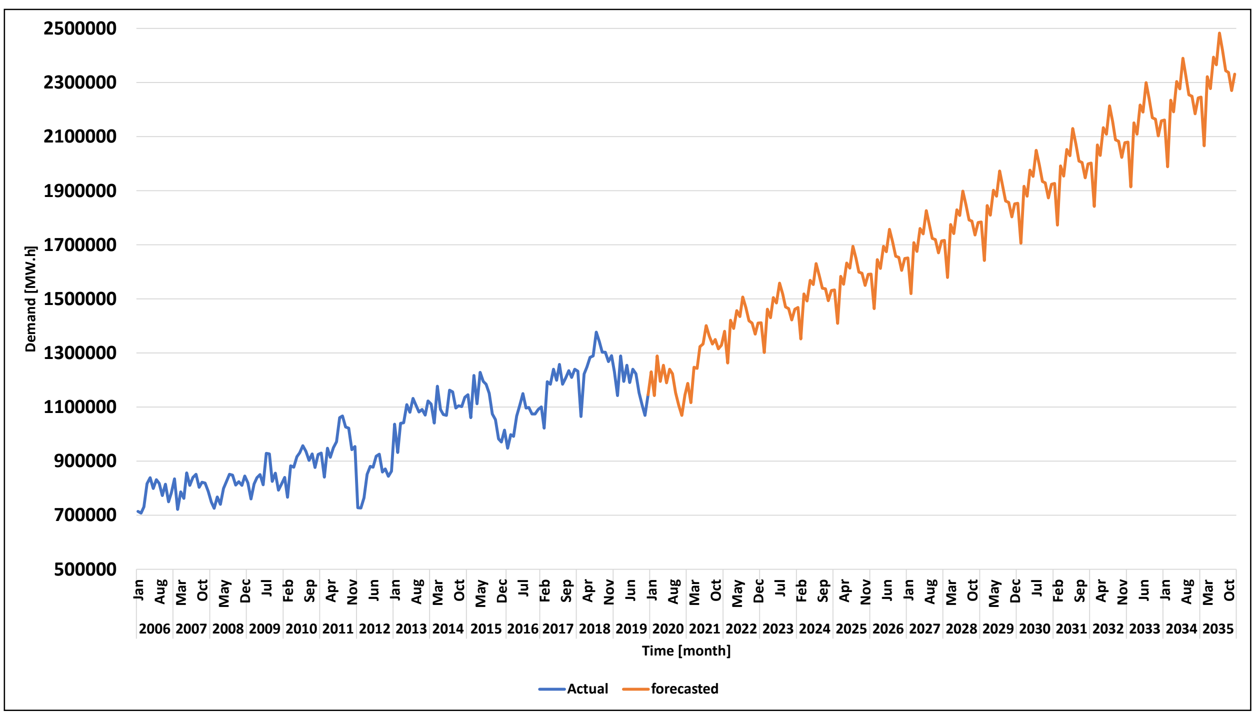

Figure 5.4. Projected Monthly electricity demand in Zambia.

5.2. Supply side analysis:

5.2.1. Baseline Scenario.

Figure 5.5 shows the optimal selection of the power generation technologies for the baseline scenario with integrated demand. After the base year, the power generated from the oil power plants with imported oil has increased to meet Zambia's electricity demand. The baseline scenario results emphasize the future dominance of Oil(FO) to meet the electricity demand. The total installed capacity for Oil(FO) is projected to increase by 51% in 2035 from 110 MW in 2019. The local coal-based power plants seem to increase but remain constant throughout time. The hydro-based power plants also remain fixed during the horizon. Oil(FO) dominates more than Oil(HSD and its contribution increases to 24.2%. Zambia recently included solar in the energy mix, so a consistent amount of solar from the base year can be seen through the horizon.

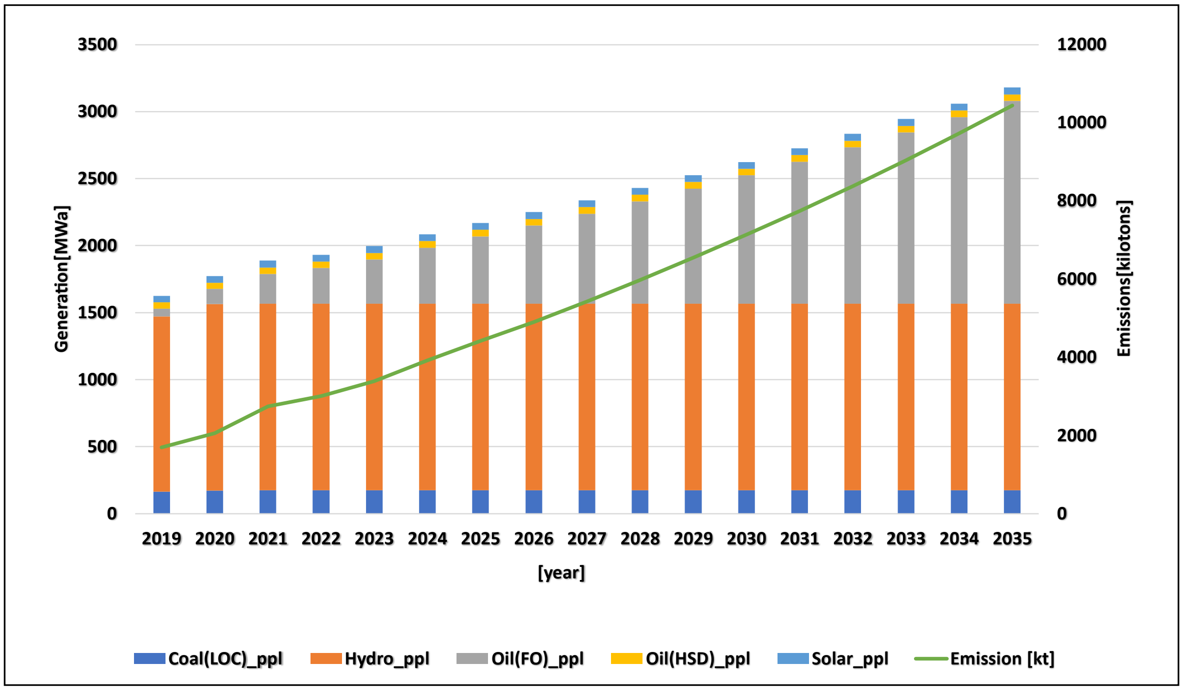

Figure 5.5. Electricity generation and emissions under the baseline scenario.

5.2.2. Zambia's Forecasted Electricity Deficit.

Zambia's failure to increase its investment in the diversification of the electricity generation mix will result in a consistent deficit, depicted in Figure 5.6. Clean energy sources are supposed to be integrated to ensure universal access to clean and affordable energy[39]. The country is targeting to reach sustainable development goals by increasing access to energy for rural and urban areas. On the renewable energy side, yet to reach its full potential in solar energy generation. The solar energy distribution and potential in Zambia have been assessed using spatial analysis in ArcGIS software[47]. The results showed that Zambia has approximately

20,422TWh/year of technical solar energy potential and receives 2109 KWh/m^2 of solar energy per year with 4403.12 hours of sunshine. Another renewable source considered is wind energy. In Zambia, wind energy is a good source when water levels in the country are low. Recent studies have been conducted to verify the stability and reliance of wind energy as a potential source in the country. In 2015, The Ministry of energy in Zambia and the World Bank launched a renewable energy wind mapping for Zambia in the Energy Sector Management Assistance Program (ESMAP) framework. The potential for wind energy in Zambia has also been assessed based on wind speed data and showed sites with potential for wind energy. Potential sites for wind energy close to the grid were also found [42].

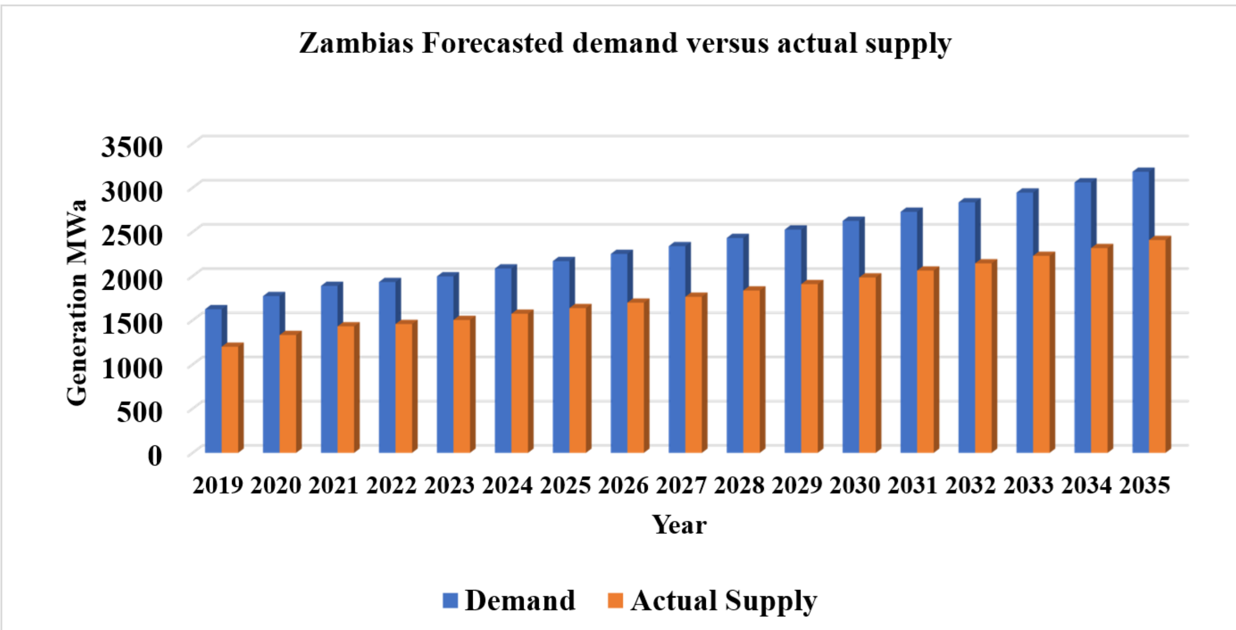

Figure 5.6. Zambia's forecasted demand versus actual supply.

5.2.3. Scenario analysis:

A scenario analysis was conducted in this study to provide solutions to mitigate the shortfall of electricity, which covers the following scenarios:

- Integration of renewable energy (RE): the total installed capacity shares of renewable energy technologies will increase to 11.89% and 30% in 2024 and 2035, respectively.
- No Coal Scenario (NC): the share of coal-based power generation decreases to zero percent in 2035.
- Emission target scenario: the GHG emissions will decrease by 10%, 20%, 30%, 40%, and 50% in 2035.

Figure 5.7 shows the share of generation from each powerplant considered in the No coal scenario. The No coal scenario shows that the share of coal in the generation mix in 2035 is zero. The model integrates more solar in the system with a percentage share of about 9.8 percent in comparison to the baseline. The restrictions in the future installation of coal-based power plants will force the model towards more affordable investments in new power plants, also accounting for the time constraint of added capacity in coming years. The model uses slightly more oil in 2035 than hydro, based on the cost minimization function and integration of available or new power plants in a specified year.

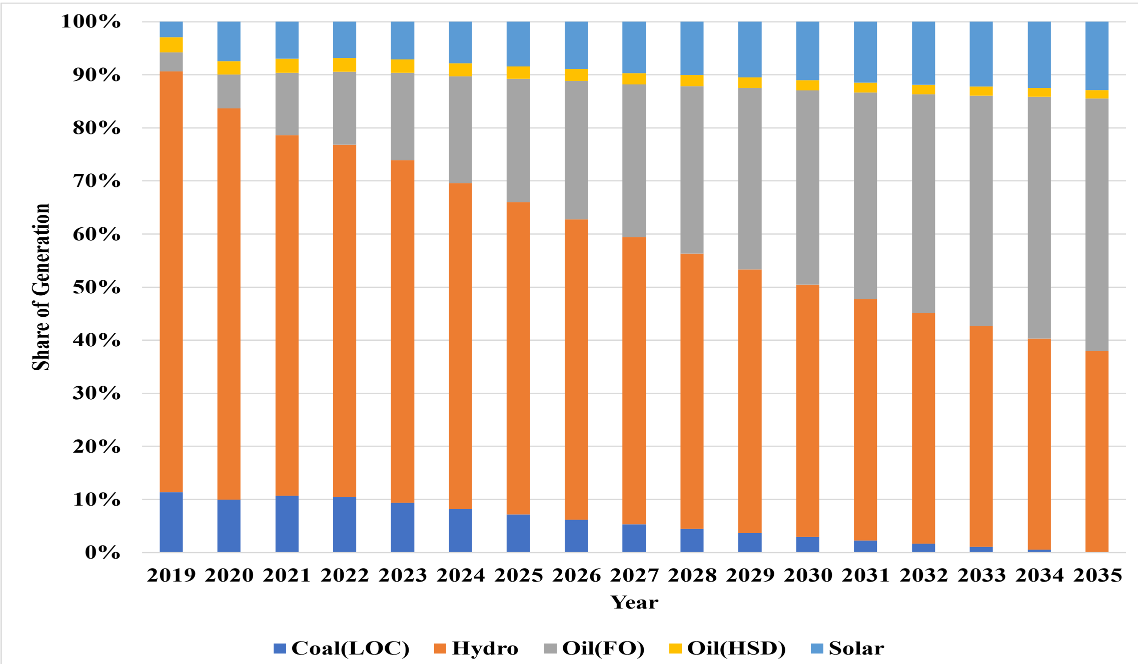

Figure 5.7. Power supply mix in the No Coal Scenario

Figure 5.8 shows the results of the baseline, renewable, and no coal scenario. The Baseline scenario assumes that no new climate policies over the horizon are implemented. The baseline also indicates the key role played by hydro, coal, and Oil(FO) technologies in the final electricity generations. These technologies have shown the least-cost competitiveness in electricity generation, which describes their importance in sustainable electricity sector development. The second is the insignificant contribution from solar PV technologies in the baseline despite their most minor operations and maintenance costs.

The displacement of oil power plants with more renewable energy technologies has reduced CO_2 emissions. The results for the RE scenario depict a considerable reduction of CO_2 emissions at approximately 50% reduction in annual CO_2 emissions by 2035. This scenario demands a more aggressive approach to ensure that the implemented policy is fulfilled, and more renewable technologies are integrated into the horizon. Additional policies, such as renewable energy feedin tariffs and institutional frameworks that are essential for the growth of renewable energy technologies, must be in place. Hydroelectricity continues to dominate the generation mix, limiting the amount of imported oil and coal. This restricts the use of coal and oil supply reserves and the installation of new fossil fuel power plants. In this scenario, the share of coal decreases by almost half, from 10 percent in the base year to 5.4 percent. However, there seems to be a shortfall in electricity, which shows that the oil supply must increase.

In the No Coal scenario (NC), the model was forced to restrict the future installation of coal-based power plants, as well as a bound on the oil imports limiting the available conversion technologies that it can fully optimize to provide minimal cost. The model showed favorable tendencies toward hydropower and solar in the future. Mainly more investment in solar technologies resulted from this scenario, which increased the renewable share to 50.84% from 45.4% in the baseline case.

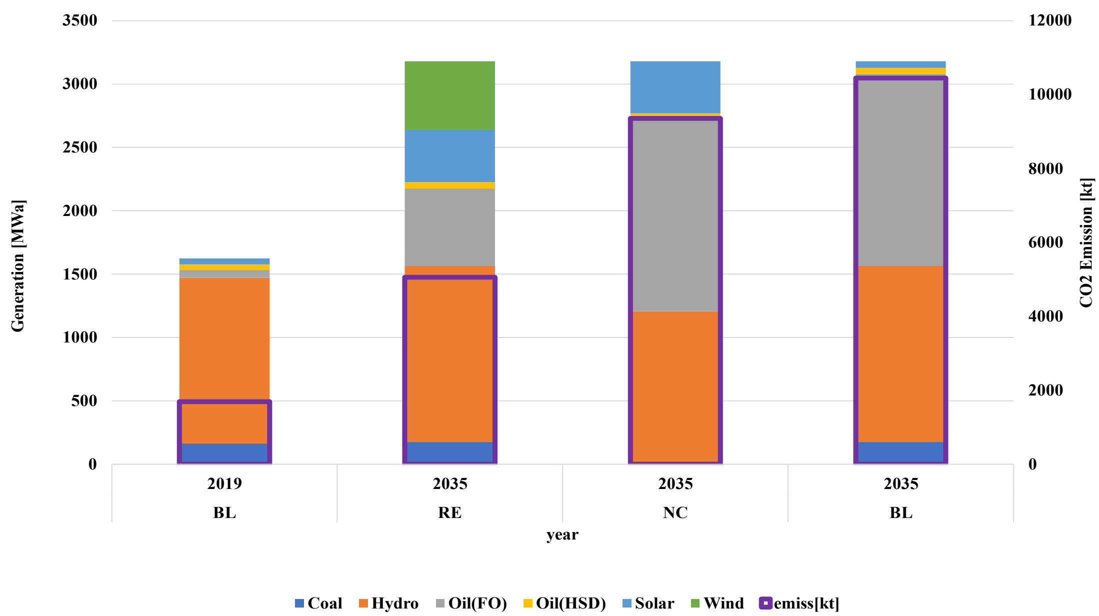

Figure 5.8. Comparison between the renewable, No coal Scenario and Baseline scenarios.

Table 5.2 summarizes emission reductions, cost, and renewable shares in the different scenarios. Local coal power plants are not the main consideration for new capacity installations in Zambia. However, with existing coal and oil, the emissions from the generation side decreased in 2035, from 10444.4 to 9357.8 kilotons in the No Coal Scenario.

Table 5.2. Summary of analysis of scenarios on the Supply side in 2035.

Scenario	**Annual emissions [kt]**	**LCOE[Cents/kWh]**	**RE share [%]** *
Baseline (BL)	104,44.4	7.68	45.40
Renewable Scenario (RE)	5,059.8	8.02	73.80
No Coal (NC)	9,357.8	7.82	50.84

*RE includes solar, wind and hydro

In the strictest emissions target (50% annual emission reduction), the contribution of local coal to the total power generation will be reduced to zero in 2034-2035. The power generation from solar power plants is increased from 2032 to 2035, showing that more solar power plants will be installed during that period to replace fossil fuel power plants. In 2035, hydro and solar together account for 65.03% of total power generation. Hence, the LCOE is slightly higher than the baseline due to the costly investment in this strict scenario (See Table 5.3). The electricity supply mix under the 50% emission target is shown in Figure 5.9.

Table 5.3. Sensitivity analysis of emission reduction targets in 2035.

Scenario	**Sub-Scenario**	**Annual Emissions [kt]**	**LCOE [Cents/kWh]**	**RE Share [%]** *
	10%	9400	7.98	51.20
	20%	8355.6	8.11	54.32
Emission Targets	30%	7311.1	8.20	57.60
	40%	6266.7	8.28	61.30
	50%	5222.2	8.36	65.03

*RE includes solar, wind and hydro

The emission reduction target scenarios demonstrate a tradeoff between efficient energy resources and utilizing energy supply resources that improve environmental quality. However, the country's ability to sustain economic growth with more energy use can still be met by increasing the renewable share in the energy mix. Figure 5.10 shows the trend in emissions reduction in all emission target scenarios with respect to the baseline scenario. The total CO_2 emission rises from 1,693.7 in 2019 to 10,444.4 kilotons in 2035 for the baseline scenario, representing an average of 545 kt yearly with increasing economic growth.

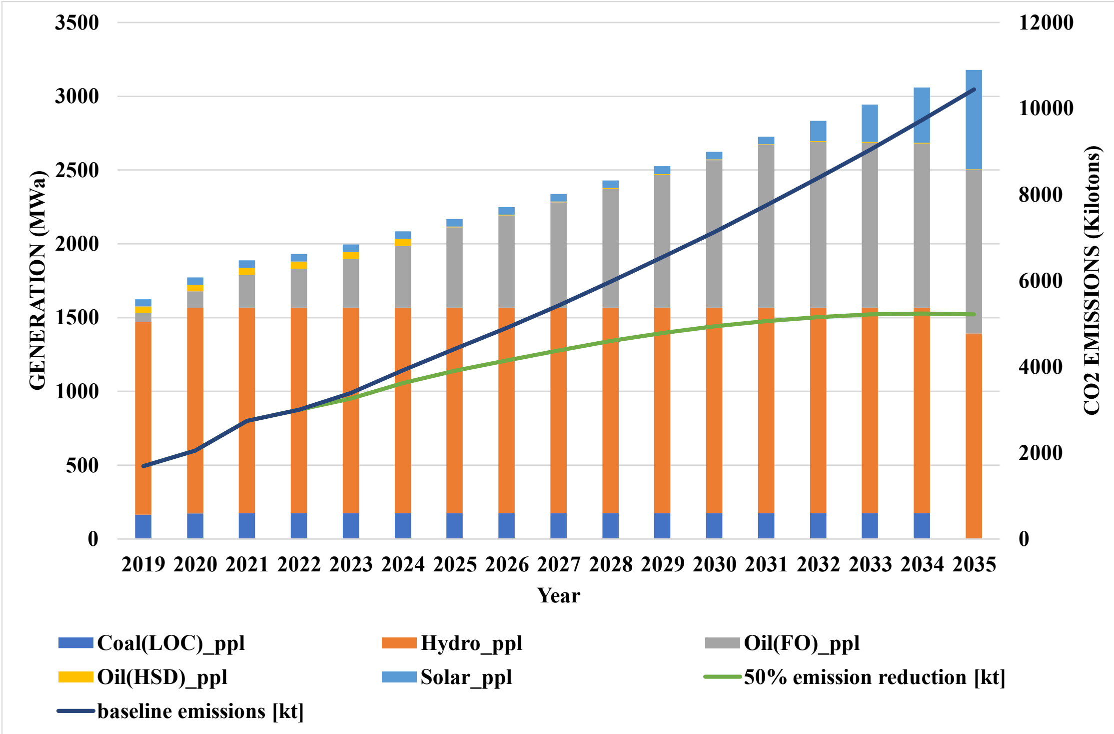

Figure 5.9. Generation mix and resulting CO_2 emissions for 50% reduction in emission scenario.

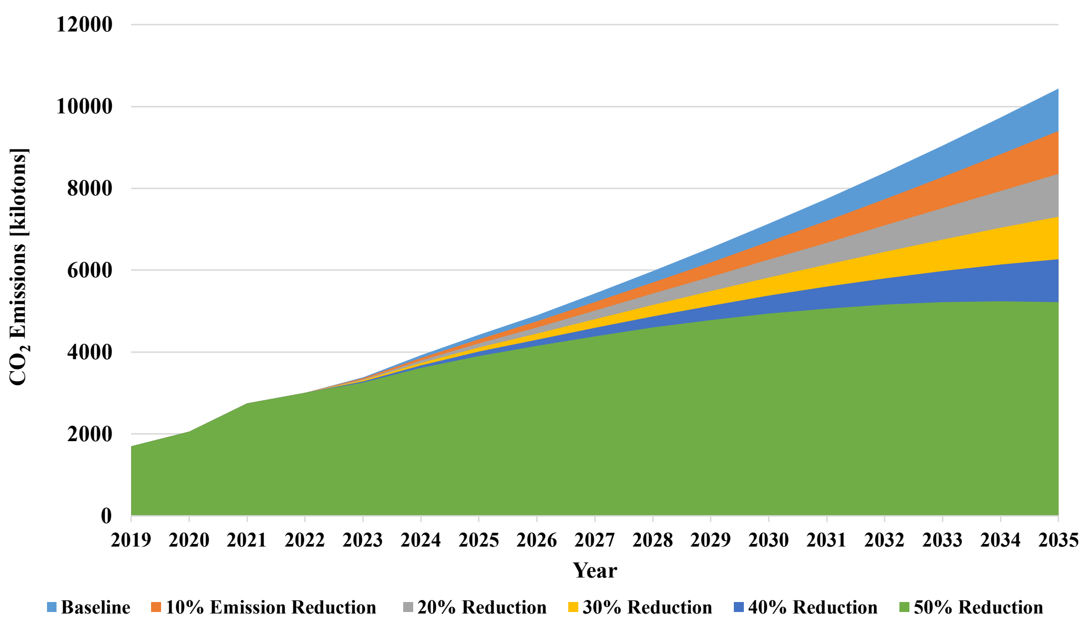

Figure 5.10. Cumulative Emissions Trends.

No coal scenario is an expensive scenario. A future governmental proposal on the NC scenario may not be ideal for comparing the operation and maintenance costs of renewable technologies. It is also beneficial to see that even if the oil is kept constant if a dry year exists, it will be likely that more oil will be needed to be imported. Else, more solar should be explored as a tangible option. The diversification of the energy mix is essential in Zambia. Integration of renewable energy sources has high potential in Zambia because of the high intensity of sunshine and good wind, even though it is a country with an increased supply of water bodies in Africa.[10] Hydro potential continues to grow as new power plants are being completed. Hydro may be fully exploited if enough investment and the effects of climate change are improved. The power sector can efficiently exploit the outstanding renewable energy potential to boost generation.

Chapter 6

Conclusions

According to the 'International Energy Agency (IEA), it has estimated that nearly 60% of the additional generation required to achieve universal access to electricity in Africa will need to come from off-grid solutions. Zambia Vision 2030 is a long-term perspective plan that aims at attaining prosperous middle-income nation status by 2030 by creating an enabling environment for sustainable socio-economic development. One of the conditions for this to be achieved is gaining universal access to clean, reliable, and affordable energy at the least economic, fiscal, social, and environmental costs and increased use of renewable energy sources.

This study focuses on developing and applying an integrated energy demand-supply modeling framework to assess the impact of environmental policies on the decarbonization of the power sector in Zambia. First, the demand side model was developed based on the Seasonal Auto-Regressive Integrated Moving Average (SARIMA) time series method. Then, the projected electricity demand in the demand-side model was given to the supply-side model, which was based on minimizing the total discounted costs for supplying future energy demands. The energy supply model considers a full horizon from 2019 to 2035. Input data for all technologies included fuel prices, capital, operation and maintenance costs, technical performance factors, demand, and policies.

The modeling results conclude a lack of self-sufficiency in the country to meet future electricity. The baseline scenario results revealed an alarming oil (FO) rate estimated on the horizon. The available generation capacity against peak demand recorded an average deficit of 623MW from 2023 to 2035. The policies that favor integrating renewable energy technologies are important to help increase electricity generation. The scenario analysis conducted in this study showed that the Zambia power sector can meet the future increase in demand (3,179 MWa in 2035) by integrating more renewable energy sources into its system.

For the integration of renewable technologies in the energy system, an increased LCOE for both wind and solar power plants was observed. To improve the shortfall of electricity while considering clean energy, diversifying energy sources by using more solar and wind while curbing the use of coal and other fossil fuels can lead to low pollution levels and increased flexible generation. The current baseline scenario has a contribution of 45.4% of the renewable share, with hydro being fixed, which makes it difficult to mitigate the effects of climate change. The cost of power for the renewable system may be competitive initially, but as a whole energy system, the costs subside eventually. An unprecedented power shortfall in 2016 prompted the Zambian government to diversify its energy sources by planning to go into solar and increase coal power[48].The seasonality of hydro is a huge concern for the country, especially with the current power cuts. The No Coal scenario contributes to about 50.84 percent of the renewable share in the energy system. The emission target scenarios constrain the use of fossil fuels by using more renewable energy while still meeting the demand of the country. The 50% emission reduction scenario shows a 65.03% renewable share contribution in 2035. These scenarios show that resource exploration in renewable energy can provide actionable global climate change policies on the current energy system. Overall, each scenario, excluding the baseline, has shown efforts in decarbonization measures such as extensive use of renewable resources.

The rationing of power in Zambia is a significant issue that needs policy diversification and integration of other energy sources. As much as hydropower is the main energy source, the severity of droughts in the country has led to power shortages. Therefore, the electricity supply must be explored to its full potential for Zambia's economic growth forecast to increase. The goal is to improve carbon emissions by using renewable sources and help provide clean energy to people in rural and urban areas at a fair cost. Climate policy is essential to ensure a future reduction in Zambia's CO_2 emissions as the country strives for higher levels of economic activity.

References

[1] Kesselring R. The electricity crisis in Zambia: Blackouts and social stratification in new mining towns. Energy Res Soc Sci 2017;30:94–102. https://doi.org/10.1016/J.ERSS.2017.06.015.

[2] Zambia - Access To Electricity (% Of Population) - 2022 Data 2023 Forecast 1990-2020 Historical. https://tradingeconomics.com/zambia/access-to-electricity-percent-of-population-wb-data.html (accessed November 26, 2022).

[3] Greenhouse Gas Emissions Factsheet: Zambia | Global Climate Change. https://www.climatelinks.org/resources/greenhouse-gas-emissions-factsheet-zambia (accessed November 28, 2022).

[4] Abdallah L, El-Shennawy T. Reducing carbon dioxide emissions from electricity sector using smart electric grid applications. J Eng (United Kingdom) 2013;2013. https://doi.org/10.1155/2013/845051.

[5] CO_2 and Greenhouse Gas Emissions - Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions (accessed November 26, 2022).

[6] CLIMATE CHANGE ADAPTATION PLANNING IN ZAMBIA Towards building resilience of economic systems, livelihoods and ecosystems.

[7] Greenhouse Gas Emissions Factsheet: Zambia | Global Climate Change. https://www.climatelinks.org/resources/greenhouse-gas-emissions-factsheet-zambia (accessed November 26, 2022).

[8] Ministry of lands NR and EP. National Policy on Climate Change. https://doi.org/April 2016.

[9] The Energy Sector Report 2019 – Energy Regulation Board. https://www.erb.org.zm/document/the-energy-sector-report-2019 (accessed November 28, 2022).

[10] Discussing climate change and renewable energy in Zambia - enelfoundation.org. https://www.enelfoundation.org/all-news/news/2020/10/discussing-climate-change-and-renewable-energy-in-zambia (accessed November 28, 2022).

[11] Zambia Electricity Cost of Service Study Final Summary Consolidated Report Energy Market and Regulatory Consultants Limited (part of the MRC Group) Draft Final Report 2021.

[12] Tembo B, Merven B. Policy options for the sustainable development of Zambia's electricity sector. J Energy South Africa 2013;24:16–27. https://doi.org/10.17159/2413-3051/2013/V24I2A3126.

[13] Allington L, Cannone C. Selected 'Starter Kit' energy system modelling data for Zambia (#CCG) 2021. https://doi.org/10.21203/RS.3.RS-480042/V2.

[14] Mwandila G, Mwanza M, Sikhwivhilu K, Siame J, Mutanga SS, Simposya A. Modeling energy requirements for a biogas-supported decentralized Water treatment systems for communities in chambishi (Zambia) and diepsloot (South Africa) townships. Renew Energy Focus 2021;37:20–6. https://doi.org/10.1016/J.REF.2021.02.003.

[15] Libanda B, Paeth H. Modelling wind speed across Zambia: Implications for wind energy. Int J Climatol 2022. https://doi.org/10.1002/JOC.7826.

[16] Mwanza M, Chachak J, Çetin NS, Ülgen K. Assessment of solar energy source distribution and potential in Zambia. Period Eng Nat Sci 2017;5:103–16. https://doi.org/10.21533/PEN.V5I2.71.

[17] Ouedraogo NS. Modeling sustainable long-term electricity supply-demand in Africa. Appl

Energy 2017;190:1047–67. https://doi.org/10.1016/J.APENERGY.2016.12.162.

[18] Mundaca L and, Neij L. Energy-economy models and energy efficiency policy evaluation for the household sector An analysis of modelling tools and analytical approaches. IIIEE Reports 2009;2.

[19] Krzemień J. Application of Markal Model Generator in Optimizing Energy Systems. J Sustain Min 2013;12:35–9. https://doi.org/10.7424/JSM130205.

[20] LEAP | EnergyPLAN. https://www.energyplan.eu/othertools/national/leap/ (accessed December 12, 2022).

[21] Mcneil MA, Letschert VE, De S. Bottom-Up Energy Analysis System - Methodology and Results 2011.

[22] Farzaneh H. Energy systems modeling: Principles and applications. Springer; 2019.

[23] Forecasting | MATH6011 | University of Southampton. https://www.southampton.ac.uk/courses/modules/math6011 (accessed November 29, 2022).

[24] (PDF) Challenges and Approaches to Time series forecasting: A Survey. https://www.researchgate.net/publication/348176423_Challenges_and_Approaches_to_Time_series_forecasting_A_Survey (accessed November 28, 2022).

[25] Hyndman, R.J., & Athanasopoulos, G. (2018) Forecasting: principles and practice, 2nd edition, OTexts: Melbourne, Australia. OTexts.com/fpp2. https://otexts.com/fpp2/seasonal-arima.html (accessed November 29, 2022).

[26] Fattah J, Ezzine L, Aman Z, El Moussami H, Lachhab A. Forecasting of demand using ARIMA model. Int J Eng Bus Manag 2018;10. https://doi.org/10.1177/1847979018808673/ASSET/IMAGES/LARGE/10.1177_1847979018808673-FIG2.JPEG.

[27] Young WL. The Box-Jenkins approach to time series analysis and forecasting : principles and applications. RAIRO - Oper Res - Rech Opérationnelle 1977;11:129–43.

[28] Malehmirchegini L, Farzaneh H. Demand response modeling in a day-ahead wholesale electricity market in Japan, considering the impact of customer risk aversion and dynamic price elasticity of demand. Energy Reports 2022;8:11910–26. https://doi.org/10.1016/J.EGYR.2022.09.027.

[29] Huppmann D, Gidden M, Fricko O, Kolp P, Orthofer C, Pimmer M, et al. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environ Model Softw 2019;112:143–56. https://doi.org/10.1016/j.envsoft.2018.11.012.

[30] Krey V, Havlik P, Kishimoto PN, Fricko O, Zilliacus J, Gidden M, et al. MESSAGEix-GLOBIOM Documentation. International Institute for Applied System Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA); 2020. https://doi.org/10.22022/iacc/03-2021.17115.

[31] Zambia Interest Rate - 2022 Data - 2001-2021 Historical - 2023 Forecast - Calendar. https://tradingeconomics.com/zambia/interest-rate (accessed November 29, 2022).

[32] Abrar S, Farzaneh H. Scenario Analysis of the Low Emission Energy System in Pakistan Using Integrated Energy Demand-Supply Modeling Approach. Energies 2021;14:3303. https://doi.org/10.3390/EN14113303.

[33] Zambia Coal reserves - data, chart | TheGlobalEconomy.com. https://www.theglobaleconomy.com/Zambia/coal_reserves/ (accessed December 19,

2022).
[34] (IRENA)International Renewable Energy Agency. ENERGY PROFILE. https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Zambia_Africa_RE_SP.pdf (accessed December 19, 2022).
[35] ZESCO Limited. https://www.zesco.co.zm/ (accessed November 30, 2022).
[36] Ministry of Energy – MOE. https://www.moe.gov.zm/ (accessed November 30, 2022).
[37] Zambia - Countries & Regions - IEA. https://www.iea.org/countries/zambia (accessed December 23, 2022).
[38] National Renewable Energy Laboratory (NREL) Home Page | NREL. https://www.nrel.gov/ (accessed November 30, 2022).
[39] 7 National Development Plan (2017-2021)Republic of Zambia 2017.
[40] Energy Regulation Board – A Proactive, Firm & Fair Energy Regulator. https://www.erb.org.zm/ (accessed November 30, 2022).
[41] Global Solar Atlas. https://globalsolaratlas.info/map?c=11.523088,8.4375,3 (accessed November 30, 2022).
[42] Global Wind Atlas n.d. https://globalwindatlas.info/en (accessed November 30, 2022).
[43] OPPORTUNITIES FOR RENEWABLE ENERGY IN ZAMBIA 2019.
[44] Zambia Coal reserves - data, chart | TheGlobalEconomy.com. https://www.theglobaleconomy.com/Zambia/coal_reserves/ (accessed December 20, 2022).
[45] Zambia Oil reserves - data, chart | TheGlobalEconomy.com. https://www.theglobaleconomy.com/Zambia/oil_reserves/ (accessed December 20, 2022).
[46] THE ENERGY SECTOR REPORT 2021 – Energy Regulation Board. https://www.erb.org.zm/document/the-energy-sector-report-2021 (accessed December 20, 2022).
[47] Mwanza M, Chachak J, Çetin NS, Ülgen K. Assessment of solar energy source distribution and potential in Zambia. Period Eng Nat Sci 2017;5:103–16. https://doi.org/10.21533/PEN.V5I2.71.
[48] Jain P. Coal Power in Zambia: Time to Rethink. South African J Policy Dev 2017;3.