Scenario analysis of the low emission energy system in Pakistan using integrated energy demand-supply modeling approach

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Scenario analysis of the low emission energy system in Pakistan by using integrated energy demand-supply modeling approach

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Abstract

Pakistan's dependence on energy imports, inefficient power generation and distribution, and lack of planned investment have made the country's economy vulnerable. Expensive power generation and then providing subsidies to make electricity affordable is resulting in the accumulation of circular debt, which is becoming a huge financial burden on the government. This often hinders the policy interventions such as investing in comparatively clean energy options and other system improvements. The power shortfall since 2006 has made the thing worst for economic sectors and inconvenience general public. Moreover, Pakistan is among the most affected country in terms of climate change, and there is an urgent need for intervention to mitigate it. All these issues related to the power sector demand comprehensive planning to foresee these challenges and allocate the resources according to ensure an affordable, reliable, and environmentally sustainable energy system. Low carbon and resilient climate development in Pakistan can help ensure climate action and reduce the chronic energy deficit ailing the country's economy, society, and environment. This study focuses on developing and applying an integrated energy supply-demand modeling framework based on a combination of microeconomics and system integration theories, which can be used to address policies that could dramatically change the future course of Pakistan toward a low emission energy system. The methodology involves medium-term forecasting of energy demand using an integration of top-down and bottom-up modeling approaches. The demand-side model is interlinked with a bottom-up technology assessment supply model. The objective of the supply-side model is to identify the optimal combination of resources and technologies, subject to satisfying technical, institutional, environmental, and economic constraints, using the cost minimization approach. The proposed integrated model is applied to enable a complete perspective to achieve overall reductions in energy consumption and generation and better analyze the effects of different scenarios on both energy demand and supply sides in Pakistan. In the baseline case, the results revealed that the energy demand is expected to increase from 8.70 Mtoe [106.7 TWh] to 24.19 Mtoe [297.2 TWh] with an annual average growth rate of 6.60%. Increasing the share of renewable energy power generation by 2030 can help reduce emissions by 24%, which is accompanied by a 13% increase in the total cost of power generation. To evaluate the impact of different policies and plans, a number of scenarios were analyzed and compared with reference (baseline) cases on both demand and supply sides. High and low economic growth (HEG and LEG), and energy efficiency and conservation (EE&C) scenarios were employed on the demand side. Whereas, Renewable (REN), No Coal (NC) and annual average emission reduction targets (10%, 20%, 30%, 40% and 50%) were analyzed on the supply side. HEG may increase energy demand and emissions by 21.74% and 19.71%, respectively, and EE&C may lower the demand by 15% with respect to the baseline case. On the supply side, REN and NC scenarios have the potential to reduce the annual average emissions by 24.48% and 37.75%, respectively. An ambitious emission reduction target of 50% will demand a renewable share of 82.74%. The levelized cost of energy (LCOE) will increase by 21.14% with respect to the baseline scenario. The idea of the learning curve was also applied to the baseline supply scenario to evaluate the impact of investment cost reduction with the increase in cumulative capacity. In this case, a higher cost reduction potential of solar generation made its share 40% in the year 2032 with a 46.6% reduction in annual average emissions compared to the baseline case.

Keyword: Integrated energy system modeling; econometrics; bottom-up technology assessment; MESSAGE, low emission development strategies; Pakistan.

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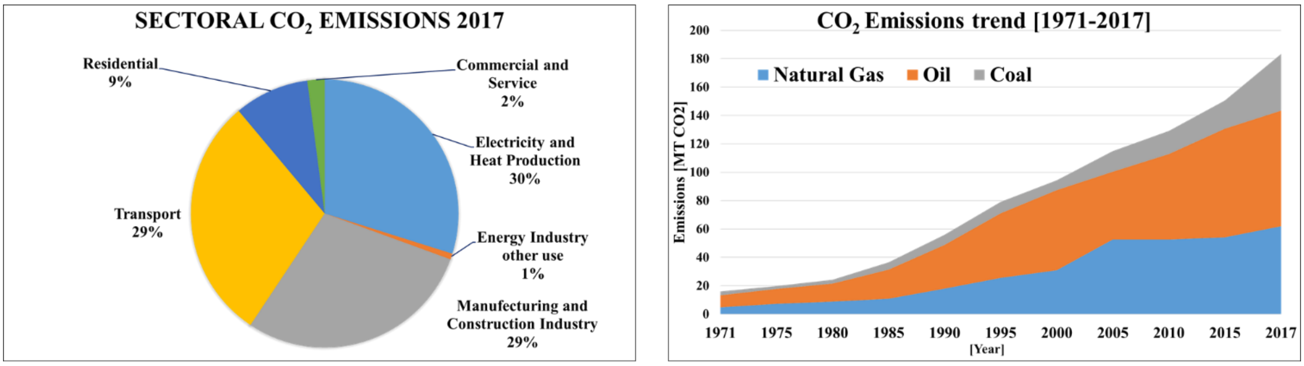
Sajid Abrar

Chapter 1. Introduction

1.1. Background

Through its CO_2 emissions in generation and consumption processes, the energy sector is the leading contributor to greenhouse gases (GHGs). According to the United Nations Framework Convention on Climate Change UNFCCC (United Nations Framework Convention on Climate Change), countries signed the Paris Agreement and pledged to reduce their GHG emissions through employing low carbon-based energy generation and efficient consumption [1]. Increasing penetration of renewable energy sources is one of the key target areas for climate mitigation efforts. To access the social, technological, and economic aspects of various strategies for climate mitigation, comprehensive and integrative energy modeling approaches are being employed to help forecast future energy needs and explore different pathways that can help realize emission reduction targets [2].

Sustainable development is about promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs, and a better quality of life for all. It is not just an environmental issue; it is about maintaining the natural capital and hence productivity and capacity of our planet to meet human needs and sustain economic activities. However, unpacking the sustainable development goals (SDGs) that measure Pakistan's progress on climate action presents a more disconcerting story. SDG 13, "Climate Action," calls on countries to take immediate action "to combat climate change and its effects". The United Nations sets out a range of actions and objectives to be taken to achieve SDG 13. A country's progress in SDG 13 is measured by integrating climate change measures into national policies, strategies, and planning. It is important to recognize that SDG 13 measures Pakistan's commitment to climate action measures to adopt and implement the National Appropriate National Reduction (NAMA). Pakistan is ranked fifth among countries most vulnerable to climate change [3] and, even with its minuscule share in global CO_2 emissions, is adversely affected by climate change [4]. Figure 1.1(a) shows the trend of CO_2 emissions from fossil fuel burning. To contribute to mitigation efforts, Pakistan ratified the Paris Agreement in 2016 and submitted its National Determined Contribution (NDC) to the UNFCCC with action items to reduce GHGs emissions in various sectors. In the energy sector, renewable energy deployment along with power generation and transmission efficiency are the critical focal points to reduce emissions. Later in 2019, the Alternative Energy Development Board (AEDB) proposed the Renewable Policy 2019 (RE-2019) to increase renewable shares substantially. It can be observed from Figure 1.1(b)that both demand and supply sectors are vital for the analysis to be realized.

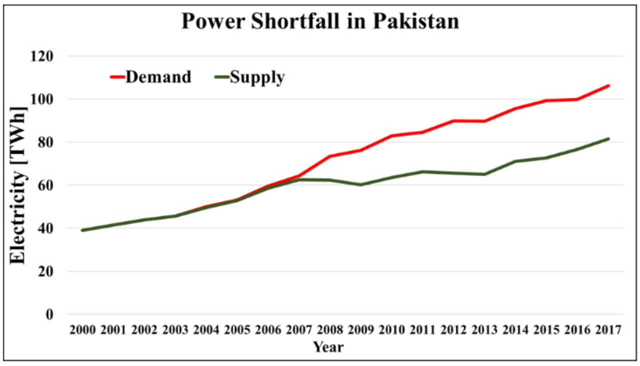


(a) (b)

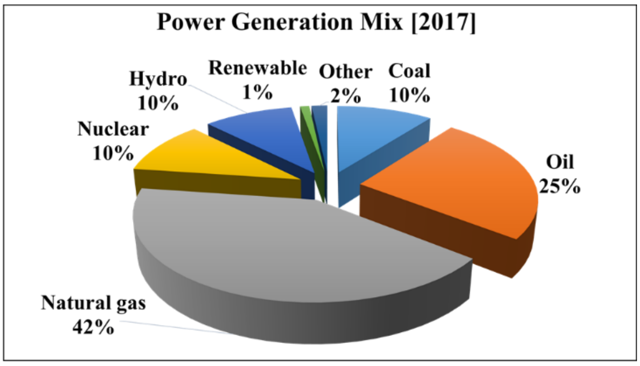
Figure 1.1. (a) Trends of CO_2 emissions from different fossil fuels. (b) Contribution of sectors of the energy system (adapted from [5]).

It is notable from this figure that the demand side is more contributor to emissions because generally, when we talk about emission mitigation, we think of generation or supply side. But this relation shows the opposite to common perception and an effective climate change policy demand both supply and demand showed e given proportional attention and consideration. On the demand side, the Transport sector having the highest share in emissions may need the highest interventions to reduce and control emissions.

Figure 1.2 shows the trend of power shortfall and the power generation mix for the base year of study. Since 2005, the demand kept on increasing similarly to that of the economic growth and the supply system expansion was not executed to meet the increasing demand. This has resulted in a prolonged power shortfall in rural and urban areas, causing an immense disturbance in the daily life of the public and economic sectors.



(a)



(b)

Figure 1.2. (a) The trend of shortfall in Pakistan (b) The power generation mix for the base year study

The base year power generation mix shows a high share of fossil fuels-based generation. This leads to higher emissions and puts a significant burden on the foreign exchequer because 62% of such energy fuels are imported at the primary level. This can be linked to energy security concerns for Pakistan. Another alarming number is a very low share of renewable energy (i.e., 11% including hydro) that can also glimpse level environmental degradation and lack of investments in clean and environmentally friendly energy sources.

1.2. Literature Review

Since the last decade, a number of efforts have been made in the context of Pakistan regarding the energy planning and assessment of energy systems under different scenarios. Different methodological methods and tools have been employed to forecast energy demand (demand-side models) and allocate energy supply sources (supply-side models). The demand-side has focused on finding the correlation of energy demand or consumption with economics to quantify the demand factors based on demographic and macroeconomics. Supply-side models have mainly focused on energy supply technologies which are characterized by a limited spatial scale, generally considering a single piece of technology, using an optimization technique to find the optimal energy supply mix.

Perwez et al. employed Long-range Energy Alternative Planning (LEAP), an integrated and accounting framework-based energy model, to analyze the power sector within the period of 2011–2030, considering different assumptions for demand policy considerations for the supply system [6]. They projected the future outlook of energy demand and supply under three different scenarios on the supply side, namely BAU (Business-as-usual), NC (New Coal), and GF (Green Future), based on the current trend and future policies on the power sector, especially the National Power Policy 2013. Their results revealed that the GF scenario requires fewer primary resources and provides a cost-effective response to emission restriction. Farooq et al. analyzed the economic and environmental impact of increasing renewable penetration in the future power sector mix for Pakistan for the horizon of 2005–2050 [7]. By employing the Market and Allocation (MARKAL) modeling framework and comparing the results for the different shares of renewable energy in their research, they suggested that a 50% share is suitable for Pakistan, and a higher share will become economical. Their results showed that concentrated solar power (CSP) is still not an economically feasible solution for Pakistan. In another effort, Arif et al. developed a comprehensive model to minimize the cost of electricity and emissions for the period 2018–2030 [8]. The model was based on multi-period mix integer programming (MPMIP) and solved by the General Algebraic Modeling System (GAMS), considering three scenarios of fuel switching, fuel balancing, and carbon capture and sequestration (CSS). The Power System Planning department of the National Transmission and Dispatch Company (NTDC) forecasted the future demand for electricity under different economic growth scenarios and then used the Wien Automatic System Planning Package (WASP) model to optimize the future generation expansion plan [9]. The main aim of this study was to encourage energy modeling and planning practices for better power network extensions. Rehman et al. forecasted the future energy demand of all energy carriers for 2015–2035 using three different models of autoregressive integrated moving average (ARIMA), Holt-Winters, and LEAP [10]. Table 1.1 summarizes the recent studies on employing energy modeling techniques in Pakistan.

Table 1.1. Related works on energy modeling in Pakistan

Purpose of Study	Focus Field	Future Model Horizon	Methodological Approach	Tool/Techniques Employed	Reference
Estimation of emissions of major air pollutants from energy transformation processes in the country	Supply	2015–2035	Optimization	ANSWER-TIMES	[11]
A forecasting study of hydroelectricity consumption in Pakistan based on the historical data of the past 53 years	Supply	2017–2030	Time Series Analysis	ARIMA	[12]
To develop Pakistan's LEAP modeling framework	Supply	2015–2050	Accounting/ Simulation	LEAP	[13]
Analyzing renewable energy policy of Pakistan and examining and finding the ways to secure energy supplies in future	Supply	2012–2030	Accounting/ Simulation	LEAP	[14]
Analyzing the long-term electricity demand for Pakistan's economy as envisaged in Pakistan Vision 2025 fomented by high economic growth	Supply	2014–2035	Accounting/ Simulation	LEAP	[15]
To explore the Granger causality relationship between electricity supply and economic growth (EG)	Supply	-	Econometrics	Granger causality	[16]
Under National Power Policy 2013, the development of an efficient and consumer-oriented sustainable and economical electric power system	Supply	2015–2035	Optimization/ Simulation	WASP	[17]
Evaluate the impact of import reduction on energy supply, resource diversification, cost energy security, and environmental emissions	Supply	2005–2050	Optimization	MARKAL	[18]

Modeling tools-based pathways for Pakistan power sector to depict the future challenges and aspects associated with its forecasting and planning	Supply	2011–2030	Accounting/ Simulation	LEAP	[19]
Energy supply modeling based on the forecasted demand in Pakistan	Supply	2005–2030	Accounting/ Simulation	LEAP	[10]
Using historical series data to forecast total and component-wise electricity consumption in Pakistan	Demand	2012–2020	Time Series	ARIMA, Holt-Winters	[20]
Electricity demand forecast based on multiple regression	Demand	2014–2037	Statistics	Multiple Regression	[21]
Revisit the relationship between electricity consumption and economic growth in Pakistan by controlling and investigating the effects of two major production factors—capital and labor	Demand	-	Econometrics	Econometric	[22]
To reinvestigate the multivariate electricity consumption function for Pakistan	Demand	-	Econometrics	ARDL	[23]

The great oil crisis in 1973 and its consequent impact on global economies (especially those dependent on imported energy supplies) was the starting point when institutions and agencies start to formally pay attention to the systematic analysis for the energy system to ensure the reliable and secure energy supplies. The main objective of such efforts was to find a way to reduce the import dependence of fossil fuels (especially oil) and evaluate the impact of different energy policies on national and regional economies. This led to extensive development of energy demand, supply and hybrid energy model and their application to different energy systems. There are models that primarily can be divided into different classes:

1. ***Technology-oriented optimization and simulation model***
2. ***Economy-oriented model***

This first class is also referred as bottom-up energy models, tries to address the first objective of finding ways to search for alternate energy sources to secure energy systems. The famous energy model based on this scheme was BESOM (Brookhaven Energy System Optimization Model) which later proved a foundation of widely applied and comprehensive MARKAL (MARKet and Allocation) model. Other notable models of this category are EFOM (The Energy Flow Optimization Model) and MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impact).

The second class involved the model-based macro-economic analysis (also referred as the top-down model). These models account for energy as an input to the economy, which can lead to quantify the impact on the economy by socks and constraints on energy supplies. The famous example of this category was ETA-MACRO employed by EMF (Energy Modeling Forum) in the United States. Table 1.2and

Table 1.3 show the details and features of different energy models used for energy demand and supply analysis [55].

Table 1.2. The summary of different energy models (Part-1)

Model	Developer	Purpose	Modelling Paradigm	Methodological Approach
EFOM	European Commission	Energy Supply	Bottom-up	Optimization
LEAP	Stockholm Environmental Institute	Integrated	Hybrid	Accounting/ Simulation
ENPEP	International Atomic Agency	Integrated	Hybrid (Demand is Bottom Up)	Macro-economic/ economic equilibrium
MARKAL	International Energy Agency	Energy Supply	Bottom-up	Optimization
MARKAL-MACRO	Brookhaven National Laboratory USA	Integrated	Hybrid	Macro-economic/Optimization
MESAP	University of Stuttgart Germany	Integrated	Hybrid	Econometrics/Simulation
MESSAGE	IIASA Austria	Energy Supply	Bottom-up	Optimization
MESSAGE-MACRO	IIASA Austria	Energy Supply linked to Macroeconomics	Hybrid	Optimization
MICRO-MELODIE	CEA France	Energy Demand	Top-Down	Macro-economic
NEMS	DOE USA	Energy Demand	Top-Down	Econometrics
WEPS	International Energy Agency	Energy Demand	Top-Down	Optimization/Simulation
RETscreen	CEDRL, Canada	Energy Supply	Bottom-up	Optimization
OSeMOSYS	Open-Source research community, UCL USA	Energy Demand	Bottom-up	Optimization
EnergyPLAN	Aalborg University	Energy Supply	Bottom-up	Optimization
POLES	European Commission	Integrated	Hybrid	Optimization
PRIMES	National Technical University of Athens (NTUA)	Integrated	Hybrid	Agent Based

Table 1.3. The summary of different energy models (Part-2)

Model	Mathematical Approach	Spatial Perspective	Time Horizon	Licensing	Software /Programming
EFOM	Mathematical Programming	National	Medium, Long	-	-
LEAP	Analytical Programming	Local, National, Global	Medium, Long	Commercial	Others

ENPEP	Mathematical Programming/ Regression	Local, National	Short, Medium, Long	-	-
MARKAL	Mathematical Programming	Local, National	Medium, Long	Commercial	GAMS
MARKAL-MACRO	Dynamic Programming	Local, National	Medium, Long	Commercial	-
MESAP	Mathematical Programming/ Regression	Local, National	Medium, Long	Commercial	-
MESSAGE	Mathematical Programming	Local, National	Short, Medium, Long	Open Source	Other (FORTRAN)
MESSAGE-MACRO	Mathematical Programming	Local, National	Short, Medium, Long	Open Source	GAMS and C
MICRO-MELODIE	Regression/ Time Series	National	Medium	-	-
NEMS	Regression	National	Medium	-	
WEPS	Mathematical Programming	Global	Medium, Long	Open Source	Other (FORTRAN)
RETscreen	Mathematical Programming	Local, National	Long	-	-
OSeMOSYS	Mathematical Programming	Local, National	Short	Open Source	Other (MathProg)
EnergyPLAN	Mathematical Programming	Regional, State, National	Short	Open Source	Visual Basic
POLES	Mathematical Programming	Global	Long	-	-
PRIMES	Dynamic Programming	Local, National	Medium, long	Proprietary	Others

1.3. Research Gap and Originality Highlights

Despite the diversity of modeling approaches highlighted in Table 1, three challenges exist with all the aforementioned methodologies. The first challenge relates to the methodological foundations of the two categories of demand and supply side, which have usually been developed by focusing on specific aspects of energy use. The second challenge posed by these models is the lack of integration between different demand and supply vectors in the Pakistan energy system, through developing equilibrium-seeking feedback processes, which yields a complex and robust modeling system. The third challenge is creating an analytical framework that explicitly captures some of the linkages between energy supply and demand sides and other aspects of climate change policies in Pakistan. These challenges can be addressed by the integrated energy supply-demand models, which look at the full set of processes within Pakistan's whole energy system, enabling a complete perspective to achieve overall reductions in energy consumption and generation and better analyze the direct and indirect effects of policies [24].

This paper aims to develop an integrated energy supply-demand modeling framework based on a combination of the microeconomics and system integration approaches in Pakistan. On the demand side, a combined top-down and bottom-up modeling paradigm is developed for comprehensive analysis of the final energy demand in not only the whole end-use sector, but also in each subsector (transport, electricity, residential, and service), considering the impacts of various scenarios for deploying patterns of efficient use of energy. The energy demand is then defined as a function of its main determinant drivers (i.e., population, dwelling size, floor area, traveled distance, etc.) and can be estimated by the demand-side model, which is interlinked to a bottom-up technology assessment supply model. The objective of the supply energy model is the minimization of the total cost of meeting exogenously specified levels of energy demand. The primary strength of the proposed modeling approach in this study is its integrated approach to produce reliable and policy-sensitive forecasts that retain the link between different demand and supply vectors in the energy system in Pakistan.

1.4. Proposed Modeling Concept

The analysis of the Pakistan energy system should be used to suggest appropriate energy and environmental policy to sustain economic growth and improve the environmental quality for better living standards in the country. This entails that, there is a tradeoff between the efficient use of energy, including environmental quality, and sustained economic growth in the long term. Hence, in this study, the main focus is developing an integrated modeling framework that can explicitly consider the impact of macro and microeconomics and reinvestment of the additional capacity requirement on the supply-demand match in the Pakistan energy system. Based on this idea, the overall framework of the integrated energy modeling concept was developed, which is presented in Figure 2. First, considering the characteristics, demand factors, and future scenarios of different sectors, the demand model, will project future energy demand on a disaggregated level. Total energy demand in Pakistan is considered as a function of the energy price, income, sectoral Gross Value Added (GVA). Second, the macro-level energy demand analysis is followed by a detailed micro-level analysis through segregating the whole energy system to its main sectors such as household, commercial, industrial, service, and agriculture sectors. This involves a bottom-up assessment that systematically relates the specific energy demand in different sectors to the corresponding social, economic, and technological factors that affect this demand. Finally, the supply model then uses this demand to optimize the energy mix considering the technical and financial aspects of technologies, resource availability, and environmental considerations.

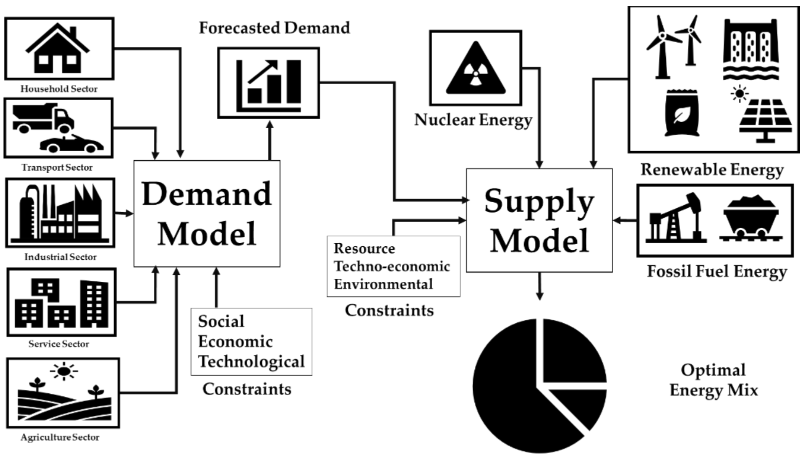


Figure 1.3. The overall concept of an integrated energy model for Pakistan

Chapter 2. Energy Demand Model

The first phase of research is to develop a comprehensive energy demand model that cab best take into account the factor affecting energy demand. The key elements can be demographic (i.e., population, lifestyle and mobility), economic (i.e., income, value-added, price) and technologies (i.e., different fuel choices). The demand model quantifies the impact of demand factors from a broader perspective or simulates various detailed parameters related to demand. The first approach is referred tom-down or economic approach and is realized using econometric modeling. The later methodology is termed as the bottom-up or engineering approach.

2.1. Top-Down Econometric-Based Demand Model

The word econometrics is derived from two Greek words, namely "*Oukovouia*" which means economy and the other is "*Uetpov*" which means measure. So, Econometrics means the measure of things in economics such as economic systems, markets, etc. [29]. Econometrics may be defined as "*The quantitative analysis of actual economic phenomena based on the concurrent development of theory and observation related by appropriate methods of an interface"* [28].In this study, econometrics involves the application of macroeconomic theories on the historical data to quantify the impact of economic factors, such as energy price, income, sectoral gross value added (GVA), etc., on energy demand and project future demand. As mentioned earlier, the demand is disaggregated into five sectors i.e., household, transport, industry, agriculture and service. It implies that demand would be a depended or explained variable, and the rest would be independent, controlling, or expanding variables. These are different notations for the variable and from now own we will use 'e*xplained and explaining variables'* notation. Using a suitable estimation method, the signification and notation of coefficients will help to infer the relationships among dependent and in-depended variables. The following economic and behavioral relationships inspire the idea of selected variables for the demand factor.

- **Price:** The price affected the demand in an inverse fashion. Within a sector, the rise in the price of one commodity may increase the use of a substitute. It implies a negative notation is expected for the price coefficient.
- **Income:** Raise in income level may improve the lifestyle. That leads to more energy consumption on transportation, household thermal comfort (more use of air conditioning and space heating), and the adoption of modern fuels (shifting from biomass to LPG for cooking and heating). This will lead to a positive notation for the income coefficient.
- **Value Added:** For economic production sectors, energy can be considered as an input along with another production factor, i.e., labor, raw material, and capital. Therefore, increasing the economic output, definitely will demand more energy. However, the different sectors will have a different proportionate of this increase depending on energy intensity (energy consumption per unit economic output) and other factors.

The combination of sectoral energy consumption, energy price, income, and sectoral value-added for different sectors is summarized in Table 2.1.

Table 2.1. Macroeconomic parameters used in the econometric model.

Sector	Explanatory Variable	Explaining Variable *
Household	Energy Consumption	Income, Energy Price
Transport	Energy Consumption	Income, Energy Price
Industry	Energy Consumption	Value Added, Energy Price
Service	Energy Consumption	Value Added, Energy Price
Agriculture	Energy Consumption	Value Added, Energy Price

* Private Consumption data is used as a proxy for income in this study.

In this study, the relationship for sectoral energy demand EC^S as a function of explaining variable energy price (EP^s) along with private consumption ($CONS$) or value-added (VA^s) can be presented as Equation 2.1.

$$\boldsymbol{EC^S = f(\alpha^S, EP^s, CONS, VA^s, \beta^S_{ep}, \beta^S_{cons}, \beta^S_{va})} \quad \textbf{2.1}$$

Here, α^S is the constant term and $\beta's$ are the coefficient for respective variables and sector. $CONS$ is superscripted with the sector as its same data for transport and household and only applicable to these sectors.

The first motivation to estimate the coefficient for involved variables, can be to formulate the above model using multiple linear regression and solve with the Ordinary Least Squares (OLS) method. For the household sector (HH) the regression equation for ***actual*** energy consumption any ***year*** (EC^{HH}_y) can be written as Equation 2.2.

$$\boldsymbol{EC^{HH}_y = \alpha^{HH} + \beta^{HH}_{ep} EP^{HH}_y + \beta^{HH}_{cons} CONS_y + \varepsilon^{HH}_y} \quad \textbf{2.2}$$

In above expression ε^{HH}_y is the error (also referred as residuals) term that accounts for all the information, effects and relations which are not fully covered and explained by the explaining variable. This term is very important to assess the credibility and effectiveness of regression analysis. If we exclude the error term from the above expression, the rest may refer as an equation for ***estimated*** energy consumption (EC'^{HH}_y) which is our interest relationships as it sole impact of our selected variables on energy consumption. OSL method solves such equation by minimizing sum of squares difference of ***actual*** and ***estimated*** energy consumption (that is error term) of the whole period under consideration (Equation 2.3).

$$\boldsymbol{minimize \ \langle \sum_{period} \left(EC^{HH}_y - EC'^{HH}_y\right)^2 = \sum_{period} \left(\varepsilon^{HH}_y\right)^2 \rangle} \quad \textbf{2.3}$$

The significance and impact of an individual explaining variable is assessed from the value of its coefficient. The parameter of overall model results such as r-squared and *p-value* provide idea about the overall performance of model. squared The OLS results also help to judge the applicability and reliability of results based on the background mathematical concepts.

Limitation of simple regression in our case- Theoretical Perspective-Derivation of ARDL Model

The regression equation 2.2 implies that energy demand for any year is a function of variables of ***only*** that year and has no effect from the previous years. This may include limitations from the theoretical perspective and statical methods that can be employed to support or test this idea. *Due to social behavior and psychological reasons, the energy consumer may not change their energy consumption pattern instantly in response to the variations in the price or income and may take some time (in this case year or so) to show the effects of such variations.* Considering this idea, the ***actual*** energy consumption for any year is ***partially*** due to change in this price or income of the same year and energy consumption need time to ***adjust*** to price or income variations of this year. This ***partial*** energy consumption denoted as EC^{*HH}_{y} may be referred as ***desired*** is of our interest as its fully explained by the explaining variables. Hence the equation 2.2 can be written for ***desired*** energy consumption.

$$\boldsymbol{EC^{*HH}_{y} = \alpha^{HH} + \beta^{HH}_{ep} EP^{HH}_{y} + \beta^{HH}_{cons} CONS_{y} + \varepsilon^{HH}_{y}} \qquad \textbf{2.4}$$

The relationship of actual and desired energy consumption can be worked out by the idea that actual change (difference of current and previous year) in energy consumption is partially due to change in desired consumption from last year's actual consumption. This may be expressed as equation 2.5.

$$\boldsymbol{EC^{HH}_{y} - EC^{HH}_{y-1} = \theta(EC^{*HH}_{y} - EC^{HH}_{y-1})} \qquad \textbf{2.5}$$

$\boldsymbol{\theta}$ ranges from 0 to 1 and is referred to the speed of adjustment. A value closer to 1 show that the actual consumption explains desired consumption to be large extant. Such a model is called the partial adjustment model. Equations 2.22.5 can be combined to get the expression for actual energy consumption, including the impact of delays or adjustment and also adjusting coefficients (α and $\beta's$) for $\boldsymbol{\theta}$.

$$\boldsymbol{EC^{HH}_{y} = \alpha^{HH} + \beta^{HH}_{ep} EP^{HH}_{y} + \beta^{HH}_{cons} CONS_{y} + \varepsilon^{HH}_{y} + \gamma^{HH} EC^{HH}_{y-1})} \qquad \textbf{2.6}$$

Here γ^{HH} is equal to $(1-\theta)$. In this case, only one lag term EC^{HH}_{y-1} is considered. Depending upon the type of system, more lags may be taken into account for plausible results. Similar is also true for the lags of the explaining variables. A simple regression model extending to consider the lag of explained variable is referred to as *Auto-Regressive Model* and one with the lags of explaining variables is called *Distributed Lagged Model*. A combination of both is referred as *Auto-Regressive and Distributed Lag* (ARDL) Model. The number of lags of both types of variables is called the order of the ARDL Model. The following equation 2.7 shows the standard representation of the ARDL model [28]:

$$\mathbf{y_t = \mu + \sum_{i=1}^{q} \gamma_i y_{t-i} + \sum_{j} \sum_{k=0}^{p} \beta_{j,k} x_{j,t-k} + \varepsilon_t} \qquad \textbf{2.7}$$

Where y_t and $x_{j,t}$ are explanatory and explaining variables, respectively; q and p are the order of lags for respective variables; μ is the constant term; γ_i and $\beta_{j,k}$ are the coefficient of lagged explanatory and explaining variables, respectively; and ε_t is the error term. Considering the above general notation for the ARDL model, our household energy consumption relation in equation (6) is ARDL (1,0,0) with q=1 and p = {0,0} *as there is one lag for explained variable and no lag for two explaining variables.* Such is the simplest form of the ARDL Model.

Limitation of simple linear regression in our case- Statistical Perspective

The reliability of the simple linear regression analysis results for time series data is governed by the fact that a certain number of underlying assumptions are satisfied. Following is one of the key assumptions for the application of linear regression that implies that errors terms or residuals of the model are independent of each other.

"There is no auto-correlation among residuals."

Even if the above-mentioned assumption is not satisfied, still, the results of the regression analysis can be significant. Of course, such results would not be legitimate and such regression is named as ***"Spurious Regression"*** having non-plausible results. To test the absence of auto correlation, Durbin-Watson (DW) Test is employed [56].

Durbin-Watson (DW) Test

A regression equation for adjacent residuals ($\varepsilon_t = \alpha + \beta\varepsilon_{t-1} + \varepsilon_t'$) for time series interval t is formulated and solved using OLS the test to the null hypothesis ($H_0: \beta = 0$) which implies that error terms are not autocorrelated. The null hypothesis is checked with the results of the *p-value* and other stats of OLS output. It simply means that ε_t and ε_{t-1} have no relationship that was the objective of this test. Durbin-Watson also introduced a Durbin-Watson Stat. (d-stat) to conduct the test. Equation 2.8 shows the calculation formula for d-stat for time series having period T and interval t.

$$\boldsymbol{d - stat} = \frac{\sum_{t=2}^{T}(\boldsymbol{\varepsilon_t} - \boldsymbol{\varepsilon_{t-1}})^2}{\sum_{t=2}^{T}(\boldsymbol{\varepsilon_t})^2} \qquad \textbf{2.8}$$

A table is also provided for critical values upper (dU) and lower (dL) for testing the d-stat of the model. The critical values depend upon the number of regressor/explain variables (k) and the number of observations of time series data (N). The value of $d - stat$ should lie between the lower and upper critical values. For time-series data analysis to be unreliable, the presence of autocorrelation among the residuals is linked to other assumptions of linear regression analysis. It says that all the involved time series should be ***stationary***. It can be tested using ***Augmented Dickey Fuller (ADF)***Test. Following are the characteristics of a time series (y_t) to be stationary.

1. The mean of the time series is consistent over the time period.
2. The variance of time series is constant over the time period.
3. Serial Covariance ($Cov(y_t, y_{t-1})$) is independent of time.

Stationary Test - Augmented Dickey Fuller (ADF)Test

It is also referred as Unit Root Test as its objective is to find the unit root in time series. The presence of the unit root makes the time series non-stationary. Following the equation for conducting the ADF Test for time series (y_t) with the first difference presented as $\Delta y = y_t - y_{t-1}$ and k showing the number of lags considered.

$$\Delta \boldsymbol{y_t} = \boldsymbol{\alpha_0} + (\boldsymbol{\alpha_1} - \mathbf{1})\boldsymbol{y_{t-1}} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{k}} \boldsymbol{\beta_i y_{t-i}} + \boldsymbol{\varepsilon_t} \qquad \textbf{2.9}$$

Here the aim is to test the null hypothesis $H_0: (\alpha_1 - 1) = 0$, which implies there is a unit root in the time series. ADF Test also uses critical stat values to judge the stationarity of time series for the different levels of confidence (1%, 5% and 10%). *p-values* of the model analysis results can also be used as a determinist factor for stationary. A *p-value* less than 0.05 will reject the null hypothesis and the times series will be stationary. The stationary time series is represented as *I (0)*, the first difference $(y_t - y_{t-1})$ stationary series is denoted as *I (1)* and called first-order stationary time series and so on. Time series data can also become stationary by converting into log (ln) form.

Short-term and long-term analysis feature of ARDL Model (Error Correction Model)

The ARDL Mode considers the lags of involved time series variables, it can be molded into different forms to take into account a variety of analytic features. Error Correction Model (ECM) form of ARDL Model can be used to assess the short- and long-term dynamics of the system under analysis. It can be derived from the standard ARDL Model as follows. First-order ARDL Model ARDL (1,1) for one explain variable from equation (7) can be written as equation 2.10.

$$\boldsymbol{y_t = \alpha_0 + \gamma_1 y_{t-1} + \beta_0 x_t + \beta_1 x_1 + \varepsilon_t} \qquad \textbf{2.10}$$

To write the y_t in first difference form, employing the y_{t-1} on both sides and using relation for speed of adjustment $\theta = (1 - \gamma)$ the above equation will be modified new form in equation 2.11 and that then can finally be written the as standard equation 2.12.

$$\Delta \boldsymbol{y_t = \alpha'_0 + \beta_0} \Delta \boldsymbol{x_t - \theta(y_{t-1} - \beta_0 - \beta'_1 x_1) + \varepsilon'_t} \qquad \textbf{2.11}$$

$$\Delta \boldsymbol{y_t = \alpha'_0} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{q}} \boldsymbol{\gamma_i} \Delta \boldsymbol{y_{t-i}} + \sum_{\boldsymbol{j=1}}^{\boldsymbol{p}} \boldsymbol{\beta_j} \Delta \boldsymbol{x_t - \theta(y_{t-1} - \beta_0 - \beta'_1 x_1) + \varepsilon'_t} \qquad \textbf{2.12}$$

This is the ECM form of ARDL mode. $\boldsymbol{\theta(y_{t-1} - \beta_0 - \beta'_1 x_1)}$ is called *Error Correction Term* and shows the long-term effect in the output. The rest of the expression is the short-term analysis of time series. This analysis helps to have a more detailed and objective analysis of time series data. The short- and short-term police and plans can be made based on such a comprehensive analysis of the system. ARDL bound test can also provide insight into the long-term relationship among the variables. This test is also providing the critical ranges for results to legitimate and verify the relationship.

Stability (CUMSUM of Squares) Test for Model

The final step is testing the stability of the model. In this study, we relied on the Cumulative Sum (CUMSUM) of Squares for residuals to verify the stability of the model. The CUMSUM of squares trend should follow the boundaries specifies for the different levels of confidence. For the specific level of significance (i.e., 5%) EViews visuals these bound for the CUMSUM of squares to follow. Th further details will be shown and explained in the result and discussion section.

Considering all the discussion so far, Figure 1.1 shows the framework adopted for quantifying the factors of energy demand in this study. The unit root test verifies the stationarity of time series data. Autoregressive and distributed lag (ARDL) takes into account sufficient lags of variables to avoid nonstationary [25–27]. The Durbin–Watson test is used to verify the reliability of the analysis. If the Durbin–Watson test is failed, the demand models are revisited to find the suitable combination and form (i.e., variables in log form).

The income and GVA were correlated with GDP using the similar ARDL approach, and future projections were subjected to the growth rate of GDP and sectoral share of the economic sector. Energy price was correlated to the inflation rate to quantify the contribution of energy price towards the overall consumer price index (CPI).

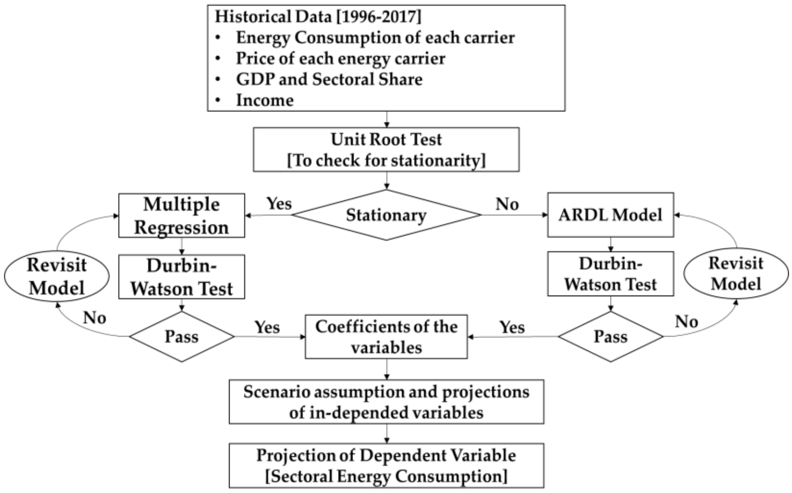


Figure 2.1. The framework of the econometric analysis of demand in this study.

2.2. Bottom-Up Simulation-Based Demand Model

The successful modeling and running of the econometric model provide the aggregate energy demand projections over the model horizon (in this case, 2017-2032). Although the econometric model is considered more accurate due to its strong theoretical background, still to have a comprehensive analysis of demand sectors, such a top-down model is insufficient mainly because of the following reasons.

1. The econometric projected demand is not disaggregated into end-use fuels (electric and non-electric)
2. The sector dynamics are not expressed, and the room for the introduction of scenarios is only limited to economic parameters (i.e., GDP) and energy prices.

To address the above-mentioned limitations of the top-down modeling approach, there is a need to introduce a model to ensure a detailed analysis of sectoral energy demand. Such a detailed model is referred as a *bottom-up model* as it builds on the detailed engineering foundation. Such a model employs simulation methodology and objectives to forecast future energy demand, considering the economic, social, and technological aspects of energy demand. The following is the elaboration of the key terms:

- ***The social aspects*** include the parameters of population, household characteristics, and lifestyle.
- ***The economic aspect*** deals with the level of activity in economic sectors or subsectors.
- ***The technological*** aspect is based on selecting different available technologies (fossil fuel, electricity, renewable and traditional fuel), taking into account their efficiency and market penetration.

The bottom-up energy demand is segregated into five main sectors: industry, transportation, household, agriculture, and service. These sectors, where applicable, are further divided into subsectors or end-use categories to include the impact of disaggregation. The model first calculates the useful energy respect of fuel and consumption technology. Then, demand is estimated and segregated into electric and nonelectric energy demand based on the efficiency and market penetration of different technologies and fuels. Figure 2.2 explained the flow chart of calculation methodology with the bottom-up model. Based on the sector, the key demand factor for each sector, such as population and lifestyle for households, is the need for mobility for transport and economic activity for economic sectors. Assuming the scenarios of growth of these demand factors, overall end-use energy demand is computed. Finally, considering the efficiency and share of available fuels (electricity, fossil fuel, etc.), the demand is disaggregated into various fuels.

The key challenge with such an approach is that its data-intensive and accurate projection requires the accurate projection of each input parameter. To find the detailed data is a problem on one side, and then the forecast such demand factor is on the other side. The one solution lies in combining this kind of model with the econometric based top-down approach-based model, where aggregated demand for each sector is known. The details unknown and roughly estimated parameters are adjusted/calibrated, ensuring that the aggregated demand is not affected. Figure 2.3 represents the framework of the bottom-up energy demand model. Considering the respective demand factors of each sector, the demand model is built for each sector. The results are compared with the results of the econometric model and parameters are revisited to obtain the baseline results. The next step would be to introduce the scenarios to quantify their impact on overall energy demand segregated into different fuels (electricity, gasoline, diesel, natural gas).

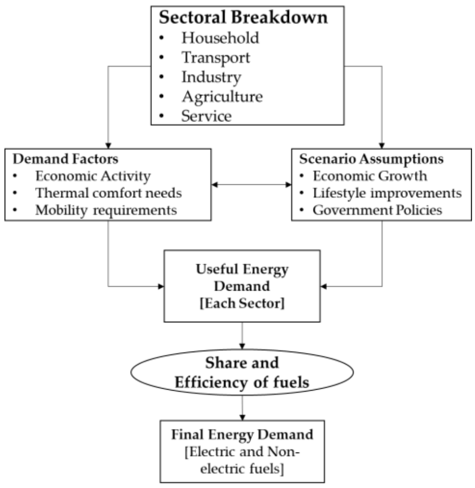


Figure 2.2. Flow chart of methodology in bottom-up energy demand model

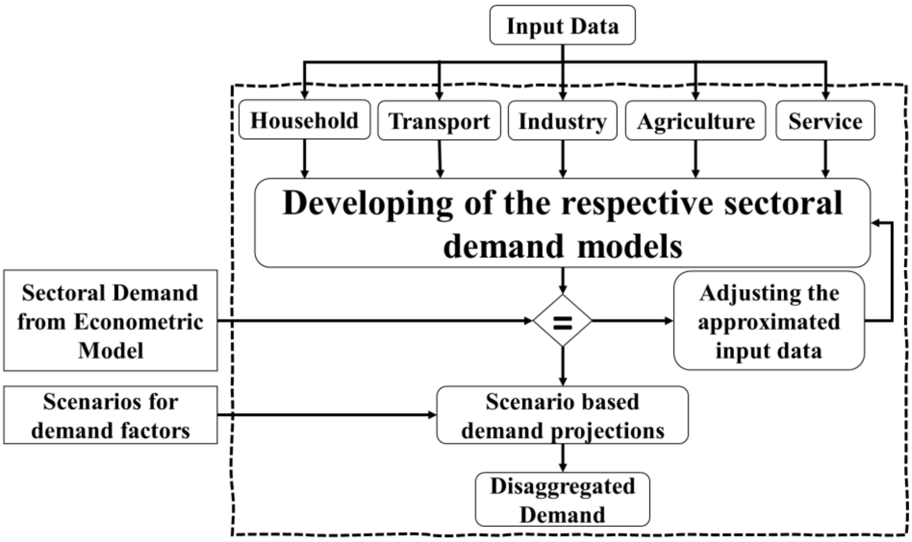


Figure 2.3. The framework of the bottom-up energy demand model.

Activity and energy intensity of any sector/sub-sector are the main factors for energy demand simulation. Table 2.2 shows the definition of activity for different sectors and subsectors. The total amount of energy consumption can be estimated from the multiplication of energy intensity to the unit of activity for each sector.

Table 2.2. Definition of the terms of activity in the bottom-up energy demand.

Sector	Sub Sector	Activity Indicator
Household	Space Heating	Heating area [m^2]
	Air Conditioning	Units [Nos.]
	Cooking	Population
	Water Heating	Population
	Electric Appliances	Units [Nos.]
Transport	Passenger Transportation	Passenger-km [PKM]
	Freight Transportation	Freight-km [PKM]
Industry	-	Sectoral Value Added [$]
Service	-	Sectoral Value Added [$]
Agriculture	-	Sectoral Value Added [$]

Considering the above definition for activity, the following is the general representation of the calculation of energy demand for each sector [29]:

$$\boldsymbol{E_U = \sum_{ss} ACT_{ss} * SH_{ss} * EI_{ss}} \qquad \mathbf{2.13}$$

$$\boldsymbol{E_f = E_U * \frac{SH_f}{\varepsilon_f}} \qquad \mathbf{2.14}$$

where E_U is the useful energy demand of sector; ACT_{ss}, SH_{ss}, and EI_{ss} represent the activity, share, and energy intensity (specific energy requirement), respectively, for each subsector; and final energy demand for any fuel E_f is calculated using its share SH_f and efficiency ε_f.

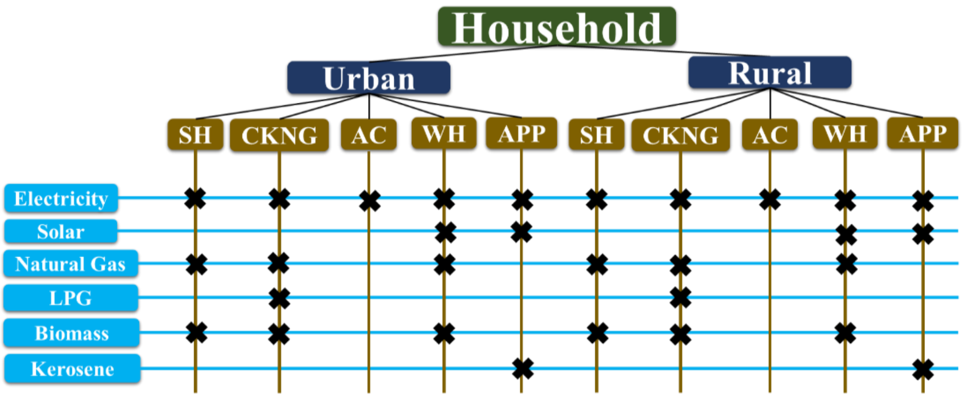
The following are the detailed equations for different sectors of the bottom-up energy demand model.

2.2.1. Household Sector:

The household sector involves the key social factors affecting the energy demand for this sector. These factors are essentially demographic such as population, urbanization, dwelling characteristic (types, size, facilities), ownership of household appliances (i.e., air conditioning), household size (person per dwelling) and climate condition. The demand for this sector is assumed to take into account all these dynamics and present a comprehensive picture level of disaggregation. The demand is segregated into space heating (**SH**), cooking (**CKNG**), air conditioning (**AC**), water heating (**WH**) and energy requirement for appliances (**APP**). Considering the urbanization ratio, the population is divided into rural and urban areas and household size of three different types, i.e., small, medium and large dwellings, to equate the number of dwellings for each type and area (urban and rural). The next step is the focus on each household's characteristics (size, heat loss, facilities such as hot water and air conditioning) and the presence of other appliances. The amount of needed space heating is quantified considering the heating degree days (HDD) approach. Equation 2.15 is used to calculate the value of daily heating degree days for a given comfortable temperature referred as *base temperature* (T_b). This value can be averaged for the monthly values of the whole year. To have a better value, a multi-year average is considered in this study.

$$\boldsymbol{HDD_{daily} = |Tb - Ta|} \qquad \textbf{2.15}$$

Cooling requirements are calculated using ownership (percentage of household with facility) of the air conditioner and its operational schedule. A similar approach is applied for other appliances (TV, fans, lights, washing machines, room cooler, etc.). Figure 2.4 shows the disaggregation of the household sector and fuel choices for each end-use category (the intersections link the end-use category with the fuel options). Specifically in rural areas, due to limited access to natural gas and abundance of crops residues, biomass is an important fuel for cooking, space and water heating. Equations 2.16, 2.17 and 2.18 show a relation to the energy demand for the household sector.



Note: ***SH:*** Space Heating, ***CKNH:*** Cooking, AC: Air Conditioning, ***WH:*** Water Heating, ***APP***: Appliances

Figure 2.4. Disaggregation of the household sector and linkage with the fuels choices for end-use categories

2.2.1.1. Space Heating:

$$E_{U,SH} = \sum_{t} NDw * DShare_t * DSize_t * HDD * EHA_t * DHL_t \tag{2.16}$$

2.2.1.2. Air Conditioning and Electrical Appliance:

$$E_{U,AC\&APP} = \sum_{t} \sum_{app} NDw * DShare_t * Own_{t,app} * Units_{t,app} * UEC_{t,app} \tag{2.17}$$

2.2.1.3. Water Heating and Cooking

$$E_{U,AC\&APP} = \sum_{t} \sum_{app} NDw * DShare_t * Own_{t,app} * Units_{t,app} * UEC_{t,app} \tag{2.18}$$

$E_{U,SH}$ is the useful energy demand for space heating [kWh]. NDw is the total number of dwellings of type t, share (%) $DShare_t$, and size (sqm) $DSize_t$. HDD is heating degree days, and EHA_t is the effective heating area (%). DHL_t is the heat loss from different dwelling types [kWh/°C m^{2}h]. $E_{U,AC\&APP}$ is the energy demand for air conditioning and other electric appliances [kWh]. $Own_{t,app}$ is the ownership, i.e., percentage of households having facility of the specific appliance. $Units_{t,app}$ is the quantity of appliance per dwelling, and $UEC_{t,app}$ is the energy intensity [kWh/unit/year]. $E_{U,WH\&CK}$ is the useful energy demand for the water heating and cooking subsectors [kWh]. It is calculated by using the $HSize$ household size (number of persons/household) and PEC_{ss} per capita energy consumption [kWh/cap]. NDw is the dwellings having the facility of water heating.

2.2.2. Transport Sector

The transport sector deals with both social and economic aspects of energy demand. The need for mobility of people to carry out their day-to-day activities and lifestyle (preference of personal mode of transport, i.e., cars) supports a social requirement, and freight delivery supports the economic sector. The case is quantified with passenger-kilometer (PKM) computed using population and per capita annual average distance traveled, while the second is called tom-kilometer (TKM). The calculation of TKM involves the detailed generation of freight/goods (tons) from different economic sectors such as industry, agriculture and service along with the distance (kilometers) to their destination. In our case, both PKM and TKM are calculated based on the sector energy demand of the economic model. The passenger's transportation is divided into intercity and intracity due to their different transportation demands and styles. Various modes of transportation for each sector are used and each has its own technical specification and energy requirements. For intercity, the large cities are considered where the deployment of urban transport system feasible. Figure 2.5 shows the disaggregation of the transport sector into sub-sectors and fuel options considered for each transportation mode. The energy intensity of each mode of transportation is with respect to its activity (PKM or TKM) which implies the load factor (person/mode of ton/mode) of each mode is considered.

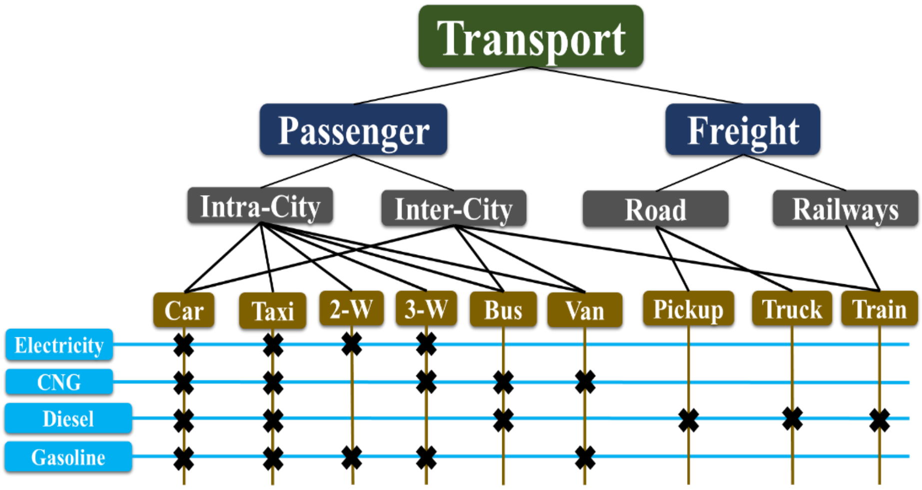


Figure 2.5. Disaggregation of the transport sector and the fuels choices

Equations 2.19 and 2.20 present the calculation method for the energy demand of the transport sector[29].

$$\boldsymbol{E_{PT} = \sum_{v}\sum_{f} PKM * Share_{f,v} * EIPT_{v,f}} \quad \textbf{2.19}$$

$$\boldsymbol{E_{FT} = \sum_{v}\sum_{f} TKM * Share_{f,v} * EIFT_{v,f}} \quad \textbf{2.20}$$

For passenger transport energy demand (E_{PT}), PKM is total passenger kilometer, and $Share_{f,v}$ and $EIPT_{v,f}$ are the share [%] and energy intensity [GJ/PKM] of vehicle category v with fuel f. For freight transport energy demand (E_{FT}), ton-kilometer (TKM) is used instead of PKM.

Low load factors and high energy intensity make the private car an important demand factor for the transport sector. Its ownership (number of cars per 1000 persons) is a strong determinant of lifestyle improvement and can be correlated to economic wellbeing, i.e., GDP. To project future growth of this mode of transportation, Gompertz Function [$\boldsymbol{V_t = \gamma e^{\alpha e^{\beta GDP_t}}}$] proposed by [57] was used to project car ownership as V_t refers to the car ownership of cars in year t, γ is the saturation level for this type of vehicle, α and β are the statistical coefficients determined through regression analysis of historical data. The saturation level depends upon the population density and structure of the urban system. For the case of Pakistan, it is considered to be 725 (Cars/1000 persons) [57].

2.2.3. Economic Sectors:

The household and transport sectors are the consumers of the economic output, and their energy demand is affected by the factor related to such behavior. On the other hand, economic sectors (industry, agriculture, and service) generate the output using energy as one of the key input production factors. This relationship of output with energy consumption is referred as energy intensity. Energy intensity is the amount of energy required to generate a unit of economic value-added. Different sectors exhibit different energy intensities depending upon the variety of operational activities. Figure 2.6 show the economic sectors along with fuel option for each sector.

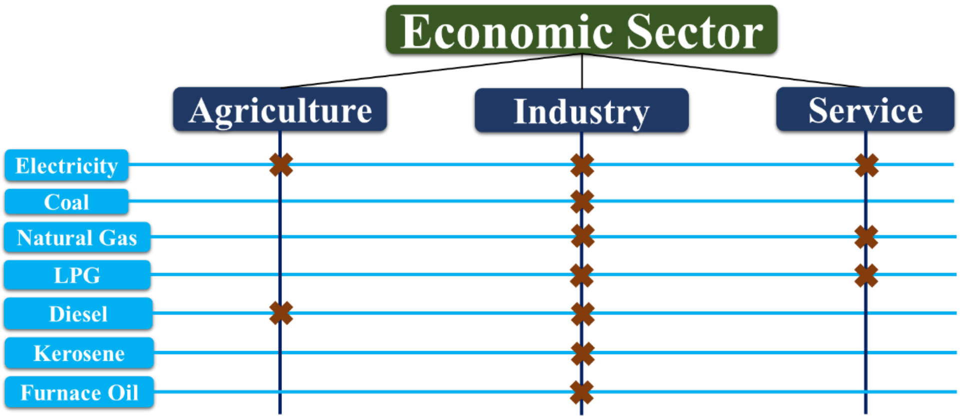


Figure 2.6. Disaggregation of economic sectors and fuel options

Equation 2.21 shows the equation applied for each economic sector's energy demand.

$$E_{ES} = \sum_{ss} GVA * Share_{ss} * EIEC_{ss} \qquad \textbf{2.21}$$

For economic sectors (industry, service, and agriculture), GVA is gross value added of these sectors [$], and $Share_{ss}$ and $EIEC_{ss}$ represent the share [%] in value-added and energy intensity [kWh/$] for each subsector, respectively.

Chapter 3. Energy Supply Model

After the computation of demand for all the sectors for the model horizon, the next step is to use the energy supply model to allocate different energy sources to meet the demand optimally. In this study, the Model for Energy Supply Systems and their General Environmental Impact (MESSAGE), an open-source tool, is used as the energy supply model, based on the flexibility of scenarios and comprehensive analysis approach [30]. The MESSAGE model involves a detailed representation of technical engineering, socioeconomic, and biophysical processes in energy and land-use systems, aiming to satisfy a given demand level at the least cost. MESSAGE Model was initially developed by International Institute for Applied System Analysis (IIASA) and International Atomic Energy Agency (IAEA) developed an interface to facilitate the application of MESSAGE. Until now, several advancements are made to this model mainly to improve the modeling of electric power system-related features. The current version of the MESSAGE Model code is solved in General Algebraic Modeling System (GAMS) and accessed through a special platform named MESSAGEix programmed in python and r language. The environmental aspect of MESSAGE involves the computation of emissions from different technologies at different stages. The bound can be sent on the overall emission, model can restrict the emission from emission-intensive technologies and favor clean options such as nuclear and renewable.

MESSAGE is a dynamic linear programming model to optimize the overall energy system covering a range of commodities, technologies and processes. It models the flow of energy from the resource (coal, crude oil, gas, uranium) extraction and primary imports until end-user sectors (such as household, industry, transport etc.) through conversion (power plants, oil refineries), processing (gas processing), transmission and distributions technological systems.

3.1. Reference Energy System

In the beginning, we need to specify the model horizon for analysis of the energy system (in this case, its 2017-2032). The periods can also be specified such as yearly, 3 or 5 yearly and so on. To have the sub-annual analysis, the load curves can be employed for defining different load regions. The same can also be done in the monthly analysis to consider the different nature of renewable energy sources on a monthly basis. To configure and develop the model in MESSAGE, we need to prepare a detailed layout showing the placement and connection among different technologies, energy flow, energy levels, demand points. This layout is termed as “Reference Energy System”. Following is the explanation of different terms used in the reference energy system in the context of Pakistan.

3.1.1. Energy Levels

Depending upon the form, application and special attributes related to energy, energy levels are defined to specify the different stages of energy flow from resource extraction until end-use categories. It helps to understand and trace the physical flow of energy commodities in the energy system. Extraction, conversion, generation, transporting, transmission, distribution technologies, explained in the next section, are connected to these levels for receiving *(Inputting)* energy and delivering *(Outputting)* processed, converted or useful energy. We are also supposed to define some special energy level, that will be explained later, to let the model know to treat them for a specific purpose. In this study, three general and three special levels are used. General levels include representing primary energy, secondary energy and final energy. These levels are termed as *Primary*

Level, *Secondary Level* and *Final Level* in the reference energy system. Special or specific levels are used to express fossil fuel-based resources, renewable resources and storage and termed as *Resource Level*, *Renewable Level* and *Storage Level*. The final energy demand of various commodities is linked to the final level. Imports are connected with either at primary or secondary level depicting the physical situations of such energy flows.

3.1.1.1. Resource Level

This level specifies the starting point of commodities flow into the energy system and represents the available finite local fossil-based energy reserves such as oil, natural gas, coal and uranium. The resources can be defined to for different grades defining upon its energy content and refinement level. Similarly, the costs of extraction and mining can be set for various grades and resources. For the resources, we also define the available resources volume or reserves, physical and technical limitation of extraction, extraction rate for depilating resources and probable future reserves depending on up current trends and exploration policy. Through extraction technologies, the resource level is linked to the primary level. In the case of Pakistan, we have coal, natural gas, oil and uranium reserves. The details related to different parameters related to resources are written in Data Inventory Section.

3.1.1.2. Renewable Level

Due to its unlimited availability nature and zero resource cost, an individual level is introduced to accommodate the renewable energy sources (wind, solar, hydro and biomass). The potential and quality (capacity factor) of renewable need to be defined those constraints their penetration. Hydro is the most explored renewable in Pakistan, followed by wind, solar and biomass. For this study, in biomass, the focus is only on bagasse (the residual of sugar production from sugar cane).

3.1.1.3. Primary Level

Extracted and pre-processed resources commodity available at the facility of processing is termed as primary level. The obvious examples can be the crude oil available at the oil refinery, natural gas at compression and processing facility and natural uranium at enrichment facility ready for nuclear fuel fabrication. In our study, the commodities at the primary level are the transported resources along with imported crude, furnace oil and Liquified Natural Gas (LNG).

3.1.1.4. Secondary Level

This level represents the processed form of energy transmitted or transported to the last stage of structured energy system flow. This includes generated electricity, processed gas, fine oil products (diesel, gasoline, LPG), refined coal, Re-Liquefied Natural Gas (RLNG), imported commodities (coal, electricity from Iran, oil products, nuclear fuel). In addition, a couple of features, such as the requirement of flexibility in the system (such as the need for storage) is modeled at this level.

3.1.1.5. Final Level

This level includes the energy commodities that can be consumed by demand sectors (household, transport, agriculture, industry and service). The final demands of all commodities are modeled and assigned to this final level. Depending upon the type of commodity, a network of transmission, distribution and transport links the secondary level with the primary level.

3.1.1.6. Storage Level

To model the storage in the energy system, a special storage level needs to be included. The motivation to do this is to accommodate the capacity to have bi-direction energy flow for charge and discharge its stored contents, unlike the resources where there is only one direction flow. The storage capacity is needed to be specified; however, the energy lower is limited by modeling chargers and dischargers capabilities. Considering the current plans of Pakistan to introduce Battery Energy System Storage (BESS) to enhance the transmission operation, storage is level is linked to secondary level through charger/discharging technologies.

3.1.2. Forms of final energy

The demand of energy commodities specified with the final energy level is defined and data is fed from the demand model. For a reliable energy system, all demand must be satisfied. In this study for Pakistan, the final level commodities are electricity, natural gas, coal, oil products (diesel and gasoline), LPG. The demand for natural gas is preferably natural gas, but RLNG is used in case there is a shortage of natural gas. Coal is fed by both local and imported in constant proportion.

3.1.3. Technologies

These are the building blocks of the reference energy system and connect different energy levels to realize the flow of energy commodities to satisfy the demand by ensuring sufficient processing or conversion and transfer operations. The technologies can be classified into two main categories, conversion and transfer. Conversion technologies convert one commodity to other, such as coal power plants converts coal into electricity and oil refinery coverts crude oil into oil products (Gasoline, Diesel and Furnace Oil, etc.). The transfer technologies facilitate the flow of commodities among different levels and demand. Examples can be the transmission and distribution of natural gas and electricity. In addition, the reference system should include current and future prospect technologies. Table 3.1 summarized the technology considered in this study.

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

Technology Category	Sub-category	Detailed Technologies
Conversion	Electric (Fossil fuel based)	Coal (Local) Power Plant
		Coal (Import) Power Plant
		Gas (CT) Power Plant
		RLNG (CT) Power Plant
		RLNG (CC) Power Plant
		Oil (FO) Power Plant
		Oil (HSD) Power Plant

		Nuclear Fuel Fabrication
	Electric (Renewable based)	Hydro Power Plant
		Wind Power Plant
		Solar Power Plant
		Waste&Bio Power Plant
	Non-Electric	Oil Refinery
		Nuclear Fuel Fabrication
		LNG Terminal
Transfer	Extraction	Coal Extraction
		Natural Gas Extraction
		Crude Oil Extraction
		Uranium Extraction
	Transmission and Distribution	Electricity Transmission and Distribution
		Gas Transmission and Distribution
	Storage	Battery Energy Storage System
	Transport and Distribution	LPG Transport and Distribution
		Oil Products Transport and Distribution
	Imports	LNG Import
		Coal Import
		Electricity Import
		Crude and Oil Products Import
		Nuclear Fuel Import

Note: *Oil Products include LPG (Liquified Petroleum Gas), Diesel, Gasoline, Kerosene Oil and Furnace Oil.*

The definition of technology in MESSAGE involves the details of technical, economic and environmental parameters along with the levels with which the technology links. Figure 3.1. Basic parameters required for the definition of technology in the MESSAGE Model., for example, the detailed requirements for a coal power plant (as an example case), and the same is true for all technologies. Model is provided with the base year and historical data on capacity and generation data to tune the starting point of the model.

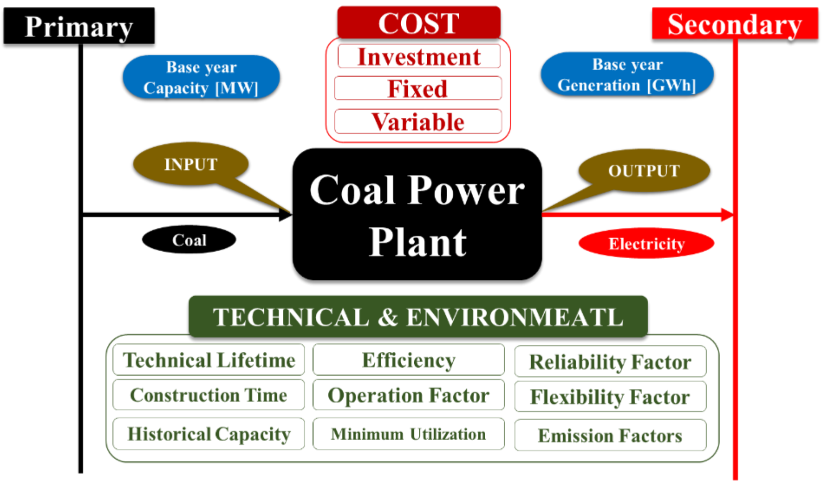


Figure 3.1. Basic parameters required for the definition of technology in the MESSAGE Model.

Capacity and energy flow are two important parameters for any technology. The parameters such as technical lifetime, construction time, capacity factor, operation factor, minimum utilization, investment and fixed cost, and reliability factor correspond to the capacity of technology. Whereas, flexibility factor, variable cost, emission factor, efficiency is related to the energy flow of technology.

Input and Output Parameters

Input and output parameters are used to specify the type of commodities that move in and out of the technology, efficiency involves with the conversion or transfer process, the levels with which technology is connected and the direction of the energy flow. The value input parameters can be referred as *"for the one-unit energy flow processed by a technology, how much units of input commodity are required"* and similar is true for the output parameter value. In our case, the ***input parameter value*** is set to take into account the conversion efficiency along with the unit conversions (As the units of input and output commodities may be different). In the case of the coal power plant, the unit of input (coal) is million tonnes (MT), and output electricity is measured GWa. Here calorific value (GJ/T) for the input fuel is used to balance the units in energy units) and the ***value*** of output is to quantify the auxiliary consumption of technology. In this way, the main energy flow of technology would be the output commodity (electricity is the case of the coal power plant) because the input commodity is already equated at the input. Equations 3.1and 3.2 are used to quantify the values of input and output parameters for any technology, with conversion efficiency (η), input commodity calorific value (σ), percentage auxiliary consumption (γ) and unit conversion factor (α).

$$\boldsymbol{input_{value} = \frac{\alpha}{\sigma * \eta}} \qquad \textbf{3.1}$$

$$\boldsymbol{output_{value} = 1 - \gamma} \qquad \textbf{3.2}$$

For example, as in our case, for local coal-based power plants with the conversion efficiency of 39.04%, input coal calorific value of 19.8 GJ/T, the auxiliary electricity consumption of 0.03%. The unit of input coal in million tonne (MT) and output electricity is giga-watt-annum (GWa = 8760 GWh), then, using 1 GWh = 3600GJ, the conversion factor (α) is computed to be 31.54. Finally, using the above expressions, the value of input will be 4.08 [MT/GWa]. This implies in this case, one GWa of electricity will require 4.08MT of local coal. The output parameter is almost equal to 0.9997 [GWa/GWa]. This way, the input value can be computed for all technologies.

In the case of an oil refinery, as the input and output have the same unit, the simple conversion efficiency of 99.7% is adjusted in input and then output is divided into gasoline, diesel, furnace oil, kerosene oil and LPG in their proportion. Here the mass balance is used to quantify input and outputs. In nuclear fuel fabrication, the mass ratio is used for the different energy content of natural uranium (500GJ/kg) and nuclear fuel (3888GJ/kg).

Vintage Structure in MESSAGE Model

This is an important concept employed in the MESSAGE Model for proper maintenance of technology during the model horizon. The ***vintage year*** is referred to as the first year when a technology capacit*y is available for its operations*. The same type of technologies having different vintage years are treated spearplay, and final optimized results are with respect of vintage year and actual operation year. Considering the technical life of a technology, this kind of approach helps the model to account for the following essential aspects of the model.

- Maintaining the technology capacities build before the first year of the model horizon.
- Retiring a technology if its technical life finishes during the model horizon.
- Account for technologies having the technical life extended beyond the completion of the model horizon.

Figure 3.2 represents the flow chart describing the process of MESSAGE modeling.

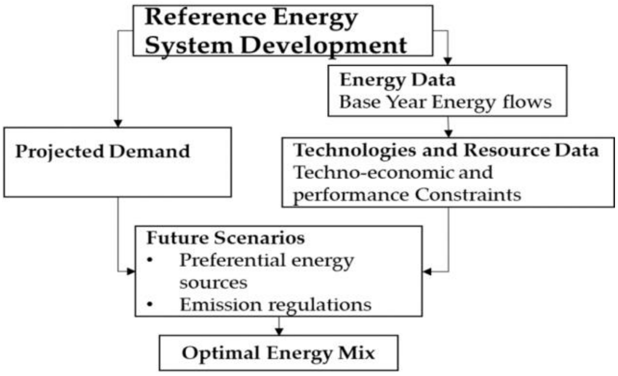


Figure 3.2. Framework of the MESSAGE energy model.

Figure 3.3 shows the reference energy system (RES) in Pakistan developed in the MESSAGE model. This reference system shows the different levels of the energy system and the linkage among the various energy conversion, processing, transmission, and distribution technologies.

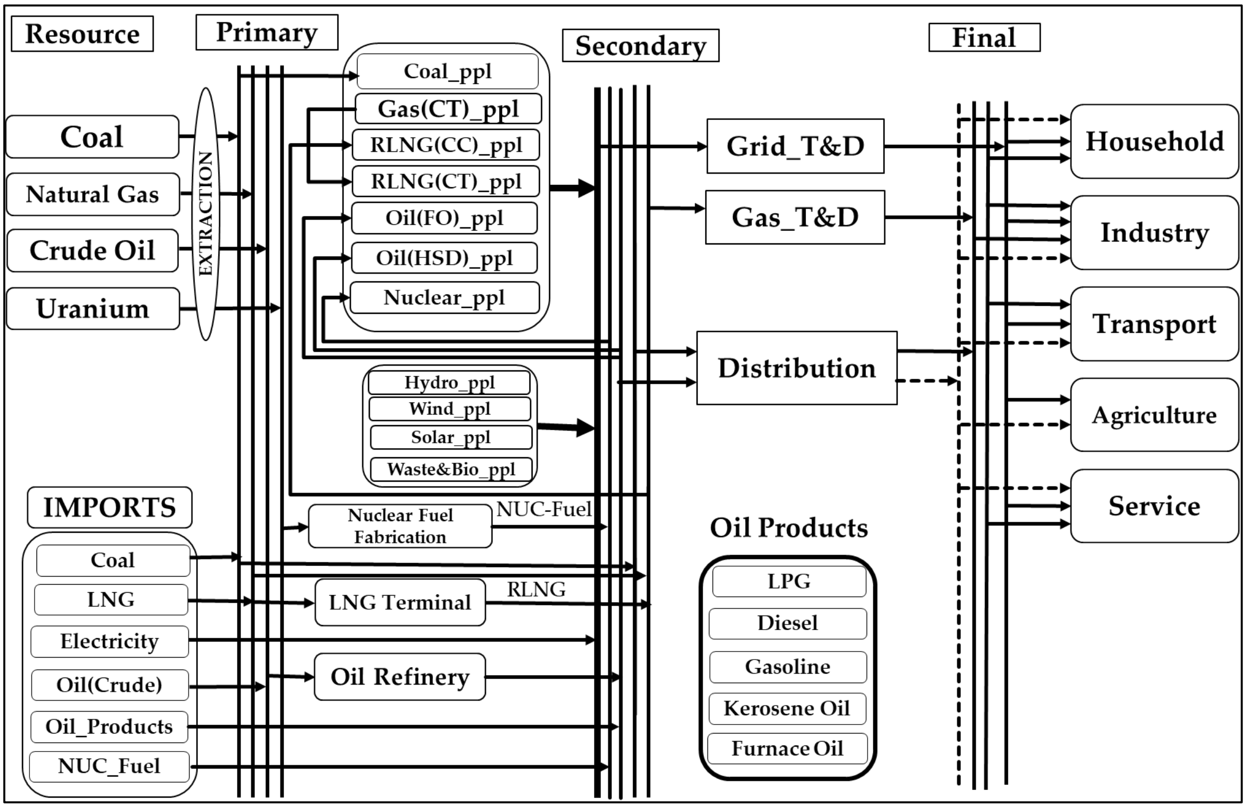


Figure 3.3. Reference Energy System (RES) for Pakistan.

3.2. Mathematical Formulation of Supply Model

The model is based on the minimization of the total discounted cost of the energy system. Following the mathematical formulation details of the supply model employed in this study.

3.2.1. Objective Function

Equation 3.3 represents the total discounted cost of the energy system through the model horizon (in this case, 2017-2032). The discounted cost is employed to consider the present value of all future cash flows through the discount rate. Thus, the cost variable represents the total cost of the resource, investment for new technology, operation and maintenance, and emissions, as follows:

$$\boldsymbol{Total\ Cost} = \sum_{y} \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{DR})^{y}} \left[\begin{array}{c} \sum_{c,g} \boldsymbol{RC}_{c,g} . \boldsymbol{EX}_{c,g} + \sum_{tec} \boldsymbol{IC}_{tec,y}\, \boldsymbol{CAP\_ADD}_{tec,y} + \sum_{tec} \boldsymbol{FC}_{tec,y} . \boldsymbol{CAP}_{tec,y} \\ + \sum_{tec} \boldsymbol{VC}_{tec,y} . \boldsymbol{EF}_{tec,y} + \sum_{tec,e} \boldsymbol{ET}_{tec,e} * \boldsymbol{EM}_{tec,e} \end{array} \right] \qquad \mathbf{3.3}$$

where DR is the discount rate; y is year; and $Cost_{\boldsymbol{y}}$ is the total cost for year y. $RC_{c,g}$ and EX_c, g are the cost and extracted resources of each commodity c and grade $\boldsymbol{g}$. IC_{tec}, FC_{tec}, and VC_{tec} represent the investment, fixed, and variable costs for each technology tec, whereas $newcap_{tec}$, cap_{tec}, and act_{tec} are the additional, maintained capacities and energy flow, respectively. $\mathrm{EF}_{\mathrm{tec}}$ represents the activity level of each technology, which is considered the energy outflow from the technology. $ET_{tec,e}$ and $EM_{tec,e}$ are the emission tax and emission amount for each technology tec and emission category e.

3.2.2. Constraints

The objective function, the total cost, is constrained to the number of technical, economic, environmental, and resource constraints. The following equations represent the main constraints of the model.

3.2.2.1. Resource and Commodity Constraints

These constraints take into account the limitation on resource availability along with extraction capacity and ensure that the commodities flows are balanced, and demand is satisfied through the model horizon.

Extraction Balance:

This constraint balances the resource extracted with the input of the technologies that feed from the resource's levels, such as oil refinery:

$$\sum_{g} \boldsymbol{EX}_{c,g,y} = \sum_{tec,m,h,l} \boldsymbol{IN}_{tec,y,m,c,l,h} * \boldsymbol{FE}_{tec,y,m,h} \qquad \mathbf{3.4}$$

$\boldsymbol{IN}_{tec,y,m,c,l,h}$ is the factor for input energy flow to technologies.

Bound on Extraction:

It limits the total amount of extraction of any recourse. It is an input parameter and into account the mining capacity and available mining technology.

$$\boldsymbol{EX_{c,g,y} = EX\_bound_{c,g,y}} \tag{3.5}$$

$\boldsymbol{EX\_bound_{c,g,y}}$ upper bound on the extraction of each resource commodity for each year.

Reserve Availability:

It limits that resource cannot be extracted more than the available reserve.

$$\boldsymbol{EX_{c,y} \leq RERE_{c,g,y} * \left(RV_{c,g} - \sum_{y'<y} DUR_{y'} * EX_{c,g,y'} \right)} \tag{3.6}$$

The extraction of resource $EX_{r,y}$ during a year must be lower the resource volume $RV_{r,g}$ and extracted during the previous year y' by the rate of extraction of the remaining resource $RR_{r,g,y}$ in each year. The remaining resource is the proportion of extraction to available reserve. The value goes down as the reserve depletes.

Commodity Balance:

This constraint ensures that the total supply (output) from one level balances with the demand (input) of the downstream level.

$$\boldsymbol{\sum_{t,n,h} OUT_{tec,y,m,c,l,h} * DUR_h * EF_{tec,y,m,h} \geq \sum_{t,n,h} IN_{tec,y,m,c,l,h} * DUR_h * EF_{tec,y,m,h}} \tag{3.7}$$

Demand constraint:

This satisfies any fixed demand connected to each level. In our case, this implies to the final level where is this fixed demand of different commodities.

$$\boldsymbol{\sum_{y,h,l,c,tec} EFt_{tec,c,h,l,y} * OUT_{tec,y,m,c,l,h} \geq DEM_{c,h,l,y}} \tag{3.8}$$

where $DEM_{c,h,l}$ is the given level of the energy demand of any energy carrier c; at level l for each load region, h must be met by the total energy flows $EF_{tec,c,h,l}$ of all the technologies feeding that level in each year y.

3.2.2.2. Technological Constraints

Capacity constraint:

This limits the energy flow through technology depending upon the capacity and capacity factor. Capacity factor refers to the percentage availability of capacity of technology for operation ($Capacity\ factor = \frac{Number\ of\ hours\ of\ operation}{Total\ Number\ of\ hours\ in\ year}$).

$$\boldsymbol{\sum_{m} EF_{tec,m,h} \leq DUR_h * CF_{tec,y,m,h} * CAP_{tec,y,m}} \tag{3.9}$$

The activity level $EF_{tec,m,h}$ of each technology under the operation mode m is constrained by the duration of the lead region DUR_h, its capacity factor $CF_{tec,y,m,h}$, and maintained capacity during the year.

Operation Constraints:

This covers the operation time limitation of the technology. It involves the maintenance and repair of the schedule and other such contract or operational obligations/limitations.

$$\sum_{m,h} \boldsymbol{EF_{tec,y,m,h}} \leq \boldsymbol{OF_{tec,y}} * \boldsymbol{CF_{tec,y}} * \boldsymbol{CAP_{tec,y}} \quad \textbf{3.10}$$

$\boldsymbol{OF_{tec,y}}$ is operation factor of technology.

Minimum Utilization Bound:

This constraint forces the technologies to have a minimum operation which otherwise may not be economical. This also can be thought of as the contract of minimum power purchase in the dispatch agreement. In the case of Pakistan, such privileges are there for RLNG and coal-based power plants.

$$\sum_{m,h} \boldsymbol{EF_{tec,y,m,h}} \geq \boldsymbol{MUF_{tec,y}} * \boldsymbol{CAP_{tec,y}} \quad \textbf{3.11}$$

$\boldsymbol{MUF_{tec,y}}$ is the minimum utilization factor for any technology.

Bound on Energy Flow and Capacity:

This constraint allows putting lower and upper limits on the installation of additional capacity, total capacity, cumulative yearly energy flow. This is done by inputting different upper and lower bound.

$$\boldsymbol{CAP\_ADD_{tec,y}} \leq \boldsymbol{UpperBound\_CAP\_ADD_{tec,y}} \quad \textbf{3.12}$$

$$\boldsymbol{CAP\_ADD_{tec,y}} \geq \boldsymbol{LowerBound\_CAP\_ADD_{tec,y}} \quad \textbf{3.13}$$

$$\sum_{y} \boldsymbol{CAP_{tec,y}} \leq \boldsymbol{UpperBound\_total\_CAP_{tec,y}} \quad \textbf{3.14}$$

$$\sum_{y} \boldsymbol{CAP_{tec,y}} \geq \boldsymbol{LowerBound\_total\_CAP_{tec,y}} \quad \textbf{3.15}$$

$$\sum_{y} \boldsymbol{EF_{tec,y,m,h}} \leq \boldsymbol{UpperBound\_EF_{tec,y,m,h}} \quad \textbf{3.16}$$

$$\sum_{y} \boldsymbol{EF_{tec,y,m,h}} \leq \boldsymbol{LowerBound\_EF_{tec,y,m,h}} \qquad \textbf{3.17}$$

3.2.2.3. Emission Constraints

This is used to specify a specific environmental target or cap on emissions.

$$\sum_{tec} \boldsymbol{EM_{tec,e,y}} = \boldsymbol{EM\_bound_{e,y}} \qquad \textbf{3.18}$$

3.2.3. Reliability of Power System

Focusing on the intermittence nature, renewable sources, especially solar and wind, are prone to high risk to the reliable operation of the power system. The reliability of the power system depends upon two main factors, i.e., sufficient capacity and operational flexibility. The adequate capacity, which can also be referred as '*firm capacity*, ensures that the system has enough generation capability to meet the maximum load demand under normal and contingent conditions. Flexibility means that how quickly the generation system can respond to the sudden changes in load. Hence the overall purpose of system reliability is that the supply system must meet the demand at all levels and at all times.

Firm Capacity

The capacity required to meet the average load of the system is referred as ***Operating Capacity.*** To meet the peak and other contingent events, there is a need for an additional capacity, termed as ***Reserve Capacity.*** Hence the firm capacity would equal the sum operating and reserve capacity. The energy supply system must maintain the firm capacity all the time to ensure the reliable operation of the system. In the MESSAGE Model, reserves capacity requirement is equated to peak demand factor ($\boldsymbol{PDF}$) and can be calculated as the ratio of peak and average load.

For conventional power generation sources (referred as *dispatchable* power sources), firm capacity requirements can be evaluated by the nominal capacity and reliability factor (calculated based on the probability of forced outage). In the case of wind and solar-based generation (*non-dispatchable generation*), nameplate rating cannot ensure the required contribution to firm capacity because of their variable nature. In this situation, the MESSAGE Model employs the capacity values for solar and wind power plants according to the share in load [31] and the following explanation is also referred to this reference. ***Capacity Value*** can be defined as the additional load that can be fed from the addition of a power generating source while maintaining the reliability level of overall system. The capacity value can be quantified as additional capacity (MW) or as the fraction of its overall capacity factor. For renewable sources, the capacity value can be quantified as their share in total energy generation. An increasing penetration will lower the overall reliability of the system, hence the capacity value. From Figure 3.4, it can be seen that until 5% share in the generation, the wind generation is 90% reliable with respect to its overall capacity factor and beyond 25%, it cannot contribute to the capacity requirement of the energy system. It implies that in this situation, we have to focus on other sources (conventional power plants) to ensure sufficient firm capacity to ensure system reliability. *To put it simple, reliability for non-dispatchable power plants depended upon their correlation with the load profile. The stronger the correlation higher will be the contribution to the overall reliable capacity of the system. Hence, with the estimated generation trend of* *renewables/non-dispatchable sources, demand response programs can be applied to get a load profile that has a better correlation with the generation of these sources. This will lead to lower investment in the conventional power plants solely installed to meet reserve capacity requirements.*

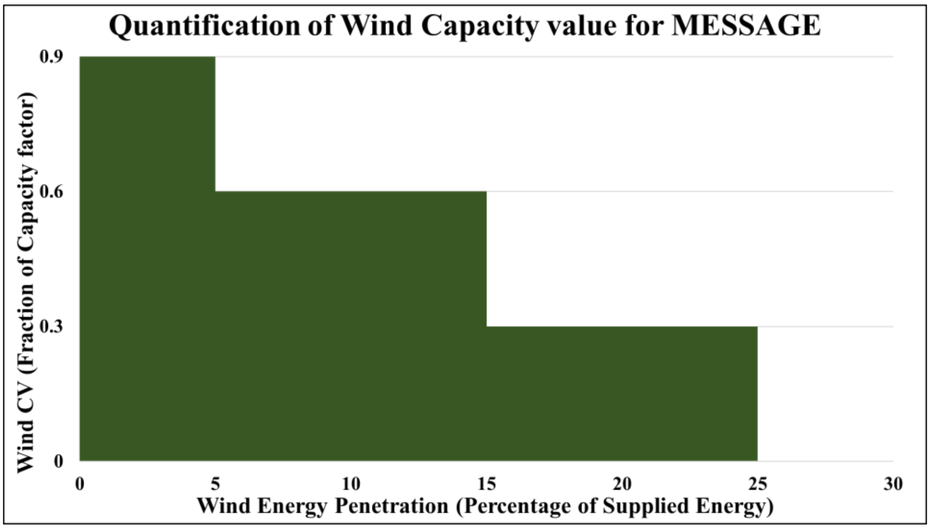


Figure 3.4. Qualification of wind capacity contribution/value [31]

In MESSAGE, the capacity value is represented with respect to ***"rating bins"***. A rating bin is defined based on the range of the share of renewable sources in the overall fed load and its value contains the capacity value for that range. In the above case, 4 rating bins ($\boldsymbol{RB}$) and corresponding reliability factor ($\boldsymbol{RF_{RB}}$)can be defined; first rating bin would cover 5% with the value of 0.09 ($\boldsymbol{RB_1 = 5\%\ and\ RF_{RB_1} = 0.09}$), second will cover 15% with the value of 0.06 ($\boldsymbol{RB_2 = 15\%\ and\ RF_{RB_2} = 0.06}$), third covering 25% will value 0.03 ($\boldsymbol{RB_3 = 25\%\ and\ RF_{RB_3} = 0.03}$), and the final bin will cover the rest of 75% with the value of zero ($\boldsymbol{RB_4 = 75\%\ and\ RF_{RB_4} = 0}$). Similar rating bins are defined for the solar power plant.

In the case of the reference energy system of Pakistan, for reliability consideration, the secondary level is vital for as all electricity supply electric power plant and electricity demanding gird is connected to this level. The yearly energy flow through the electric grid technology (tec) ($\sum_{\boldsymbol{h}} \boldsymbol{IN_{tec} * DUR * EF_{tec,h}}$) is actually the load ($\boldsymbol{load_{rel}}$) that require the reliability for the supply technologies connected to the secondary level. Considering this load, the energy flow based on rating bins (i) ($\boldsymbol{EF\_RAT_{tec,y,c,h,i}}$) for solar and wind power plants can be linked to electric load ($\boldsymbol{load_{rel}}$) in Equation 3.19 and finally the sub of $\boldsymbol{EF\_RAT_{tec,y,c,h,i}}$ all rating bins should be equal to output of each of these technology (notation for dispatchable as $\boldsymbol{tec}$ and non-dispatchable $\boldsymbol{tec'}$) as expressed in Equation 3.20).

$$\boldsymbol{EF\_RAT_{tec,y,h,i} \leq RB_i * load_{rel}} \quad \mathbf{3.19}$$

$$\sum_{\boldsymbol{i}} \boldsymbol{EF\_RAT_{tec,y,h,i} = IN_{tec,y,h} * DUR_h * EF_{tec,y,h,}} \quad \mathbf{3.20}$$

Finally, to ensure the reliability of the grid load ($\boldsymbol{load_{rel}}$) having peak demand factor ($\boldsymbol{PDF}$), energy flow along with reliability factor must satisfy the following relationship.

$$\sum_{\boldsymbol{tec,h}} \boldsymbol{RF_{tec,y,h} * EF_{tec,t,y,h}} + \sum_{\boldsymbol{tec',i,h}} \boldsymbol{RF_{tec',i,y,h} * EF\_RAT_{tec',y,h,i} \geq PDF_y * load_{rel,y}} \quad \mathbf{3.21}$$

Operational Flexibility

Employing the analysis discussed in [31], where the flexibility of different power plants and associated technologies are quantified as a factor ranging from -1 to 1 (referred as flexibility factor ($\boldsymbol{FF_{tec}}$)). The positive sign is used for the technologies that can provide flexibility and the negative for the technologies that require additional flexibility for integration with the power system. The magnitude of the factor shows the extent of this flexibility. Table 3.2 shows the flexibility factors of technologies involved in this study. Minimal and negative values for wind and solar power plants show that they require flexibility from conventional flexible sources, especially gas, high-speed diesel (HSD), and hydro-based power plants or electric storage. From the reference [31], *the value of flexibility factors are computed by running the unit commitment programs for a limited grid having all of the below technologies considering their operational parameters (startup cost, ramp rates, heat rate curves and minimum off/on time for thermal power plants) along with limitation on transmission capability*.

Table 3.2. The flexibility factor used in MESSAGE Model for this study [31]

Technology	Flexibility Factor [%]
Coal(IMP)_ppl	0.15
Coal(LOC)_ppl	0.15
Gas(CT)_ppl	1
RLNG(CT)_ppl	1
RLNG(CC)_ppl	0.5
Oil(FO)_ppl	0.5
Oil(HSD)_ppl	1
Nuclear_ppl	0
Hydro_ppl	0.5
Waste&Bio_ppl	0.3
Elect_T&D	-0.1
Storage	1
Wind_ppl	-0.08
Solar_ppl	-0.05

The flexibility factors can also be related to the rating bins for non-dispatchable power plants, but in our study, it is considered the same. Just like the above reliability factor, similar the need of the flexibility of grid load $\boldsymbol{load_{rel,y}}$ must be met be the sufficient generation for all sources. The negative value of the flexibility factor for wind and solar, as mentioned earlier, will limit their contribution to load satisfaction.

$$\sum_{tec} \boldsymbol{FF_{tec,y} * EF_{tec,y,h} \geq FF_{y,h} load_{rel,h,y}} \qquad \textbf{3.22}$$

This flexibility requirement may help to realize the need for storage in the system in such annual-based analysis. The negative flexibility factor can be balanced with the positive signed storage factors.

3.2.4. Technological Learning Curves

3.2.4.1. Basic of Learning Curves

In the MESSAGE model, the specific investment cost is an input parameter and any future trend of this cost need to be formulated exogenously. Samadi [60] presented the review where there was a strong correlation between the reduction in the specific cost of Solar PV and Wind turbines and their cumulative installed capacity over time. This idea can lead to the application of learning curves to better estimate the cost reduction for supply technologies, especially renewable (i.e., solar and wind), which are comparatively expensive but show a promising reduction potential with their growing installation. This, at some point, may help them to be competitive with conventional technologies to be chosen in a higher proportion in the optimization process.

The concept of technological learning curves is based on the theory that "*the performance of a technology improves with the accumulation of experience of technology*". The performance can be quantified in a couple of terms, such as efficiency, per unit production cost, specific investment cost, and other external impacts. The experience can be categorized into two main types of learning, "*learning-by-doing*" and "*learning-by-using*". *Learning-by-doing* can be understood in the manufacturing process where gained experience helps to make the process more efficient and thereby to reduce per-unit production cost. *Learning-by-using* implies that the user may gain experience on how to install and use technology, leading to an increase in the public acceptance of technology and thereby reduction in cost. This can be thought of as an increase in the cumulative installation of such technology. In this study, we focused on *specific investment cost ($/W)* of power technology as a performance indicator along with *cumulative installed capacity (MW)* as an experience indicator, as shown in Figure 3.5.

To quantify and include the learning curve phenomena for any technology, it is defined as *the specific investment cost (SIC) is reduced by a constant factor, termed as progress ratio (pr), each time the cumulative installed capacity (CC) is doubled.* Referring to the work [59] for the MARKEL energy model, the idea can be written mathematically as equation 3.23.

$$\boldsymbol{SIC = a \cdot (CC)^{b}} \qquad \textbf{3.23}$$

a is the constant term calculated using initial values of SIC and CC. b (termed as learning elasticity) is related to progress ratio as $pr = 2^b$ and have a negative value in usual cases. The complement of progress ratio $(1 - pr)$ is termed as Learning Rate (lr). A technology with a learning rate of 12% (leading to pr = 0.88 and b=-0.18) means that with each doubling of commutative capacity of this technology, the investment cost will be reduced by a factor of 0.8 (or 12%). The learning elasticity and hence the learning rate is estimated by applying the historical data on specific investment cost and growth of installation of the capacity of any technology.

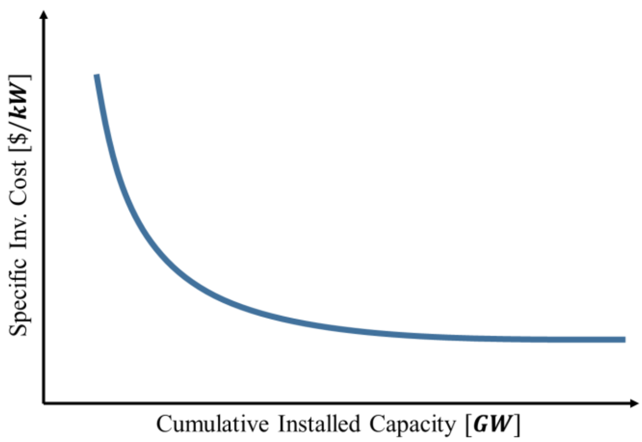


Figure 3.5. Concept learning curve for power technology

3.2.4.2. Endogenizing the learning curves in the MESSAGE Model

Referring to Figure 3.5, the expression for the cumulative investment cost (*CIC*) for the given level of cumulative installed capacity (*CC*) can be evaluated by finding the area under the specific investment cost (*SIC*) and cumulative installed capacity (*CC*) curve.

$$\boldsymbol{CIC = \int_0^{CC} a \cdot (C)^b dC = \frac{a}{1+b} CC^{1+b}} \qquad \textbf{3.24}$$

The above expression is a convex problem and can no longer be solved with a linear programming (LP) solver, whereas the basic MESSAGE model is linear and solved using LP. In this situation special feature of Mixed-Integer Programming (MIP) named Special Order Set type 2 (SOS2) can be applied. SOS2 is a set of variable elements where *only two elements can be non-zero, and these two elements should be adjacent*. Following are steps involved in including the learning curves in the energy supply model.

Segmentation of the cumulative cost and capacity

Application of SOS2 variable requires the segmentation of cumulative cost-capacity curve by selecting the suitable number of segment points $k = \{0,1,2, \dots . N\}$ (that also defines the number variable elements in SOS2 Set) along with initial and maximum values of cumulative investment cost and capacity. Equation 3.25 shows the uniform segmentation of between initial (CIC_0) and maximum (CIC_{max}) cumulative investment cost into N+1 number of points.

$$\boldsymbol{CIC_k = CIC_0 + k . \frac{(CIC_{max} - CIC_0)}{N}} \qquad \textbf{3.25}$$

The discrete cost (CIC_k) can be applied to Equation 3.24 to calculate the corresponding points on cumulative capacity (CC_k).

$$\boldsymbol{CC_k = \left(\frac{b+1}{a} \cdot CIC_k\right)^{\frac{1}{1+b}}} \qquad \textbf{3.26}$$

The above segmentation is uniform and linear, but the initial section of the learning curve is steeper and becomes flattered as the capacity growth progresses. It implies that there should be more segment points in the beginning to have a better estimation. In this situation, a no linear segmentation is proposed in equation 3.27.

$$\boldsymbol{CIC_k = CIC_0 + e^{(\frac{k}{10}-1)} . \frac{(CIC_{max} - CIC_0)}{e^{(\frac{N}{10})}}} \qquad \textbf{3.27}$$

All these nonlinear expressions are computed as in parameters, i.e., prior to optimization. To put it simple, we prepare a look-up table for a possible combination of cumulative capacity and cost.

Interpolation of Cumulative Capacity

In this step, the segmented capacity is combined with SOS2 variable set ($\boldsymbol{\lambda} = \{\lambda_0, \lambda_1, \lambda_2, \lambda_3, \dots \dots \lambda_k\}$) to write the expression for interpolated cumulative capacity for any year (t). In this case, the SOS2 set will try to find the point on the cost-capacity curve that corresponds to the required capacity for generation during a specific year (Equation 3.28). Figure 3.6 shows the segmented curve along with the corresponding λ variables.

$$CC_t = \sum_{k=1}^{N} \lambda_{k,t} \cdot CC_k \qquad 3.28$$

Interpolation of Cumulative Investment cost

The corresponding expression for the cumulative investment cost for year (t) is written as follows in equations 3.29.

$$CIC_t = \sum_{k=1}^{N} \lambda_{k,t} \cdot CIC_k \qquad 3.29$$

Condition for λ variables

For any year, to make sure that segmented capacities are added to the total capacity for the selected variable of SOS2 Set, the sum of all the variables should be equal to 1 (Equation 3.30).

$$\sum_{k=1}^{N} \lambda_{k,t} = 1 \qquad 3.30$$

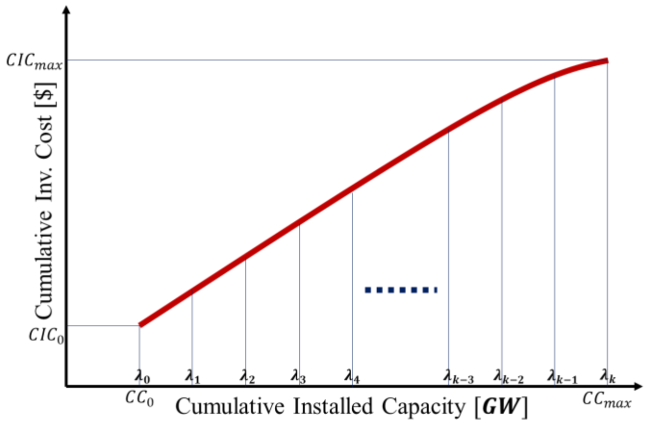


Figure 3.6. Segmented cumulative cost-capacity curve

The investment cost is calculated using ($CIC_t - CCT_{t-1}$) and added to the main cost variable in the objective function. The above explained equations was added to the existing MESSAGE model in GAMS and the solver changed from LP to MIP. Due to the LP solver in basic MESSAGE formulation, the unit sizing was also not included in the current version. As of now, we have to use MIP, so the unit size is also included to make sure the additional or new capacity is an integer product of the given unit sizes.

3.3. MESSAGE Interface- MESSAGEix

IIASA has developed MESSAGEix platform that is supported with ixmp (Integrated and cross-cutting modeling platform) for interacting with the MESSAGE Model. This platform facilitates the process of inputting data to the main optimizing tool GAMS (General Algebraic Modeling System). Once the model is solved for the optimal solution, it can store and display the results in an interactive way. Python or R Application Programming Interface (API) can be used for data interface, whereas *Java Database* is used for the temporary storage of input data and post solution results.

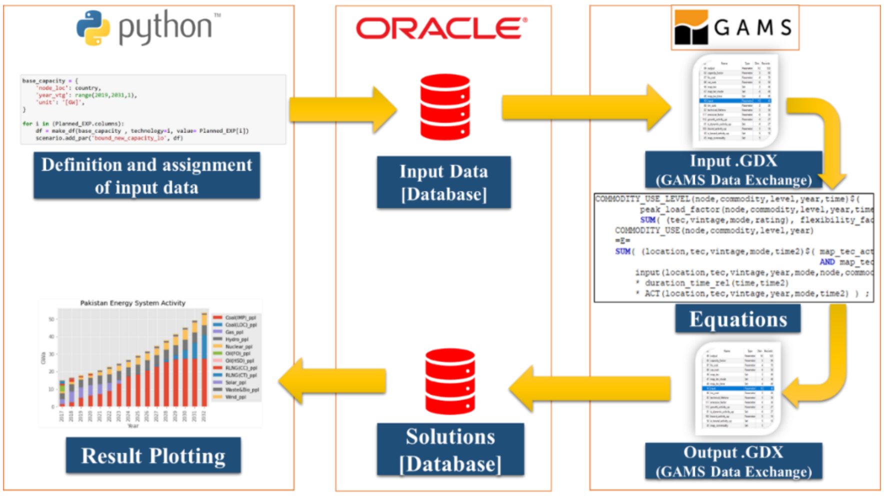


Figure 3.7. Computation and data flow mechanism of MESSAGEix Platform

All the equations for optimization are implemented in GAMS files. Input data regarding the reference system, base year commodity flows, technological-economic and constraints are entered with the help of Python or R APIs. This data is stored on Java Database. While solving the model, the data from Java Database is shifted to GAMS input file in.gdx (GAMS Data Exchange) formats that is linked to core GAMS codes containing equations. Model is solved and results are written to an output GAMS file of same.gdx format. Finally, the results are store to the Java Database that can be accessed again using Python or R interface to visualization and interpretation of results. Figure 3.7 shows the flow chart of MESSAGEix platform. The model can also be solved through the command line and through GAMS files.

3.4. Integration of Demand-Supply Models

The top-down econometric-based model is used for the future projection of total sectoral energy demand. The bottom-up energy demand model disaggregates this demand into different fuels by adjusting its assumption and considering the efficiency and market penetration of energy carriers. The top-down sectoral aggregated energy demand helps to calibrate the detailed bottom-up models as it contains a large number of parameters that are otherwise difficult for projects for the future. Finally, this demand is given to the MESSAGE model to optimize the supply mix (see Figure 7), considering the cost and constraints on the supply side. Scenarios based on government policies and objectives are introduced on either side of the model to assess their impact on the overall energy system. The emission factor for different energy model sections helps compute the emissions from the demand and supply sides.

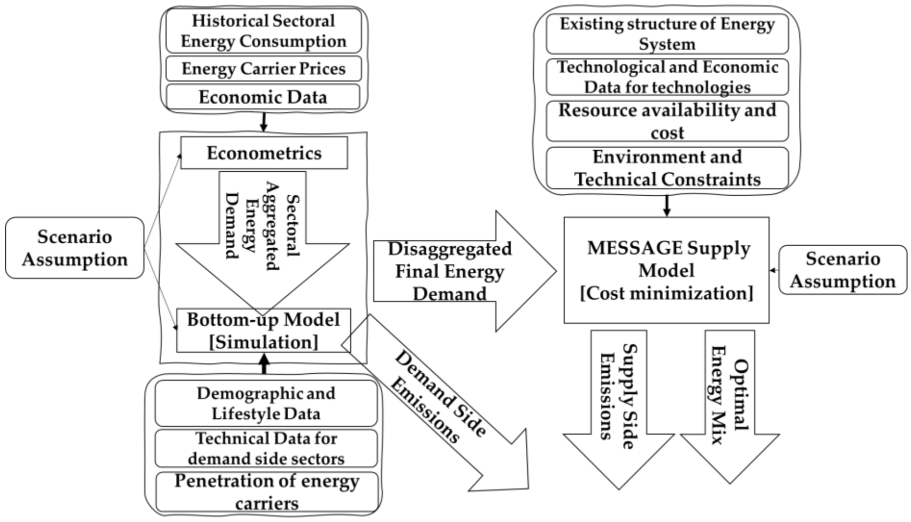


Figure 3.8. Integration of demand and supply models in this study

Chapter 4. Data Inventory

Annual Energy Yearbooks (EYB) published by the Hydrocarbon Development Institute of Pakistan (HDIP) are the main sources of data on energy consumption, energy prices, resource cost and reserve details, and the activity of different energy conversion technology (i.e., power plants, oil refineries, gas processing plants) [32]. The economic and social data are collected from the World Bank [28], Economic Survey of Pakistan [29], and Pakistan Bureau of Statistics (PBS) [30].

4.1. Top-Down Energy Demand Data

All energy-related data for this analysis section is collected from the various editions of the Energy Yearbook from HDIP [32]. Energy consumption data is disaggregated into different fuels in five sectors. The prices of fuels, especially electricity and natural gas, are updated nonuniformly throughout the year. For the yearly analysis, the time-weighted average is calculated for both of these carriers. Moreover, the overall sectoral energy price was computed using the energy consumption weighted average of the price of fuels. Due to the unavailability of household income at a yearly frequency, the data on private consumption is referred to as a proxy for income. The data on private consumption, sectoral, and overall value-added is collected from the World Bank Development Indicators [33]. Real prices were calculated using the GDP deflator, referred to as World Bank Development Indicators [33]. Table 5 shows the descriptive analysis of the involved time series data in log form for econometric analysis. Figure 4.1 represents the historical data (1996–2017) on the abovementioned data.

Table 4.1. Descriptive analysis of variables (in log form) for econometric analysis.

Sectors	Variable	Mean	Median	Max.	Min.	Std.Dev.	Obs.
Household (HH)	$\ln(EC\_HH)_t$	8.94	8.96	9.36	8.48	0.27	22
	$\ln(EP\_HH)_t$	6.09	6.06	6.41	5.91	0.13	22
	$\ln(CONS)_t$	8.75	8.78	9.21	8.35	0.25	22
Transport (TRNS)	$\ln(EC\_TRNS)_t$	9.29	9.28	9.83	8.93	0.25	22
	$\ln(EP\_TRNS)_t$	6.62	6.59	6.93	6.33	0.18	22
	$\ln(CONS)_t$	8.75	8.78	9.21	8.35	0.25	22
Industry (IND)	$\ln(EC\_IND)_t$	9.44	9.58	9.93	8.99	0.30	22
	$\ln(EP\_IND)_t$	6.06	6.05	6.47	5.80	0.17	22
	$\ln(VA\_IND)_t$	7.34	7.43	7.80	6.87	0.31	22
Service (SRV)	$\ln(EC\_SRV)_t$	7.09	7.26	7.61	6.50	0.37	22
	$\ln(EP\_SRV)_t$	6.99	7.00	7.29	6.77	0.14	22
	$\ln(VA\_SRV)_t$	8.35	8.40	8.86	7.87	0.31	22
Agriculture (AGRI)	$\ln(EC\_AGRI)_t$	6.61	6.59	6.75	6.49	0.08	22
	$\ln(EP\_AGRI)_t$	6.95	6.93	7.35	6.63	0.19	22
	$\ln(VA\_AGRI)_t$	7.48	7.50	7.72	7.21	0.17	22

EC = Energy Consumption, *EP* = Energy Price, *VA* = Value Added, and *CONS* = Private Consumption.

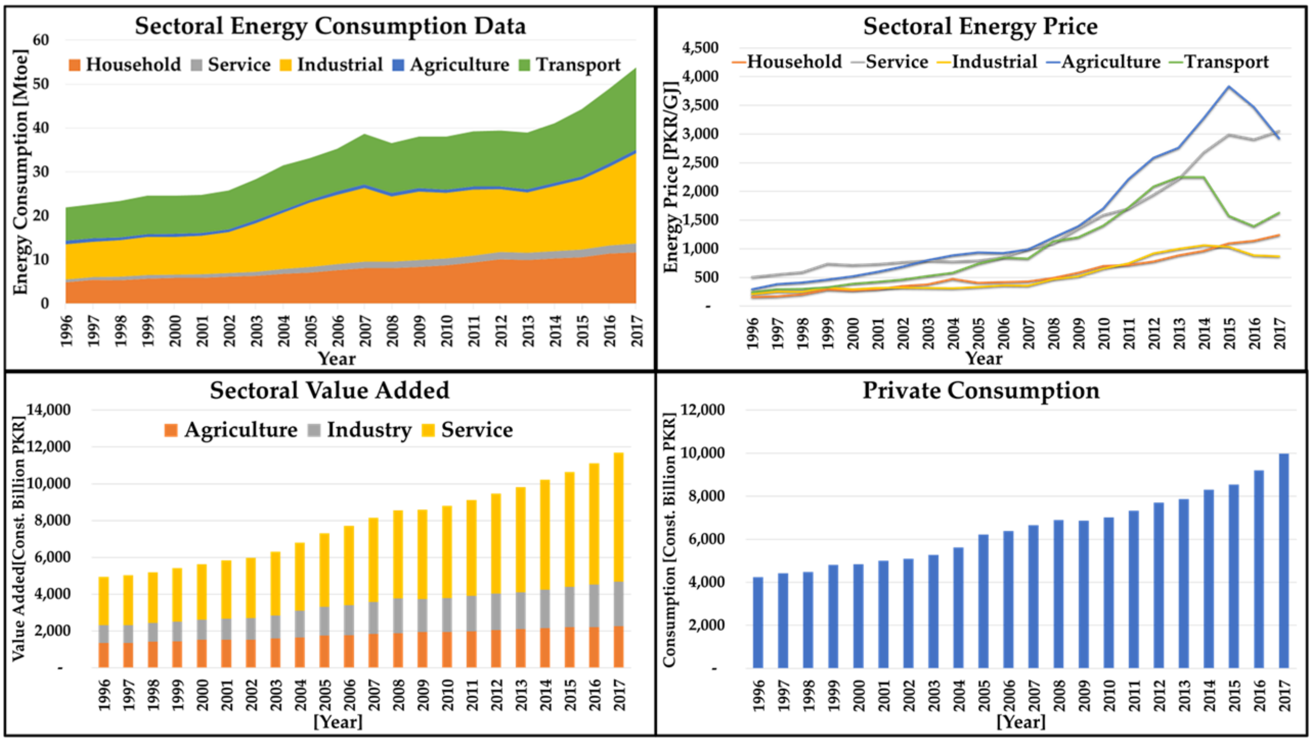


Figure 4.1. Timeseries data of parameters used in top-down energy demand model.

4.2. Bottom-Up Energy Demand Data

The data on household characteristics, ownership of electric appliances, and fuel choices were adapted from the Pakistan Social and Living Standards Measurement (PSLM) and the Household Integrated Economic Survey (HIES) periodical conducted by the Pakistan Bureau of Statistics (PBS) [35]. The Pakistan National Census 2017 conducted by PBS [36] is referred to as the latest data for urban and rural populations, the number of households, and the share of the urban population. The future trends of the population were collected from the medium-variant projection made by United Nations Report [37]. The Economic Survey of Pakistan [34] was used for collecting required data (i.e., vehicle population for different categories) in the transport sector. The data used in the bottom-up assessment of the energy demand in different subsectors are given in Table 4.1 to Table 4.7.

Table 4.2. Basic demographic data [36].

Parameter	Unit	Value
Population	[million]	207.77
Urban		
Urban Population	[million]	75.58
Urban Dwellings	[million]	12.19
Share of Urban Population	[%]	36.38
Urban Household Size	[Capita/HH]	6.2
Share of Population in Large Cities	[%]	19.1
Rural		
Rural Population	[million]	132.19
Rural Dwellings	[million]	20.01
Rural Household Size	[Capita/HH]	6.61

In this study, the households are categorized into small, medium, and large, assuming the common area of household in local units to be 3 marla (76 sq.m), 5 marla (126 sq.m), and 7 marla (177 sq.m), respectively. The effective area for heating is calculated on the basis of the area of the standard room size of 9.3 sq.m. The heat losses were calculated using the Building Codes of Pakistan 2017 [38]. The heating degree days (HDD) values are calculated from [39].

Table 4.3. Characteristics of different household categories [35,36,38,40–42].

Parameter	Unit	Urban			Rural		
		Small	Medium	Large	Small	Medium	Large
Dwelling Share	[%]	24.87	69.25	5.89	30.4	64.4	5.2
Total Area of Dwelling	[sqr. m]	76	126	177	126	177	253
Effective Area for Space Heating	[%]	12	22	32	11	23	32
Heat Loss	[Wh/sqm/°C/h]	0.54	0.53	0.53	0.54	0.53	0.53
Share of Dwelling Having AC Facility	[%]	21.7	21.7	21.7	3.8	3.8	3.8
Specific Energy for Cooking	[kWh/cap/yr]	2728	2728	2728	2728	2728	2728
Specific Energy for Water Heating	[kWh/cap/yr]	110	110	110	110	110	110
Share of Dwelling with Hot Water Facility	[%]	77	77	77	42	42	42

Table 4.4. Ownership and energy requirement details of electric appliances and the share of different fuels and household sectors [32,35].

Home Appliance	Dwelling Type	Urban [%]	Rural [%]	Units	Wattage	Usage (day/yr)	Usage (hrs/day)
Air Conditioner	Small	21.7	3.8	1	1460 @ 75%	120	4
	Medium	21.7	3.8	1	1950 @ 75%	120	4
	Large	21.7	3.8	2	1950 @ 75%	120	5
Television	All	86.4	48.1	1	100	365	5
Refrigerator	All	77.1	41.9	1	220	365	6
Room Cooler	All	25.1	11.2	1	185	180	8
Washing Machine	All	82.9	44.4	1	500	53	2
Water Pump	All	68.3	46.8	1	380	365	1
Fan	All	99.4	95.9	3	60	300	8
Lights	All	99.4	95.9	5	40	365	4

Fuel	Urban [%]			Rural [%]		
	Space Heating	Water Heating	Cooking	Space Heating	Water Heating	Cooking
Biomass	11.71	11.71	11.71	81.33	81.33	81.33
Electricity	2.0	2.0	2.0	2.0	2.0	2.0
Solar	0	0	0	0	0	0
Fossil Fuel	86.3	86.3	86.3	16.7	16.7	16.7

Share	Natural Gas	LPG	Kerosene
Fossil Fuel [%]	91.7	0.94	7.39

Car ownership (number of cars per 1000 persons) is computed using population and on-road cars [33,34]. The rest of the parameters in Table 9 are calculated for the given demand of energy consumption in the transport sector[32].

Table 4.5. Basic information related to passenger and freight activities**.**

Parameter	Unit	Value
Intracity Distance Travelled	[km/prsn/day]	38.17
Intercity Distance Travelled	[km/prsn/yr]	13931
Car Ownership	[person/car]	25.47
Intercity Car-km	[km/car/yr]	4000
Freight ton-km (TKM)	[10^9 tkm]	349.6

Table 4.6. Detail of passenger and freight transport [34,43,44].

Subsector	Vehicle Category	Vehicle Type	Modal Share [%]	Load Factor [person/vehicle]	Fuel type	Share by Fuel [%]	Energy Intensity [l/100 km] *
Intercity Passenger Transport	Private	Car	-	2.6	Gasoline	82	9.1
					Diesel	10.5	10
					CNG	7.5	8.1
					Electricity	0	16.5
	Public	Vans	35.72	12	Gasoline	100	5
					CNG	0	5.61
		Bus	47.2	50	Diesel	100	28.6
		Train	17.1	-	Diesel	100	3.1
Intracity Passenger Transport	Private	Car	37.06	2.6	Gasoline	82	9.1
					Diesel	10.5	10
					CNG	7.5	8.1
					Electricity	0	16.5
		2 Wheelers	47.21	1.6	Gasoline	100	2.5
					Electricity		3.3
	Public	Taxi	2.91	2.6	Gasoline	91.6	7.1
					CNG	8.37	6.4
					Electricity	0	13.3
		3 Wheelers	1.82	1.8	Gasoline	91.6	4.55
					CNG	8.37	8.1
					Electricity	0	6.1
		Vans	5.79	12	Gasoline	91.6	5
					CNG	8.37	5.61
		Bus	5.21	50	CNG	100	23.14
Freight Transport	-	Pickup	5.2	-	Diesel	100	6.7
		Truck	91.6		Diesel	100	2.3
		Train	3.24	-	Diesel	100	2.3

* For electric fuels, passenger trains, and freight transport, the units of energy intensity are kWh/100 km, kWh/100 pkm, and l/100 tkm, respectively.

Table 4.7. Economic sectors details [32,33].

Economic Sector	Value Added [Tr. PKR]	Share in GVA [%]	Energy Intensity [kJ/PKR]	Share of Fuels [%]				
				Oil	Natural Gas	Coal	LPG	Electricity
Agriculture	2.25	19.3	15.6	1.8	-	-	-	98.2
Industry	2.43	20.8	355.1	8.87	37.9	42.1	-	11.1
Service	7.01	60.0	12.0	-	37.4	-	27.76	34.9

4.3. Energy Supply Data

The input data for the MESSAGE model involves the technical details and limitations of technologies, resource availability and cost, emission factors, and energy balance for the base year, which are given in Table 4.8 and Table 4.9.

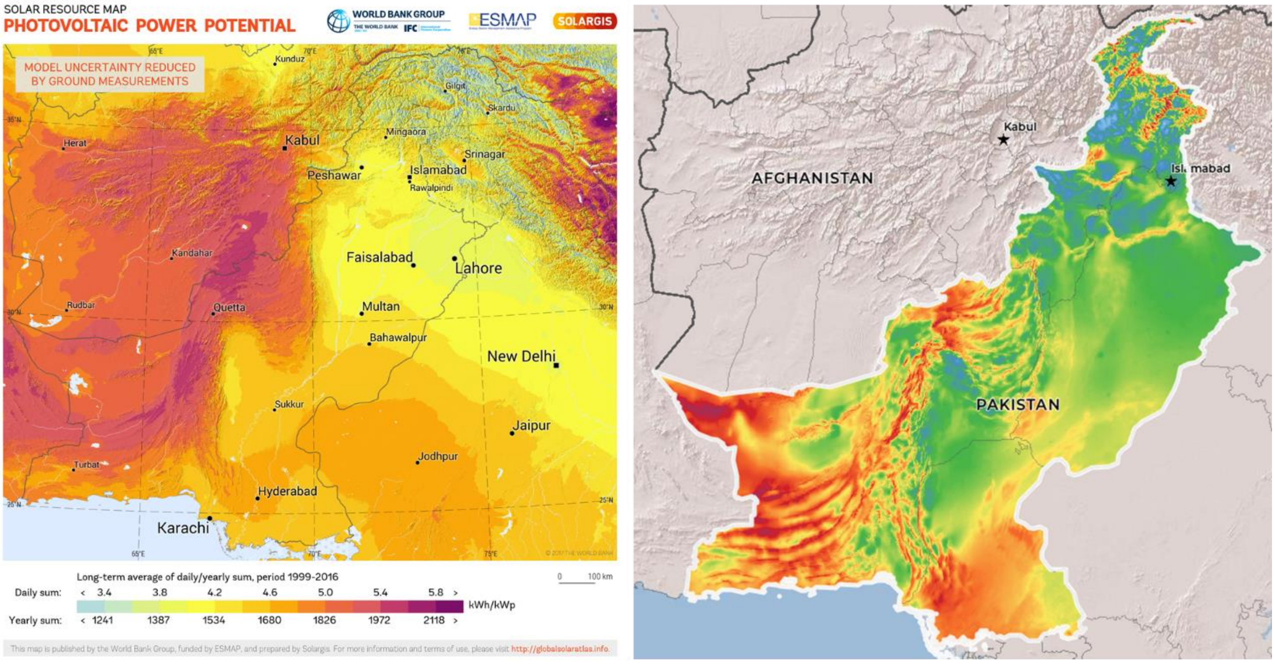
Table 4.8. Technical details and base year status of technologies [9,32].

Parameters	Efficiency [%]	Capacity Factor [%]	Operation Factor [%]	Reliability Factor [%]	Aux. Power [%]	Base Year Generation [GWa]	Base Year Capacity [GW]	Min. Utilization [%]
Coal(IMP)_ppl	39.04	100	92	93	0.03	1.24	2.84	25
Coal(LOC)_ppl	39.04	100	92	93	0.03	0.00	0.03	0
Gas_ppl	34.39	100	89	95	2.58	3.10	8.01	50
RLNG(CT)_ppl	34.39	100	89	95	2.58	1.40	4.02	50
RLNG(CC)_ppl	55.69	100	89	95	2.58	1.12	3.67	50
Oil(FO)_ppl	38.77	100	92	95	5.48	3.28	8.42	50
Oil(HSD)_ppl	33.77	100	92	95	2.01	0.09	0.13	50
Nuclear_ppl	36.75	100	84	95	7.12	1.13	1.47	80
Hydro_ppl	100	50	97	93	0.81	3.19	8.72	0
Wind_ppl	100	32.76	97	100	0	0.24	1.05	0
Solar_ppl	100	21	100	100	0	0.09	0.43	0
Waste&Bio_ppl	100	57	97	93	0	0.11	0.42	0

Table 4.9. Cost and environmental parameters of power technologies [9,32,45].

Parameters	Plant Life [Years]	Construction Time [Years]	Investment Cost [$/kW]	Investment Cost Reduction [%]	Fix. Cost [$/kW-Year]	Var. Cost [$/kWa]	Emission Factor [MT CO2/GWa]
Coal (IMP)_ppl	40	4	1556	0.30	25.56	32.32	6.31
Coal (LOC)_ppl	40	4	1556	0.30	173.28	61.32	6.31
Gas_ppl	30	2	534	0.54	19.2	16.64	4.53
RLNG(CT)_ppl	30	2	534	0.54	19.2	16.64	4.53
RLNG(CC)_ppl	30	2	694	0.59	17.16	31.19	4.53
Oil (FO)_ppl	40	4	694	0.00	55	6.48	5.96
Oil (HSD)_ppl	30	4	534	0.00	36	9.63	6.68
Nuclear_ppl	40	7	4342	0.54	71.76	17.52	0.00
Hydro_ppl	50	5	2488.4	0.00	13.16	36.79	0.00
Wind_ppl	50	2	2500	1.78	25.48	0.00	0.00
Solar_ppl	30	2	1300	1.80	40.82	0.00	0.00
Waste&Bio_ppl	30	2	4000	0.30	109.01	47.55	3.50

Coal is the leading reserve in Pakistan with limited extraction. The government has started the extraction of domestic coal for power generation use and will lower the extraction of natural gas resources in the next few years. Crude oil has already crossed its peak. On the renewable energy side, Pakistan is blessed with immense potential, especially solar and wind. Being an agriculture-based country, hydro is the most explored and promising renewable resource. Figure 4.2 shows the potential map for solar and wind energies in Pakistan. The resource availability in Pakistan and energy imports are given in Table 4.10 and Table 4.11.



(a) **(b)**

Figure 4.2. (a) Solar potential and (b) wind speed map [50,51].

Table 4.10. Resource cost and availability data [9,32,46,47].

Category	Resource	Reserve		Cost		Base Year Extraction	
		Unit	Value	Unit	Value	Unit	Value
Fossil Fuel	Coal	[MT]	7779.8	[$/T]	19.1	[MT/Year]	4.3
	Natural Gas	[BCF]	20958.9	[$/MCF]	5.1	[BCF/Year]	1166.0
	Crude Oil	[MT]	51.1	[$/T]	-	[MT/Year]	4.4
	Uranium	[T]	33288.0	[$/kg]	360.0	[T/Year]	45.0
Renewables	Hydro	[GW]	40	-	-	-	-
	Wind	[GW]	120	-	-	-	-
	Solar	[GW]	2900	-	-	-	-
	Waste and Bio	[GW]	4.068	-	-	-	-

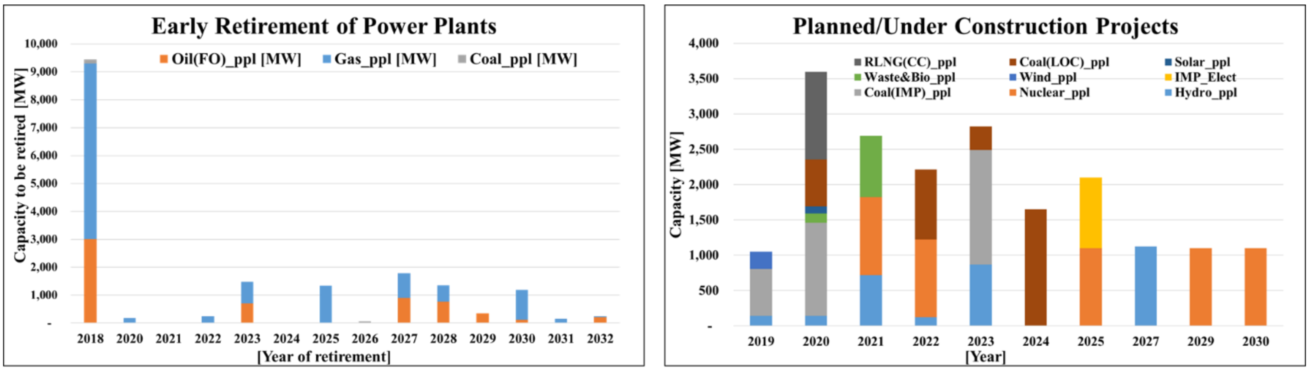
Table 4.11. Cost and quantity of imports [9,32].

Commodity	Imports		Cost *	
	Unit	Value	Unit	Value
Electricity	[GWa]	0.06	[$/kWa]	587
Crude Oil	[MT]	10.33	[$/T]	-
High-Speed Diesel [HSD]	[MT]	3.85	[$/T]	892
Petrol	[MT]	5.01	[$/T]	-
Furnace Oil	[MT]	5.87	[$/T]	555
LNG	[BCF]	320.18	[$/MCF]	12.5

Coal	[MT]	13.68	[$/T]	131
Nuclear Fuel	[T]	19.10	[$/kg]	2830
LPG	[MT]	0.40	[$/T]	-

* Only power generation-related costs are considered.

MESSAGE model also considered the historical installed capacity and maintained it depending upon its vintage year and cost-to-benefit. For the base year, the capacity must be able to satisfy the energy demand for the base year. Figure 4.3shows the historical capacity of the different power plants. Also, there is a need to specify the power plants that are planned or under construction. As these power plants are must-install plants and model is forced to consider these plants even if they do not economically fit in our scenarios.



(a) (b)

Figure 4.3. Retirement and future planned power projects

4.4. Main Assumptions for Demand and Supply Models

The following are the main assumptions used in developing the energy demand and supply models.

- The analysis is restricted to annual time, which implies that the load regions of the load duration curve are held for the future.
- Local and imported coal have a share of 77.3% and 22.7% in total final energy demand, respectively.
- The peak demand factor (ratio of annual peak load to average yearly load) for electricity is about 2.19 [9] and is assumed to be constant throughout the model horizon.
- Air conditioning and electric appliances are the major consumers of electricity in buildings.
- The future anticipated domestic natural gas production is estimated based on the Oil and Gas Regulatory Authority (OGRA) [48].
- For coal extraction, the maximum production is assumed to be increased at an annual growth rate of 40% with respect to the base year as planned in Pakistan Vision 2025 [49].
- Considering the international obligations, extraction of domestic natural uranium is limited to 45 T/year. The additional demand for nuclear fuel is met through the import of fabricated nuclear fuel.
- The resource cost and imported fuel prices are assumed to be constant throughout the model horizon.
- As mentioned in the data inventory, the potential for investment cost reduction is modeled exogenously through a constant downward growth rate.

Chapter 5. Results and Discussion

5.1. Scenario Definition:

Once the demand and supply models are populated with input data and constraints, the next step is to project energy demand and consequently the supply mix for the proposed model horizon. This step involves the assumption or predictions of future trends of key factors involved in model analysis. For the econometric model, these are the value-added, GDP and energy prices. The bottom-up energy model has many such parameters, such as fuel choices, energy efficiency improvement, change in lifestyle, etc. One way is to conduct the scenario analysis, focusing on one or multiple parameters at a time and running the model. Scenario analysis involves running the models under different future *pathways*, which provide the policymakers with an analysis of the impacts of considering and adopting these pathways. The other aims may involve elaborating the details on resource utilization and their depletion, cost of energy (mainly electricity in our case), energy security and environmental degradation through emission under different scenarios. This approach helps to assess the impact of individual or multiple policies on the overall system situations. Governmental plans, policies, international obligations, current developments and the researcher’s personal assessment of the situation are the main source of scenario definitions. Baseline is the basic scenario that tries to depict the system's behavior in the usual fashion and not special policy intervention is introduced. Next, various scenarios are introduced, and results are interpreted regarding the baseline scenario and key conclusions drawn for each scenario. Based on the conclusion, key policy recommendations can help policymakers improve the existing energy system.

5.1.1. Demand Side

5.1.1.1. Baseline (Reference)

- The future GDP growth rate and inflation are assumed to be 5.5% and 4.1%, respectively. The sectoral share of GVA is assumed to be consistent with the base year for economic sectors.
- The projection of population is referred to as the medium variant of estimation of the United Nations. The share of different fuels in all sectors is assumed to be constant at the base year level.
- The detailed parameters in the bottom-un energy demand model such as household size, the share of different types of households and ownership of air-conditioning and appliances are projected for the future considering the compounded annual growth rate ($CAGR = \left(\frac{End\ period\ Value}{Start\ period\ Value}\right)^{1/period} - 1$) calculated for the available historical data on these parameters.
- The share of different fuels in all the sectors is assumed to have the same share.

5.1.1.2. Economic Growth [EG]

In the demand model development theory, economic activity or growth is the key driver of energy demand both in the production and consumption side aspects of the economy. On the production side, it helps to assess the energy demand to realize such growth. On the consumption side, it improves the public lifestyle, equating with equivalent energy demand to sustain such improvement. However, comparatively reliable and dynamic estimation for economic growth of any country may be possible only for the short run and it isn't easy to extend it to the medium and long run. In the case of Pakistan, the government plans hypothetical ambitious plans to achieve a high level of economic growth that is realty supported by the analytical tools and ground realities and hence they are not realized. In this study, to assess the impact of economic growth concerning the baseline scenario, two economic growth scenarios are devised, as follows:

- ***High Economic Growth (HEG):*** A growth rate of 7% is assumed to this level of economic activity.
- ***Low Economic Growth (LEG):*** A growth rate of 3% is considered in this scenario. It is lower than the baseline scenario.

5.1.1.3. Energy Efficiency and Conservation [EE&C]

Energy efficiency and conservation are an important measure to reduce the energy demand and resulting emissions. This involves the replacement of old and energy intensive household and other appliances, improvement in building designs, upgradation of the transport system and efficient industrial processes. Asian Development Bank (ADB) [58] conducted a comprehensive analysis of Pakistan energy demand and quantified the potential of energy saving. According to the outcome of the ADB study, the energy demand can be lowered by 25.08%, 23.9%, 19.6%, 13.9% and 11.11% in Households, Commercial/Service, Agriculture, Transport and Industry, respectively. The Energy Efficiency and Conservation (EE&C) scenario is proposed to show the impact of such measures on demand and supply. In this scenario, it is assumed these potentials are achieved linearly until the end of the model horizon, i.e., 2032.

5.1.2. Supply Side

In the context of affordable electricity generation and minimizing the environmental impact, the supply system often comes under discussion as it offers a more diverse option to realize an improved energy system. Consequently, a couple of policy interventions are introduced for the supply system, such as increasing the share of renewable energy (wind and solar), restricting the future deployment of coal power plants, and focusing more on hydro and nuclear power projects to ensure energy security with the climate action. Below is the scenario considered on the supply side. For these scenarios, the energy demand of the baseline case is considered.

5.1.2.1. Baseline (Reference)

This is the reference scenario where there is not a special policy is considered. The minimum cost energy supply system is optimized. This reference scenario is used to compare the system for other special and specific scenarios.

5.1.2.2. Renewable [REN]:

According to the Renewable Policy 2019, the system gradually accommodates a 20% share by 2025 and a 30% share by 2030 of solar, wind, and waste/biomass-based power plants.

5.1.2.3. No Coal [NC]:

In the wake of climate change challenges, referring to a recent statement by the government regarding the commitment to no more installations of new coal-based power plants, the existing planned and under-construction coal-based power plants are considered for the analysis.

5.1.2.4. Technological Learning Curves [TLC]

To assess the impact on the inclusion of learning curves and unit sizing in supply technologies, this scenario is the extended version of the baseline based on the mathematical formulation discussed in section 3.3. Table 5.1 shows the selected data for the learning rates is referred from [60,61].

Table 5.1. The technological data for inclusion of learning curves in TLC case [60,61,61]

Technology	Segments for interpolation	Initial Investment Cost	Initial Cumulative Capacity	Learning Rate	Maximum Cumulative Capacity	Unit Size
	[No.]	[$/KW]	[GW]	[%]	[GW]	[MW]
Coal (IMP)_ppl	40	1,556	0.86	0.0	30.4	330
Coal (LOC)_ppl	40	1,556	0.03	0.0	18.6	330
Gas_ppl	40	534	8.01	0.0	16.4	1243
RLNG (CT)_ppl	40	534	3.62	0.0	4.2	400
RLNG (CC)_ppl	40	694	1.22	6.0	6.8	1243
Oil (FO)_ppl	40	694	8.07	0.0	8.6	350
Oil (HSD)_ppl	40	534	0.11	0.0	0.1	350
Nuclear_ppl	40	4,342	1.47	5.0	9.7	1100
Hydro_ppl	40	2,488	7.72	1.4	38.3	40 & 375
Wind_ppl	40	2,500	0.80	5.0	64.2	50
Solar_ppl	40	1,300	0.43	12.0	83.5	100
Waste&Bio_ppl	40	4,000	0.41	0.0	8.9	15

5.2. Demand-Side Analysis

5.2.1. Econometric Model [Baseline Scenario]

In this study, EViews software was employed to analyze the data sets of each demand sector. This is a commercial tool, but a free student version is also available. The data sets are organized in an excel file and then exported the time series data to EViews. This tool provides the opportunity to work with a wide range of statistical methods for the analysis of such data.

5.2.1.1. Stationarity Test

Following the procedure introduced in the methodology section, the Augmented Dickey–Fuller (ADF) test is used to check the stationarity of the time series data. Table 5.2 summarizes the result for the stationary test of all the time series in the log form and t-stat and p-value are the test determinants. The result revealed that none of the variables is stationary at its level (i.e., I(0)). This suggests that multiple regression cannot be applied. This situation leads to the application of the ARDL model.

Table 5.2. Results for Augmented Dickey–Fuller test to check stationarity.

Sectors	Variable	Level		First Diff.		Decision
		t-Stat	*p*-Val.	t-Stat	*p*-Val.	
Household (HH)	$\ln(EC\_HH)_t$	−0.589	0.853	−6.556	0.000	*I(1)*
	$\ln(EP\_HH)_t$	−2.469	0.137	−5.040	0.001	*I(1)*
	$\ln(CONS)_t$	0.794	0.991	−3.887	0.009	*I(1)*
Transport (TRNS)	$\ln(EC\_TRNS)_t$	1.065	0.996	−4.050	0.006	*I(1)*
	$\ln(EP\_TRNS)_t$	−1.625	0.453	−3.837	0.009	*I(1)*
	$\ln(CONS)_t$	0.794	0.991	−3.887	0.009	*I(1)*
Industry (IND)	$\ln(EC\_IND)_t$	−0.840	0.785	−2.475	0.136	*I(2)*
	$\ln(EP\_IND)_t$	−1.60758	0.461	−6.5936	0.000	*I(1)*
	$\ln(VA\_IND)_t$	−0.47101	0.879	−4.20294	0.0043	*I(1)*
Service (SRV)	$\ln(EC\_SRV)_t$	−1.05949	0.71	−2.64199	0.1015	*I(2)*
	$\ln(EP\_SRV)_t$	−2.31065	0.178	−5.88428	0.0001	*I(1)*
	$\ln(VA\_SRV)_t$	0.094845	0.957	−2.33057	0.1727	*I(2)*
Agriculture (AGRI)	$\ln(EC\_AGRI)_t$	−2.24377	0.198	−3.29012	0.0293	*I(1)*
	$\ln(EP\_AGRI)_t$	−1.77701	0.38	−2.90758	0.0621	*I(2)*
	$\ln(VA\_AGRI)_t$	−0.77251	0.806	−6.0167	0.0001	*I(1)*

Note: The critical values of the ADF test were referred to [54].

5.2.1.2. ARDL Model Analysis

Table 5.3 summarizes the optimal lag orders of variables in the ARDL model and the performance of the statistical analysis. R^2 results are convincing, and the Durbin–Watson test is within limits. However, the order of the model is different depending upon the behavior of the system to different conditions of input drivers. The household sector shows the simplified ARDL case, which implies that the only first-order auto regression is sufficient.

Table 5.3. The results for econometric analysis for different sectors.

Sectors	Model Specification ARDL(q,p,p)	R^2	F-Statistics	Durbin–Watson Stat
Household	ARDL (1,0,0)	0.99	615.24	2.07
Transport	ARDL (3,2,2)	0.98	97.08	1.84
Industry	ARDL (2,0,0)	0.99	104.83	2.41
Service	ARDL (1,0,1)	0.99	389.64	1.79
Agriculture	ARDL (3,3,1)	0.77	7.61	1.82

For the given number of explaining variables and number of observations, the range of Durbin–Watson Stat is 1.54 to 3.08 based on the analysis of Savin and White [52].

Table 5.4 shows the long-term results extracted from the ARDL model. Energy price has an expected negative sign, and consumption/value-added has a positive sign. Different sectors exhibit different behavior. The household and transport sectors are less affected by the energy price. This may be a possible consequence of the energy subsidies provided in this sector and low tariffs for domestic natural gas. However, income has a significant positive impact in both sectors.

Table 5.4. Results for long-term analysis.

Sectors	Variable	Test Stats			
		Coefficient	Std. Error	t-Stat	*p*-Val.
Household (HH)	ln $(EP\_HH)_t$	−0.095	0.075	−1.269	0.222
	ln $(CONS)_t$	1.032	0.040	25.569	0.000
	Constant	0.516	0.644	0.801	0.434
Transport (TRNS)	ln $(EP\_TRNS)_t$	−0.370	0.358	−1.034	0.341
	ln $(CONS)_t$	1.193	0.274	4.349	0.005
	Constant	1.369	0.383	3.577	0.012
Industry (IND)	ln $(EP\_IND)_t$	−0.644	0.053	−12.064	0.001
	ln $(VA\_IND)_t$	0.692	0.021	32.551	0.000
	Constant	8.241	0.470	17.526	0.000
Service (SRV)	ln $(EP\_SRV)_t$	−0.353	0.047	−7.515	0.002
	ln $(VA\_SRV)_t$	1.120	0.029	38.300	0.000
	Constant	0.248	0.538	0.460	0.669
Agriculture (AGRI)	ln $(EP\_AGRI)_t$	−0.502	0.046	−10.805	0.000
	ln $(VA\_AGRI)_t$	0.558	0.045	12.358	0.000
	Constant	5.897	0.149	39.529	0.000

Table 5.5 shows the short run and detailed coefficients of the ARLD Model. Different notation, magnitude and *p*-value are observed for the lags of each model. This shows the significance of each lag term and collectively, they predict energy demand better. The overall effect, the contribution of each explaining variable depicted in long-term analysis where the coefficient follows the expected notation.

Table 5.5. Short-term results for econometric analysis of demand.

Sector	Variable	Coefficient	Std. Error	t-Stat	Prob.
Household (HH)	$\ln(EC\_HH)_{t-1}$	0.402	0.179	2.249	0.038
	$\ln(EP\_HH)_t$	−0.046	0.057	−0.814	0.427
	$\ln(CONS)_t$	0.622	0.189	3.289	0.004
	Constant	−8.568	2.680	−3.196	0.005
Transport (TRNS)	$\ln(EC\_TRNS)_{t-1}$	0.652	0.254	2.568	0.030
	$\ln(EC\_TRNS)_{t-2}$	−0.554	0.271	−2.046	0.071
	$\ln(EC\_TRNS)_{t-3}$	0.202	0.229	0.879	0.402
	$\ln(EP\_TRNS)$	−0.289	0.071	−4.080	0.003
	$\ln(EP\_TRNS)_{t-1}$	0.255	0.129	1.976	0.080
	$\ln(EP\_TRNS)_{t-2}$	−0.265	0.120	−2.213	0.054
	$\ln(CONS)_t$	0.616	0.382	1.611	0.142

	$\ln(CONS)_{t-1}$	−0.776	0.568	−1.365	0.205
	$\ln(CONS)_{t-2}$	1.055	0.448	2.357	0.043
	Constant	−13.009	3.605	−3.608	0.006
Industry (IND)	$\ln(EC\_IND)_{t-1}$	0.876	0.248	3.533	0.003
	$\ln(EC\_IND)_{t-2}$	−0.406	0.193	−2.109	0.052
	$\ln(EP\_IND)_{t}$	−0.283	0.116	−2.434	0.028
	$\ln(VA\_IND)_{t}$	0.402	0.152	2.654	0.018
	Constant	−0.911	2.196	−0.415	0.684
Service (SRV)	$\ln(EC\_SRV)_{t-1}$	0.677	0.175	3.864	0.001
	$\ln(EP\_SRV)_{t}$	−0.108	0.075	−1.434	0.171
	$\ln(VA\_SRV)_{t}$	1.191	0.558	2.136	0.049
	$\ln(VA\_SRV)_{t-1}$	−0.853	0.594	−1.435	0.171
	Constant	−4.559	3.360	−1.357	0.194
Agriculture (AGRI)	$\ln(EC\_AGRI)_{t-1}$	0.289	0.212	1.362	0.206
	$\ln(EC\_AGRI)_{t-2}$	0.400	0.220	1.815	0.103
	$\ln(EC\_AGRI)_{t-3}$	−0.750	0.178	−4.199	0.002
	$\ln(EP\_AGRI)_{t}$	−0.578	0.133	−4.329	0.002
	$\ln(EP\_AGRI)_{t-1}$	0.288	0.158	1.824	0.102
	$\ln(EP\_AGRI)_{t-2}$	0.057	0.136	0.416	0.687
	$\ln(EP\_AGRI)_{t-3}$	−0.309	0.162	−1.905	0.089
	$\ln(VA\_AGRI)_{t}$	−0.507	0.571	−0.888	0.397
	$\ln(VA\_AGRI)_{t-1}$	1.152	0.617	1.866	0.095
	Constant	−0.077	3.773	−0.020	0.984

5.2.1.3. Stability Test of proposed ADRL Model

The cumulative sum (CUMSUM) of squares stability plots were obtained to assess the overall stability and applicability of different models. The results are supposed to follow the boundaries for a given range of freedom (5% significance). All the models show good stable results. The results for each sector model are presented in Figure 5.1Figure 5.1. Model Stability Test for sectoral energy models (a) Household (b) Transport (c) Industry (d) service (e) Agriculture below.

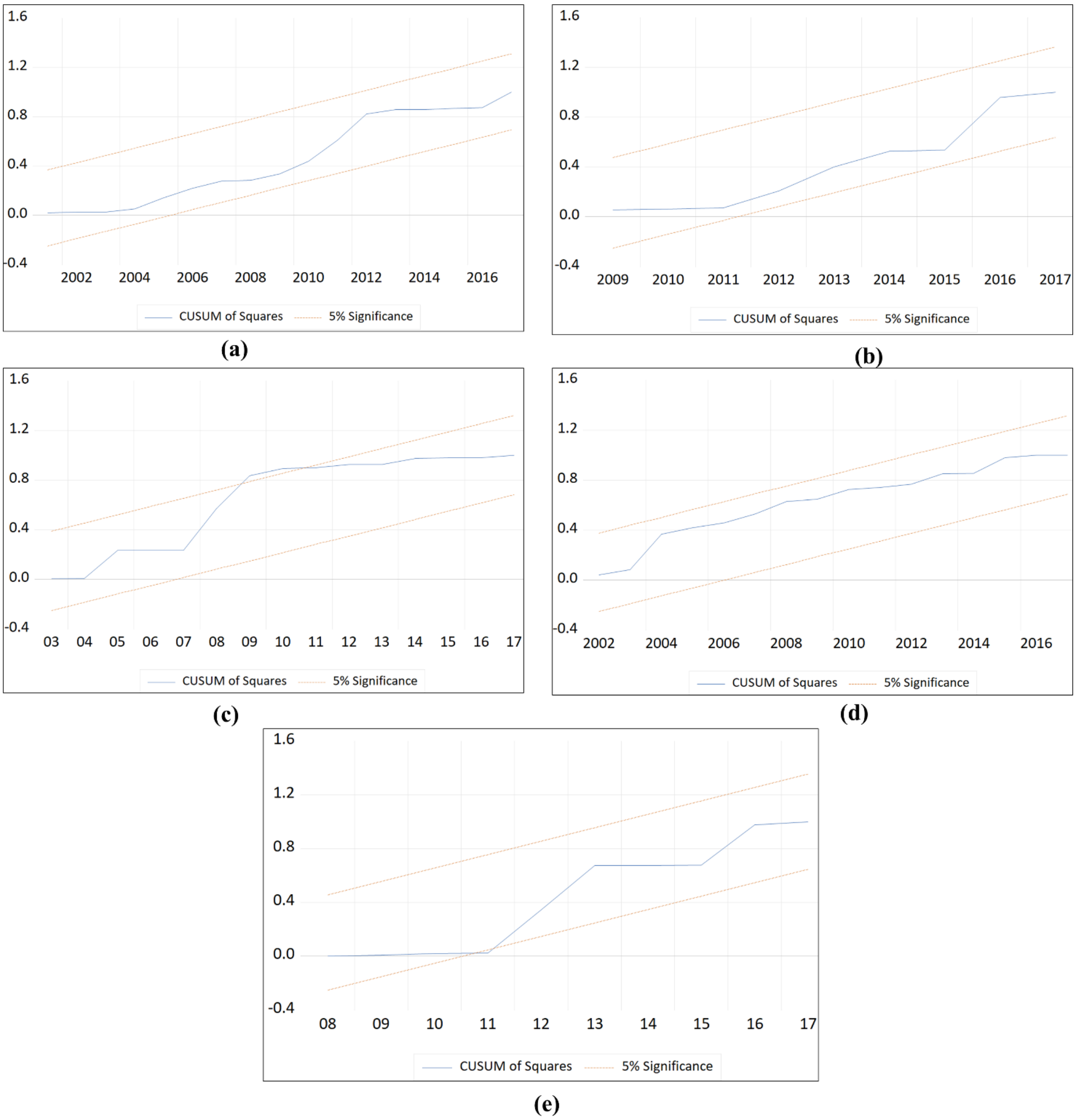


Figure 5.1. Model Stability Test for sectoral energy models (a) Household (b) Transport (c) Industry (d) service (e) Agriculture

5.2.2. Bottom model and future projections

Figure 5.2 shows the projected sectoral energy demand for the period 2017–2032. Figure 5.3 provides an outlook on the demand for different fuels within the model horizon. On an aggregative level, the transport sector shows the highest growth of overall energy demand. For the given growth rate of GDP, the ownership of cars, a comparatively high energy-intensive transport mode, is estimated to increase from 39 vehicles/1000 person to 260 vehicles/1000 person. This trend may be referred to as moderate economic growth, increasing transportation demand due to improved incomes and sustaining economic growth. The rising of the total energy demand can result from enhanced lifestyle, urbanization, and economic activities.

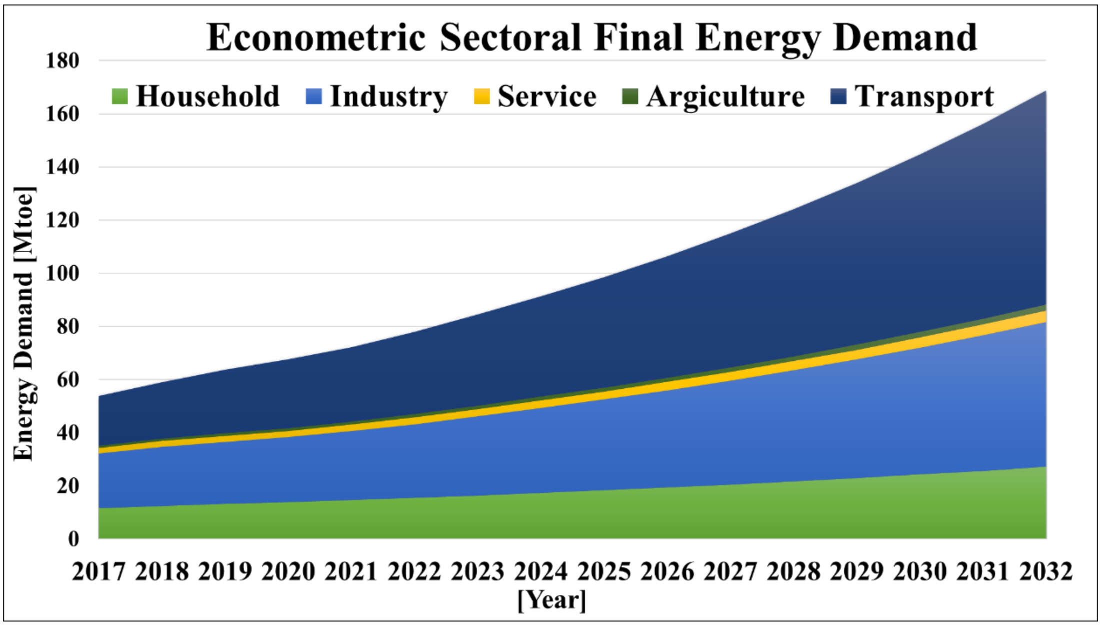


Figure 5.2. Results for sectoral energy projections from Econometric Model

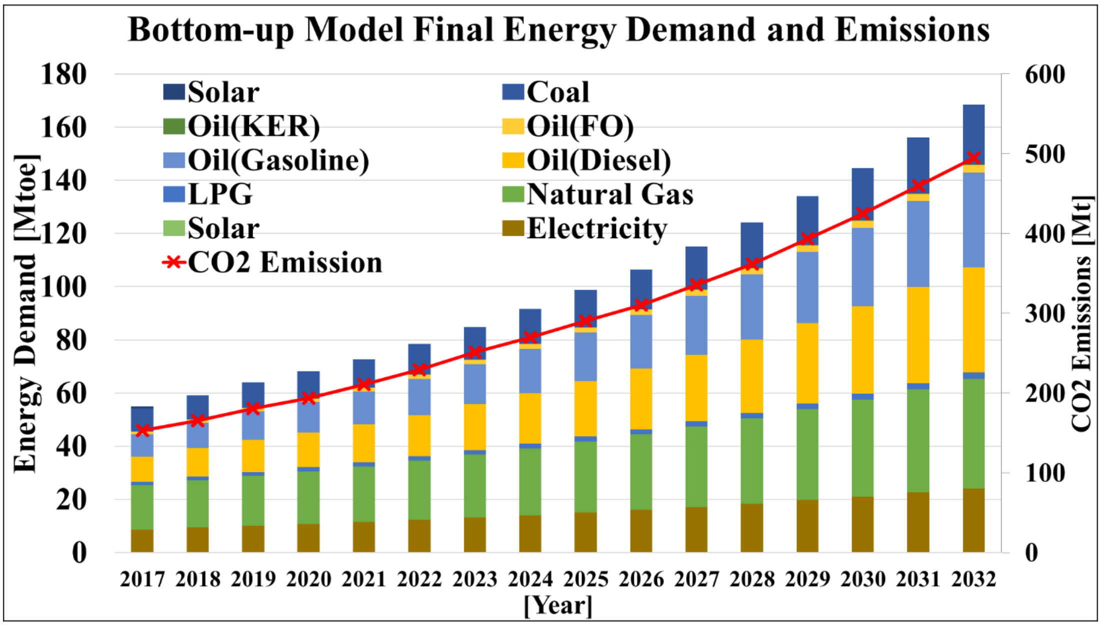


Figure 5.3. Disaggregated energy of demand along with CO_2 emissions from the bottom-up demand model

The electricity demand is expected to increase from its current 8.70 Mtoe [106.7 TWh] to 24.19 Mtoe [297.2 TWh], with an annual average growth rate of 6.60%. The results are comparable to other recent studies. The NTDC [9] projected 303.55 TWh for the year 2032–33, Miraj et al. [13] estimated 330.1 TWh for the year 2030, Gul and Qureshi [19] projected 368 TWh in 2030, and Perwaiz et al. [53] 312 TWh in 2032.

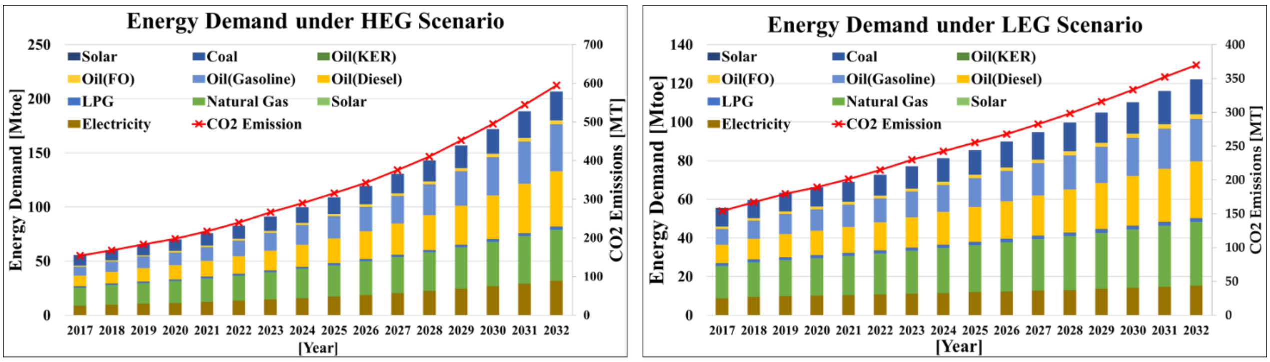
Natural gas demand is expected to grow at an annual average rate of 5.85%. The results of natural gas demand forecasting by the Oil and Gas Regulatory Authority (OGRA) [48] showed a yearly growth rate of 4.13% until 2028, which is lower than this study. The demand for other fuels, i.e., gasoline, HSD, FO, coal, LPG, and kerosene oil, is estimated to grow at 9.55%, 9.30%, 6.26%, 3.68%, and 4.41%, respectively, on an average annual basis. Considering the emission factor for different fuels from IPCC, CO_2 emissions are expected to increase from 153 MT to 495 MT with an annual growth rate of 7.60%.

5.2.3. Economic Scenario

First, the econometric model was used to project the sectoral aggregate energy demand that was then segregated by the bottom-up model. Figure 5.4 shows the results for energy demand for each fuel and resulting emissions. The overall energy demand and emission are 28.13% and 25.55% lower than the baseline demand in the LEG case. For HEC, the overall energy demand and emission are 21.74% and 19.71% higher than the baseline demand. Government always strives to raise the economic growth levels; the high economic growth scenario gives an idea about the estimated energy demand that will be needed to reach this level of economic growth and then sustain at that level.

5.2.4. Energy Efficiency and Conservation

The sectoral energy demand from the econometric model was adjusted for the energy-saving potential and then the bottom-up model disaggregates the energy demand computed the resulting CO_2 emissions. In year 2032, under this scenario, the overall energy demand is lowered from 169 Mtoe to 144 Mtoe (15% reduction) with respect to the reference scenario. The electricity demand is reduced by 20.5% from 24.32 Mtoe to 19.35 Mtoe. Demand side CO_2 emissions can be reduced by 15% from a reference level of 497 MT to 423 MT in year 2032. This reflects the significance of energy saving on the demand side, but its realization is constrained by the economic situation of people and country. The intervention of the government is critical to introduce policies and support the implementation of this measure.



(a) **(b)**

Figure 5.4. Energy demand and CO_2 emissions under economic scenarios

5.3. Supply-Side Analysis

5.3.1. Baseline Scenario

Figure 5.5 shows the optimum selection of power generation technologies for the given baseline scenario demand from the demand model. A significant technological change can be observed during the prediction horizon. HSD- and RLNG (CT)-based power plants are excluded from the power supply mix after the base year due to high fuel cost, and a major contribution is provided by the additional capacity installation of natural gas-based power plants. Natural gas-based power plants also started to retire gradually after 2021 and will phase out by 2024. This corresponds to the depletion of natural gas production after 2021. Imported coal shows a consistent rise from 8.3% in 2017 to 46% in 2032. Local coal contribution increases to 22.6% in the energy supply mix from 2020 to 2032. Nuclear power plants show relatively slow progress from 7.5% to 14.2% within the model horizon. RLNG-based combined-cycle power plants operate until 2022, after which they lose their economic competitiveness to local and imported coal. On the renewable side, the share of hydropower is reduced from 21.2% [2017] to 13.9% [2032]. Other than the planned deployment, the rest of the renewables are selected for a new installation, and hence their share in power generation is declined over time. Coal (local and imported) power plants are the main consideration for new capacity installations. The emissions from the generation side are increased from 55 MT to 182.3 MT. The increasing share of coal-based power generation is the main reason for such a rapid rise in emissions. The overall Levelized cost of energy (LCOE) is computed to be 7.00 Cents/kWh. The model was given the option to include storage as needed, but the flexibility provided by the other sources (mainly hydro) was sufficient to accommodate RE share, even in the subsequent scenarios involving high RE penetration.

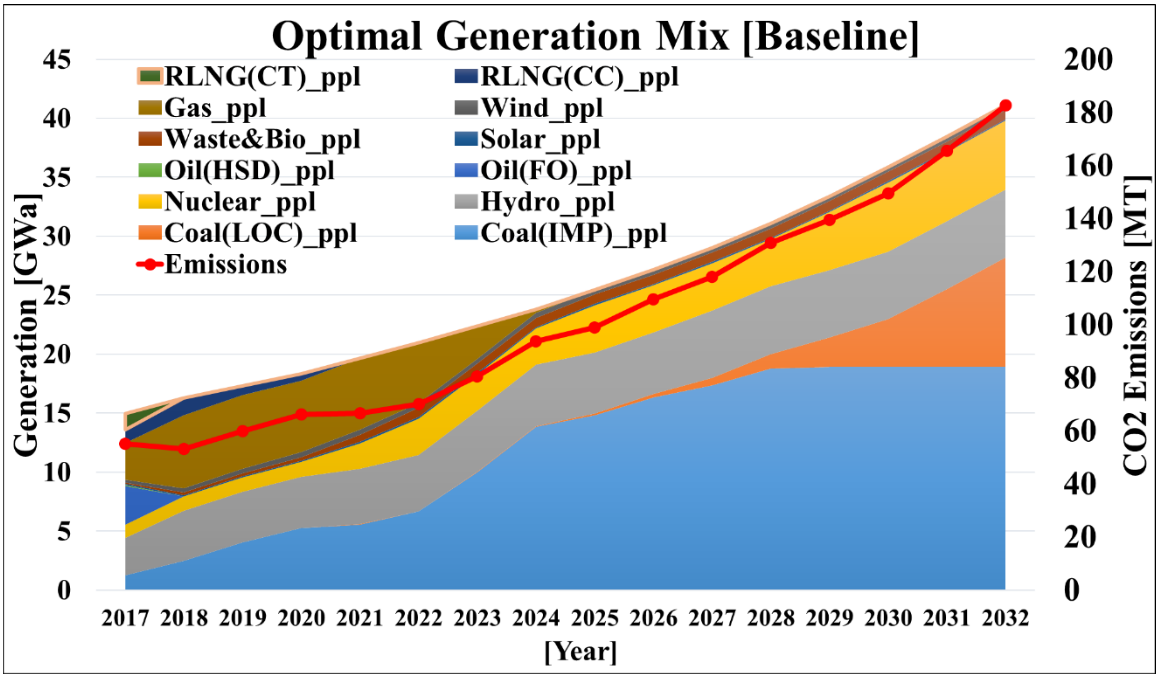


Figure 5.5. Optimal generation mix along with resulting emissions for the baseline scenario.

5.3.2. REN and NC Scenario

Figure 5.6 shows the comparison of the renewable and no coal scenarios with the baseline case. In the NC scenario, restrictions on the future installation of coal-based power plants will force the model toward significant investment in hydropower during the period of 2023–2024, solar and wind, respectively, in subsequent years, leading to a share of 62.61% in 2032.

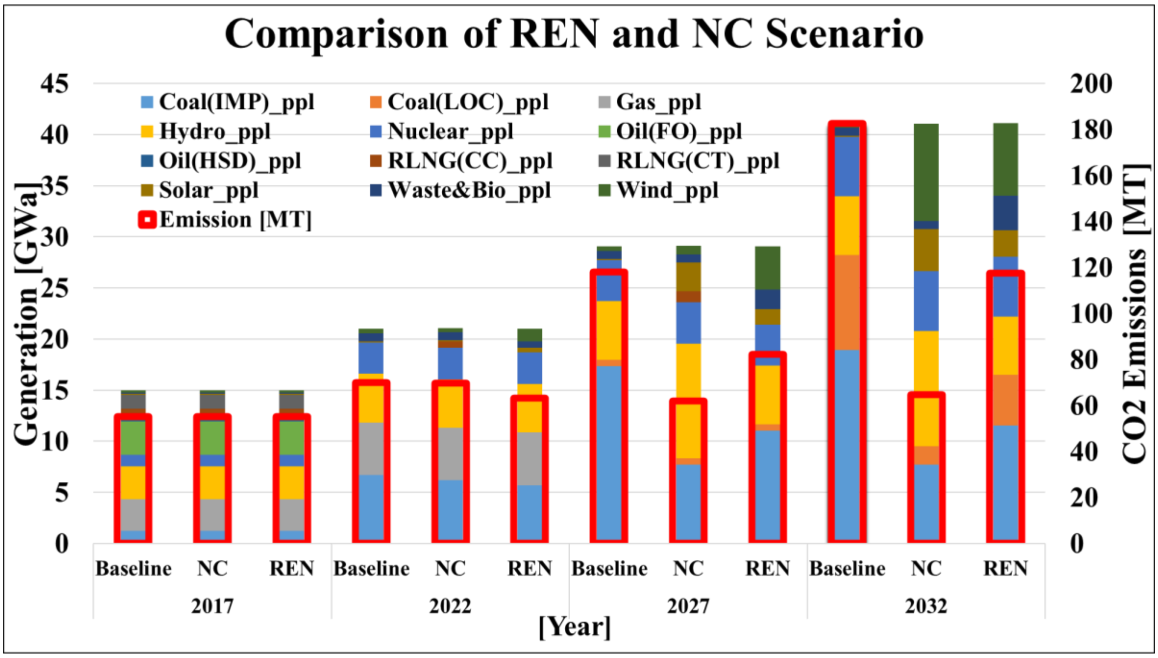


Figure 5.6. The comparison of REN and NC Scenarios with the baseline

In the REN scenario, the enhanced share of solar, wind, and waste and bio offset the installation of coal-based power plants. The rest of the power plants do not have any impact on their investment decisions. In terms of LCOE and emission reduction potential, NC is an expensive scenario with 8.00 cents/kWh but has more potential for emission reduction. For the REN scenario, the emissions are 24.48% lower than the baseline case. Table 5.6 shows the summary of emission reductions, cost, and renewable shares in the different scenarios. The impact of energy demand reduction by the demand side energy efficiency and conservation (EE&C) scenario is also analyzed on supply side and results are included in Table 5.6. This scenario leads to 18.37% reduction in annual average emissions through the model horizon. LCOE is also reduced as lower electricity demand saves capital and running expenses for generation.

Table 5.6. Summary of analysis of different scenarios on the supply side.

Scenario	Sub scenario	Average Annual Emissions [MT]	LCOE [Cents/kWh]	RE Share [%] in 2032
Baseline	-	102.5	7.00	17.16
REN	-	77.4	7.94	45.69
NC	-	63.8	8.00	62.61
EE&C	-	83.8	6.84	21.40

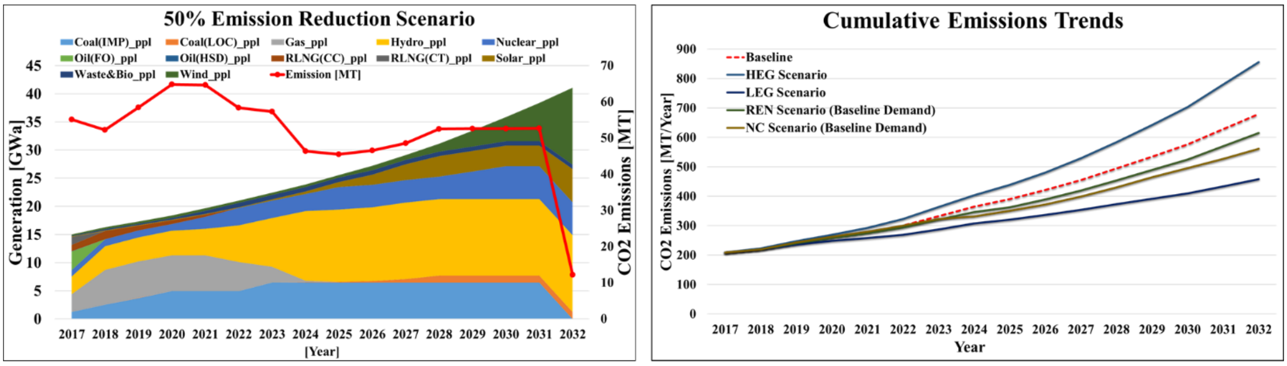
5.3.3. Emission Reduction Targets

Setting emission reduction targets will result in a sharp rise in renewable penetration and phasing out of coal-based power plants. Table 5.7 summarizes the impact of different emission-bound targets on the cost and generation mix.

Table 5.7. Sensitivity analysis of emission reduction targets.

Scenario	Sub-Scenario	Average Annual Emissions [MT]	LCOE [Cents/kWh]	RE Share [%] in 2032
Emission Targets	10%	32.47	7.36	32.47
	20%	82.0	7.60	45.12
	30%	71.7	7.70	52.92
	40%	61.5	7.87	60.92
	50%	51.2	8.48	82.74

In the strictest target (50% annual emission reduction), the renewable share is estimated to reach 82.74%, compared to 17.16% in the baseline. As a result, the contribution of imported coal to total power generation will be reduced to zero in 2032. However, local coal has a small share due to cost consideration, as shown in Figure 5.7 (a). Hydropower replaces natural gas-based power plants in 2024. In 2032, hydro and wind together account for 66% of total power generation. Hence, the LCOE is 21% higher than the baseline due to investment in comparatively expensive options.

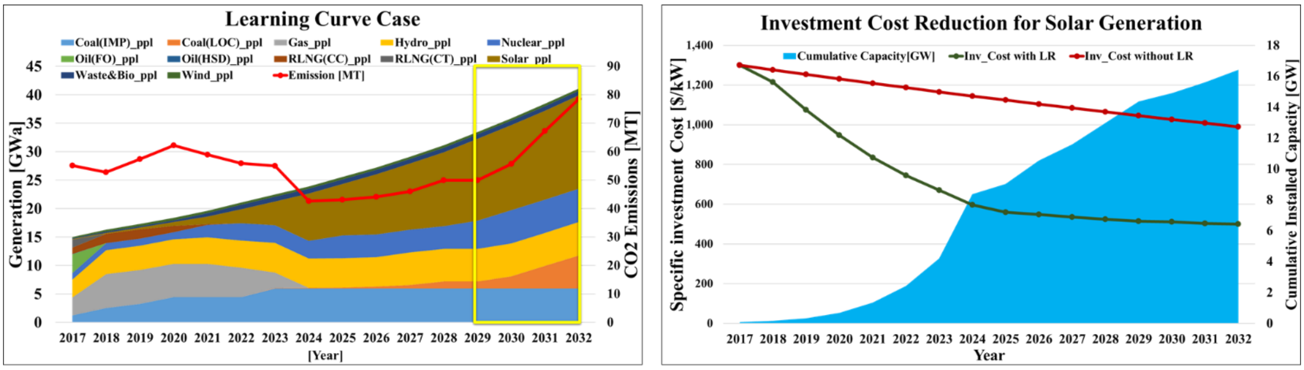


(a) (b)

Figure 5.7. (a) Generation mix and resulting CO_2 emissions for 50% reduction in emission scenario (b) Overall CO_2 emissions under different scenarios

5.3.4. Technological Learning Curves [TLC]

Figure 5.8 shows the analysis of the supply system with endogenized learning curves for baseline demand. The resulting mix shows a significant share of solar generation that is primarily due to a high learning rate (i.e., 12%) which implies each time the cumulative capacity is doubled; the specific investment cost is reduced by 12%. As the initial solar capacity is very small (i.e., 0.09 GW in 2017), the fast doubling process makes this decline in cost very rapid in the beginning and saturates as we head toward the end of the model horizon.



(a) (b)

Figure 5.8. (a) Generation mix and CO2 emissions in TLC case (b) The comparison of cost reduction of solar generation under TCL and baseline case.

Until 2023, domestic and inexpensive natural gas-based generation dominates the mix, and after that, a rapid increase in the solar capacity installation by 19.8GW is observed during year 2024. CO_2 emission also declined sharply during the same period same time, remains stables until 2029 and then start to increase from there on as highlighted in box on Figure 5.8 (a). This phenomenon can be explained as follow. As the solar requires flexibility from the system, rapid growth in its generation from year 2023 causes a gradual decline in overall system flexibility that eventually becomes zero in 2030. Solar contribution is highest, i.e., 42.9% in year 2029 and flexibility constraint forces the reduction in this contribution to 39.9% in year 2032. This reduction is compensated by the local coal-based generation that jumps from its level of 0.6% in year 2029 to 14.1% in 2032. The sharp increase in CO_2 emissions is the result of enhanced coal generation during last years. LCOE, annual average emission and RE share (in year 2032) are 6.97 [Cents/kWh], 54.7 MT/year and 57%, respectively, in the TLC case, which is better as compared to the baseline case without the inclusion of learning curves. Excluding the impact of increased solar penetration and flexibility forced local coal-based generation, the other technologies perform quite similar to the baseline case.

5.4. Integrated Demand-Supply Scenarios Analysis

Integrated energy modeling, used in this study, combines the effect of macrolevel demand analysis with its bottom-up supply dynamics, considering the technological details and constraints. Such a modeling approach may be helpful to assess the overall outlook of energy systems under a wide range of policies, targets, and constraints on either the demand or supply side. The proposed approach should not be perceived as an alternative, but rather as an intermediary step to more traditional and comprehensive energy-related models. This model analysis, which is dynamic and consisting of three phases (top-down and bottom-up on the demand side and bottom-up on the supply side), can be applied for assessing the consistency of future scenarios and policy requirements to reduce energy intensity while simultaneously promoting the cost-efficient use of sustainable (i.e., renewable) energy sources in Pakistan. The implications of this type of analysis may involve the evaluation of various energy sector-related frameworks planned in the National Climate Change Policy introduced by the Government of Pakistan in 2012 aimed at curbing climate change impacts. Figure 5.7 (b) presents the cumulative (demand- and supply-side combined) emissions trends under different scenarios. For supply-side scenarios, the baseline demand is considered. In demand-side scenarios, the emissions contribution from the supply side is more significant than the demand side. For example, in high economic growth (HEG), the cumulative emissions are increased at an annual average of 14.94%, whereas the demand and supply side show an increased rate of 10.51% and 27.76%, respectively. This quantification and evaluation can cover other areas, such as resource explorations, regional energy trade, improvement in energy efficiency, rural electrification, structural reforms, and electrification of traditional fossil fuel-based applications in the household and transport sectors.

5.5. Challenges and Opportunities

Pakistan is an underdeveloped country; its government is always striving to intervene through various policies on the economic front to raise the level of economic activity and consequently the wellbeing of the public. Based on the analysis of energy demand in this study, energy demand is a key driver of economic growth, both on the production and consumption sides, and thus has significant economic, social, and environmental impacts following the baseline trend. The analysis and projection of future demand under different scenarios conducted in this study may help the government to be well prepared to intervene in advance with policy measures to foresee growing demand and counter its resulting environmental impacts under different levels of economic activity growth. The improved economic situation may help offset reasonable investments made on the demand side to reduce carbon footprints, such as improvement in energy efficiency. The sectoral analysis of demand can help estimate the overall demand impact of emphasizing specifically, i.e., the low energy-intensive sector. For the same level of economic activity, the energy demand drastically differs as the economic structure changes.

On the supply side, policy interventions based on the Renewable Policy 2019 by the Alternate Energy Development Board (REN Scenario) and restrictions on future coal-based power generation (NC Scenario) suggest the NC scenario as a more practical option in reducing emissions, although it has its economic implications. The coal phase-out will be compensated by high-capacity investments in renewables (hydro, wind, and solar) and raising the level of domestic energy reliance. For example, under this scenario, the capacity of the hydro power plant is estimated to reach a level of 23.22 GW in 2032, including a large additional capacity of 7.54 GW in 2024. The high-capacity investment in hydropower can assist the power system with absorbing more of the other less flexible renewable sources. Solar and wind power will require a total installed capacity of 19.69 GW and 29.97 GW in 2032.

On the other hand, the nuclear power contribution is not quite significant compared to the baseline scenario. These are critical policy decisions that the government must consider while pursuing such ambitious environmental protection and energy security enhancement targets. In the short run, if the policy decisions are made to invest more in RLNG-based power plants, with less environmental impact than coal-based plants, to react to coal restrictions, it will cause an increased burden on foreign exchange, circular debt, and the cost of electricity. These are the different trade-offs that the government needs to be considered to realize a better energy system and management of resources.

Until 2032, a renewable share of 20% by 2025 and 30% by 2030 (REN Scenario) will replace coal-based (local and imported) generation. The rest of the options do not contribute to this change significantly. However, due to the reliability limitation of high renewable penetration, the overall required system capacity in 2032 will be 77.45 GW, which is 47% more than the baseline scenario. This is one of the main challenges to deploying renewable for the same amount of electricity generation, such that the demand for capacity and storage become significant. To avoid the curtailment of renewable energy, a special analysis of the correlation of renewable generation with the electricity demand profile and the design of special demand response programs must help to prepare an operational/dispatch plan. For this model horizon, the existing generation options are sufficient to provide the flexibility demanded by renewable sources. However, as we head into the future with similar targets of renewable energy, this flexibility requirement will become very critical and may require the exploration of different kinds of storage options or investment in conventional flexible options, such as RLNG-based power plants.

Chapter 6. Conclusions and future work

This study aimed to introduce a comprehensive and integrated energy model for Pakistan to project energy demand and optimize the supply mix under different scenario options. The research emphasized developing an integrated energy modeling framework in order to have a comprehensive analysis of the energy sector in Pakistan, which may lead to effective policy and decision-making. Reliable forecasting of economic parameters in the short and long term can help obtain better energy demand projections. By analyzing energy supply and demand and carbon emission data for the scenarios, it is obvious that energy demand will continue to grow up to 2030, resulting from enhanced lifestyles, urbanization, and economic activities in Pakistan. According to the results, in the baseline case, the energy demand is estimated to increase from 8.70 Mtoe [106.7 TWh] to 24.19 Mtoe [297.2 TWh], with an annual average growth rate of 6.60%. The total energy demand and emission are estimated to be 21.74% and 19.71% higher in the HEG scenario and, on the other hand, 28.13% and 25.55% lower in the LEG scenario, compared to the baseline scenario. On the supply side, coal-based power generation is the most economical option but has the worst environmental impact. The depletion of domestic natural gas production will result in a substantial change on the power generation side. A policy to ban the installation of new coal-based power plants (i.e., NC scenario) reduces average emissions by 37.4%, which requires an increase in the share of renewable energy in power generation up to 62%. In the REN scenario, increasing the share of renewable energy power generation by 2030 can help to reduce emissions by 24%, which is accompanied by a 13% increase in the total cost of power generation. The results of this study indicate that the REN and NC scenarios meet most of Pakistan's economic and environmental requirements. Following the proposed scenarios, Pakistan's energy supply system could be independent of imports, thus reducing both costs and pollution. However, strict environmental regulation will demand renewable energy penetration and investment in the power sector. Decarbonization is the basic characteristic of the structural changes to energy supply and demand in Pakistan. Renewable energies will replace coal as the largest energy source prior to 2030 in a 50% reduction scenario. In the context of environmental protection, the significant achievements of low-pollution strategies in Pakistan's energy system can be obtained through concurrent improvements on both the supply and demand sides. In this context, the application of energy systems modeling with further policy formulation would be needed to test various hypotheses and policy perspectives. Future research will involve the following areas.

- Expending the model horizon to accommodate advanced and prospective carbon mitigation technologies (i.e., carbon capture and utilization, coal liquefaction);
- Evaluation of capacity value or contribution (based on the correlation of generation with load profile) for renewable sources.
- Enhancement of temporal resolution to include more details on operation and load patterns (i.e., seasonality).
- Analysis of conventional schemes, various storage options, and demand response programs to match the flexibility requirements in high penetration of renewable energy sources in the future.
- Updating the estimation of the trend of extraction of local resources.
- Estimating the future costs of local resources and imported energy commodities, especially the analysis of imported LNG in case of the depletion of domestic natural gas reserves.

- Study of more scenarios on the demand and supply sides, such as the impact of fuel switching (from traditional biomass to modern and clean options) in the residential sector.

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