MULTIPLE OBJECTIVE ENERGY AND ENVIRONMENTAL POLICY ANALYSIS

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ABSTRACT

MULTIPLE OBJECTIVE ENERGY AND ENVIRONMENTAL POLICY ANALYSIS

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Energy policy research studies need to consider several objectives since the energy sector is closely related with economy, environmental quality, and supply security. Before 70s, studies were based on a one-way relationship between the energy sector and the economy, and they tried to estimate energy demand given the level of economic activity. However, the Arabic oil embargo, which doubled the energy prices, resulted in an economic crisis since energy is an intermediate good which is used in almost all production activities. These events brought about the consideration of a two-way relationship between the energy sector and economy. Furthermore, most greenhouse gasses (GHG) that cause global warming are emitted by energy generation or consumption activities. Consequently, the level of energy generation and resource types used directly affect the level of GHG emissions. Another point to consider on energy studies is the security of energy resources. During the Arab oil embargo, countries that import oil from Arabic countries were stranded. Therefore, whether to supply energy resources domestically or not is another important question. Above-mentioned concerns point out the requirement of a multi objective decision support system that combines engineering and economics perspectives. The main purpose of this study is the development of such a decision support system.

For this purpose, the impact of GHG emissions and foreign energy dependence restrictions on economic welfare is investigated by using a mathematical model that represents economy and energy sector together. This is accomplished by integrating a one-sector neoclassic growth framework with a detailed activity analysis model representing energy sector and environmental consequences. Then, level of economic welfare corresponding to different level of emissions and energy dependence is evaluated and relationship between these objectives is presented. In addition to relationship between objectives, reaction of economy and energy sector to the restrictions is investigated so that how a country meets specific goals is presented. Literature studying energy and environmental policy analysis is based on quantification of economic burden resulting from commitment to certain international agreements such as the Kyoto protocol. On the other hand, this study explores the level of economic burden and change in energy sector for different levels of emission and foreign energy dependence restrictions. Moreover, robust policies against world energy price shocks are searched for. This knowledge is expected to help decision makers to make informed strategic decisions.

Keywords: Energy Policy, Multiple Criteria Decision Making, Climate Change

ÖZ

ÇOK AMAÇLI ENERJİ VE ÇEVRE POLİTİKALARI ANALİZİ

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Enerji politikalarını araştırmak üzere yapılan çalışmalar birçok amacın aynı anda sağlanmaya çalışıldığı çalışmalardır. Bunun sebebi de bu sektörün ülkelerin ekonomisi, çevre kalitesi, enerji kaynaklarının güvenliği gibi birçok konu ile ilişkili olmasıdır. 70'li yılların öncesinde yapılan araştırmalar ekonominin enerji talebi yarattığı tek yönlü bir ilişkiyi değerlendirmekteydi. Ancak, 1973 Arap petrol ambargosu sonucunda enerji fiyatlarının iki misline çıkması ile yaşanan ekonomik şok, enerji sektörü ve ekonomi arasındaki çift yönlü ilişkiyi ortaya koydu. Bunun sebebi enerjinin hemen hemen tüm iktisadi faaliyetlerde girdi olarak kullanılmasıdır. Ayrıca küresel ısınmaya sebep olan sera gazı salınımlarının birçoğu enerji üretim ya da tüketim faaliyetleri sırasında açığa çıkmaktadır. Dolayısı ile, ne kadar ve hangi aktiviteler aracılığı ile enerji üretildiği, sera gazı salınım miktarlarını doğrudan etkilemektedir. Enerji politikaları oluşturulurken dikkate alınması gereken bir diğer nokta enerji kaynaklarının güvenliğidir. Arap petrol ambargosu sırasında bu ülkelerden pertol ithal eden ülkeler zor durumda kalmıştır. Dolayısıyla enerji kaynaklarının ne ölçüde ülke içinden karşılandığı önemli bir konudur. Yukarıda belirtilenler, ülkelerin enerji politikalarının değerlendirilmesinde mühendislik ve iktisat bakış açılarının birlikte ele alındığı, çok amaçlı bir karar destek sisteminin yararını göstermektedir. Bu çalışmada, böylesi bir karar destek sisteminin oluşturulması amaçlanmaktadır. Bu amaç doğrultusunda kullanılan model neoklasik bir büyüme şablonu ile enerji sektörü ve enerji sektörünün çevreye etkisini temsil eden detaylı bir aktivite analiz modelinin birleştirilmesi ile elde edilmiştir. Daha sonra değişik sera gazı salınımı ve enerjide dışa bağımlılık miktarlarına karşılık gelen ekonomik aktivite hesaplanmış ve bu kriterler arasındaki etkileşim gösterilmiştir. Ayrıca belirli kısıtlara karşı enerji sektörü ve ekonominin tepkisi incelenerek belirli amaçlara ne şekilde ulaşıldığı da ortaya konmuştur. Literatürde enerji ve çevre politikaları konusunda yapılan çalışmalar belirli uluslararası antlaşmaların sonuçlarını incelerken, bu çalışma farklı seviyedeki birçok kısıt için ekonomik sonuçları araştırmaktadır. Ek olarak Dünya enerji fiyatlarındaki değişimlerden az etkilenecek politikaların neler olduğu incelenmiştir. Bu bilgi, stratejik karar vericilerin daha bilgili şekilde en uygun kararları vermelerine destek verecektir.

Anahtar Kelimeler: Enerji Politikaları, Çok Amaçlı Karar Verme, Küresel Isınma

For those who would do much better if they had my opportunities

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ABBREVATIONS

BAU	Business as Usual
CCS	Carbon Capture and Storage
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CH_4	Methane
CO_2	Carbon Dioxide
GWh	Giga watt hours
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Giga watt hours
IPCC	International Panel on Climate Change
Ktoe	Thousand ton of petrol equivalent
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Value Theory
MCDM	Multi Criteria Decision Making
N_2O	Nitrous Oxide
TL	Turkish Lira
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization
WTP	Willingness to Pay

CHAPTER 1

INTRODUCTION

Global climate change is a serious problem for the future of the earth and humanity. It is known that the earth surface temperatures of the last three decades were successively the warmest ones since 1850. Moreover, the globally averaged combined ocean and surface temperature has increased from 0.65 to 1.06 centigrade degrees from 1880 to 2012. As a result, global mean sea level rose by 0.19 meters between 1901 and 2010. The rate of sea level rise from mid-19th century on is larger than the rate of the previous two millennia [1]. These changes have significant impacts on natural and human systems such as increased number of extreme events and changes in living patterns of many species. Even if the emission of GHGs, which is the primary reason of climate change, is stopped, the earth surface temperature is expected to continue increasing. However, higher amount of GHG emissions, which end up with higher earth surface temperature, increases the risk of irreversible changes in the earth system [1]. These facts about global warming indicated the importance of studies regarding abatement of GHG emissions.

The increasing concerns on global climate change started with [2], which proposed a plot, known as Keeling Curve. This study showed the increase in carbon dioxide concentrations in the atmosphere. During 70s and 80s, computational power increased substantially, which made it possible to use more complex models. Therefore, it was possible to make more precise predictions on global climate change. The resulting scientific findings on global climate change transformed into public awareness during 80s. The emerging public opinion led to the establishment of Intergovernmental Panel on Climate Change (IPCC) in 1988. IPCC was founded by United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO) in order to provide a clear scientific knowledge on global warming and its environmental and socio-economic impacts [3]. Then, Rio Summit was signed in 1992. Although it was not binding to set limitations on GHGs, it proposed an agenda to negotiate timetables, which resulted in Kyoto Protocol in 1997 [4]. Its main goal is the "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [5]. It assigned different responsibilities to different countries. Reduction of emission levels were assigned to developed countries as they are historically responsible for climate change. Although United States, China and India did not sign the treaty, Kyoto Protocol is a very important step as it imposes restrictions on emission levels for signatory parties. International negotiations on climate change continued after the Kyoto Protocol which ended up with Bali Action Plan in 2007. Bali Action Plan, which is an outcome of United Nations Framework Convention on Climate Change talks, concerns the actions to be taken after 2012.

The increasing level of GHG emissions is attributed mainly to increasing level of energy generation or consumption activities due to increasing level of economic activities. Therefore, increasing energy efficiency or using more environmentally-friendly energy resources are the main methods of reducing GHG emissions. This fact indicates the close relationship between energy sector and environmental objectives. Another issue closely related with energy sector is the economic performance of a country. Although the share of the energy sector within the economy can be limited, it is used as an intermediate input to almost all economic activities. For that reason, economy of a country can be affected by disturbances in energy sector.

Before 1970s, studies on energy sector were mostly centered on forecasting energy demand given the level of economic activity. However, economic burden caused by four-fold increase in petrol prices in 1973, because of Arabic petroleum embargo, gave rise to considering the two way relationship between the energy sector and the economic performance of a country. Therefore, studies started to also consider the impact of changes in energy sector to functioning of the economy. Moreover, economic burden of an increase in oil price is more significant for developing countries which depend on foreign energy. As energy is imported by foreign exchange, of which most developing countries are in short, their economies are more vulnerable to these fluctuations [6].

It is expected for a functioning market mechanism to allocate economic resources optimally in normal circumstances. However, existence of environmental externalities prevents this situation. Externality is the non-market priced impact of an economic activity to a third party. For instance, air pollution caused by motor vehicles affects the health of people who are unrelated with the transportation activity. As the cost of global climate change is not charged to any agent who emits GHGs, environment is used as a free good which causes market failure. In this particular situation, government intervention to the market is required for firms to account for environmental hazards caused by their activities.

Another thing to note on preventive measures for global warming is the leakage problem. As countries impose taxes or quotas on environmentally-unfriendly economic activities, those activities simply move to tax or quota free countries. Therefore, policies to prevent global warming need the cooperation of all countries. This fact is the main reason behind multinational agreements such as Kyoto Protocol. On the other hand, each country requires quantifying the economic impact of different environmental policies for her own policy making purposes.

Energy supply security is another important issue. As energy is a strategic commodity, energy-supplying countries can insert political power on energy importing ones. Increasing the share of domestic resources is the most prominent solution to avoid such risks. Therefore, use of domestic resources can be preferred even if they are more expensive.

Given the above-mentioned concerns, energy policy decisions for a country should be designed to satisfy several objectives. Firstly, energy policies should be designed to satisfy energy needs of an economy as cheaply as possible. Secondly, energy resources used should be chosen not to cause irreversible global climate change problems. For this purpose, environmentally-friendly resources that produce less or no GHG emissions should be chosen. Lastly, energy resources should be chosen in such a way that energy supply security is established. The higher the share of domestic energy resources, the higher the supply security is for a country. However, those three objectives are generally conflicting. Environmentally-friendly energy resources are more expensive in general. Moreover, domestic energy resources of a country can be environmentally-unfriendly. Performing better in one objective can simultaneously cause deterioration in others. [7] discusses the increasing importance of quantitative tools that aim to define tradeoff analysis. Motivated by these facts, the main purpose of this study is to investigate the tradeoffs between economic welfare, level of GHG emissions, and foreign energy dependence for a developing country. Efficient set is generated by maximizing economic welfare, minimizing GHG emissions, and minimizing share of imported energy among total energy usage. Then, reaction of energy sector to different levels of quotas set on emissions is investigated. Some level of emission abatement is achieved by fuel substitutions while some is achieved by decreasing energy usage. Lastly, how the outcome of the study changes with changing world fuel prices is explored. Literature studying energy and environmental policy analysis is based on the quantification of economic burden resulting from commitment to certain international agreements such as Kyoto Protocol. On the other hand, this study explores the level of economic burden and change in the energy sector for different levels of environmental restrictions by generating the efficient frontier. In addition, minimizing foreign energy dependence objective is investigated in this study for the establishment of energy supply security.

The mathematical model used in this study is based on [8]. This modelling approach combines a one-sector neoclassical growth model to a detailed activity analysis model which represents the energy supply sector in detail. Moreover, investment, energy cost, and consumption are separated as domestic and foreign in order to observe the trade deficit as in [9]. Although the approach used in this study is generic to be applied to any developing country, the model is used to analyze the case of Turkey between years 2012 and 2038. Realistic and useful outcomes are obtained by using real data.

The outcome of the study indicates that it is very costly to decrease GHG emissions for Turkey. The economy adapts to environmental restrictions by decreasing energy use or by inter-fuel substitution. It is preferred that solid fuels and electricity to be substituted by petroleum and natural gas. The reason why electricity is perceived as an emission intensive energy type is that most of the electricity is generated by solid fuels in business as usual (BAU) scenario. In terms of electricity generation, carbon capture and storage (CCS) technology is the most important mitigation option. However, it is efficient only after massive amounts of economic burden. When the objective of supply security is considered, it is seen that some improvements are possible without significant sacrifice from other objectives. However, it is not possible to decrease foreign energy dependency of the country below 90% with acceptable consumption losses.

This thesis is organized as follows. Chapter 2 provides a brief literature review. Chapter 3 underlines the main modelling attributes and explains the general approach used. Section 4 presents macroeconomic and energy sector data used in the model. In addition, functional parameters used in the model are explained in this section. Section 5 provides the BAU scenario projections of the mathematical model used with sensitivity analysis on some important model parameters. Then, Section 6 presents results regarding emission and foreign energy dependency restrictions. Finally, Section 7 concludes the thesis and provides further research questions.

CHAPTER 2

LITERATURE REVIEW

The research questions proposed in this study require representation of the relationship among energy, economy and environment. This chapter composes of two parts: the first section discusses different modelling approaches in the representation of the relationship among energy, economy and environment. Strengths and weaknesses of different mathematical models are also underlined in this part. Once the representation of the relationship among energy, economy and environment is established, it is also important to compare alternative courses of action under multiple objectives. As mentioned above, the objectives of maximizing economic welfare, minimizing GHG emissions and minimizing dependency on foreign resources can be conflicting. The second section of this chapter briefly revises the tools of multiple criteria decision making (MCDM).

2.1 ENERGY-ECONOMY-ENVIRONMENT MODELING

This section comprises of two parts. The first part is devoted to introducing different modelling approaches for energy-economy-environment modelling. In this part, strengths and weaknesses of different approaches are underlined. Moreover, several illustrative examples are provided. The second part explains alternative modelling assumptions used in the literature. In this part, the assumptions used in this study, along with their motivations are also explained.

2.1.1 ALTERNATIVE APPROACHES TO ENERGY-ECONOMY-ENVIRONMENT MODELING

Alternative approaches for energy-economy-environment modelling are mainly categorized into four: top-down, bottom-up, hybrid and econometric approaches. Top-down modelling approach mostly focuses on representing the relationship between energy supply and selected set of economic variables, which makes them strong in terms of answering economy-wide consequences of a selected energy policy. On the other hand, bottom-up models try to find out the minimum-cost energy supply options, for a given level of energy supply. These models are especially strong in representing alternative energy supply technologies and inter-fuel substitutions, realistically. Hybrid models try to capture strengths of both the top-down and bottom-up models by integrating the two approaches. Lastly, econometric models try to explain the relationship between energy and economic variables by using tools of statistics.

2.1.1.1 TOP-DOWN MODELLING APPROACH

The most commonly used tool of the top-down approach is the Computable general equilibrium (CGE) modeling. General equilibrium theory [10] tries to find out a set of prices with supply and demand quantities which satisfy a set of equilibrium conditions in all the markets of an economy. This abstract structure is used with real data that represents the macroeconomic structure (social accounting matrix) of a country and is for policy evaluation. CGE models are based on utility maximization of households subject to their income constraints and profit maximization of producers subject to production technology. Utility maximization problem of household C is given in (1)-(2). In this problem, $g_{i,C}$ represents the consumption of good i by household C while p_i indicates the market price of good i. Income level of household C is determined by the endowments of the household. Function U is the utility function. In (2), μ_C represents the income level of household C.

$$Max\ U^C\left(g_{1,C},\ldots,g_{N,C}\right) \tag{1}$$

$s.t.$

$$\mu_C = \sum_{i=1}^{N} p_i g_{i,C} \tag{2}$$

Similarly, profit maximization problem of producer j is provided in (3)-(4). Here, p_j represents the price of good j while y_j indicates the amount of production. $x_{i,j}$ represents the quantity of intermediate good i used for the production of good j, while $v_{f,j}$ and w_f stand for primary input f used for the production of good j and price of factor f, respectively.

$$Max\ \pi_j = p_j y_j - \sum_{i=1}^{N} p_i x_{i,j} - \sum_{f=1}^{F} w_f v_{f,j} \tag{3}$$

$s.t.$

$$y_j = \phi(x_{1,j},\ldots,x_{N,j},v_{1,j},\ldots,v_{F,j}) \tag{4}$$

Material and value balance equations are also required in a CGE framework. Firstly, total production of a good must be equal to total consumption and usage of the good as an intermediate product, which can be traced from (5). Secondly, total demand for each primary factor of production must be equal to its endowment; condition represented in (6). Zero (economic) profit condition, which states that the value of any good produced should be equal to its total production cost in a perfectly competitive environment can be observed in (7). Lastly, income of household c should be equal to income of the household generated by its endowments. This equality is represented in (8), in which $\theta_{c,f}$ indicates the share of household c for factor f.

$$y_i = \sum_{j=1}^{N} x_{i,j} + \sum_{c=1}^{C} g_{i,c} \quad \forall i \tag{5}$$

$$V_f = \sum_{j=1}^{N} v_{f,j} \quad \forall f \tag{6}$$

$$p_j y_j = p_i \sum_{i=1}^{N} x_{i,j} + w_f \sum_{f=1}^{F} v_{f,j} \quad \forall j \tag{7}$$

$$\mu_C = \sum_{f=1}^{F} w_f V_f \theta_{c,f} \quad \forall c \tag{8}$$

The general framework of a CGE model emerges when the optimality conditions obtained from (1)-(4) are added to equations (5)-(8).

The framework obtained is calibrated according to data presented in the social accounting matrix of an economic region. Social accounting matrix represents the flow of economic transactions within a macroeconomy. In addition, outcome of econometric methods can be used to determine the value of selected parameters used in the production or utility functions. After calibration, the base-results of the equation system, which consists variables y_i, p_i, w_f , μ_c and $x_{i,j}$, are obtained. These results are expected to replicate the BAU scenario of an economy. Next, price or quantity disturbances are introduced to the equation system in order to investigate the corresponding response of the solution vector. Thus, it becomes possible to observe the relative impact of a policy [11].

According to research questions proposed, some other agents such as government which represents the collection of taxes and re-distribution can be introduced to a CGE framework. Moreover, it is possible to disaggregate the economy into separate sectors. For instance, energy sector can be disaggregated into sub categories when questions on environmental policy are investigated.

CGE models are widely used tools for policy analysis as they are able to show economy wide impact of a policy change by representing the economic mechanisms. In addition, they are able to evaluate the relative quantitative responses resulting from a policy change. Moreover, CGE models are capable of incorporating the behavior of heterogeneous agents via the maximization schemes of producers and consumers. On the other hand, these models lack statistical background in the standard calibration process. Besides, the results of a CGE model are sensitive to the choice of a base year. Although some approaches to alleviate these problems are proposed, these criticisms continue to exist as main pitfalls of CGE approach [12].

In sum, top-down modelling approach is used to investigate the economy wide consequences of energy or environmental policies. Under this approach, it is also possible to explore the impact on different agents or sectors within an economy. Change in gross domestic product or welfare due to environmental restrictions are the most common topics investigated by employing top-down models. However, these models generally omit explicit capital representation of the energy supply sector as they use economic variables in an aggregated manner; hence they are considered weak in representing the technological restrictions in detail. Moreover, top-down approaches are based on past data and assume rational agents so that they are also weak in representing inter-fuel substitution possibilities. As a result, top-down approaches tend to overestimate the cost of mitigation options [13].

Although general equilibrium theory for economic policy analysis has been used since [10], it was typically based on allocation of privately owned resources. It was [14], who first used general equilibrium theory for environmental externalities. [15] categorizes MIT-EPPA [16] and WORLDSCAN [17] as multiple sector general equilibrium models. GTAP-E [18] model, which is an extension of GTAP model to investigate energy related questions, can be added to this list. GEM-E3 [19] and PACE [20] are also different examples of applied general equilibrium models.

2.1.1.2 BOTTOM-UP MODELLING APPROACH

Bottom-up modelling approach tries to find out the low cost energy supply technology options for a given level of energy supply. The most commonly used method is linear programming. The main structure of bottom-up models is presented in (9)-(11). Here, vector z_t represents the level of energy activities for each time period while A_t matrix stands for technical parameters. Equation block (10) calculates the level of energy generated as a result of energy supply activities. Equation (11) indicates the minimum level of energy required which is represented by vector b_t. Vector b_t is evaluated externally in line with the needs of the economic system. Lastly, objective function, presented in (9), tries to find out the minimum cost alternative. Here, vector c_t represents the cost of energy activities.

$$\min \textstyle\sum_t [c_t][z_t] \qquad (9)$$

$s.t.$

$$[A_t][z_t] = [E_t] \qquad (10)$$

$$[E_t] \geq [b_t] \qquad (11)$$

It is possible to represent all the available processes of energy production or usage by utilizing additional constraints in this framework. Contrary to the top-down approach, the bottom up models are capable of representing technical restrictions of the energy supply sector in detail by providing the capital stock dynamics explicitly. Moreover, these models utilize cost data and availability of possible future technologies, which makes them able to capture inter-technology substitution possibilities [13]. Nevertheless, bottom-up approach lacks the advantages of top-down modelling. Models following bottom up approach are not able to represent behaviors of different agents. In addition, these models cannot explain the economy wide impact of a policy change, such as introduction of environmental taxes or quotas. [21] categorizes EFOM-ENV [22], MARKAL [23], MESSSAGE-III [24] and RETscreen [25] as bottom-up models.

2.1.1.3 HYBRID APPROACHES

Considering the strengths and weaknesses of the top-down and bottom-up approaches, integration of these has been required, also to achieve a more realistic analysis environment. Such integration is achieved in three alternative ways [26]: the first method describes the utilization of soft-link models. In this approach, two separate bottom-up and top-down model are iteratively run until their results converge. At each run, price and quantity variables regarding energy sector are passed in-between the two models. This method is criticized because of the inconsistencies between the assumptions of the two models. One of the examples of this approach can be seen in [27]. Initial examples of this method are [28], [29] and [30].

The second method of integrating these two approaches is to build hard-link models. This method uses mixed complementarity representation of general equilibrium equations of a top-down model. Kuhn-Tucker optimality conditions that originate from the optimization model of the bottom-up approach are added to this set of equations so that a complete integration is achieved [31].

The last method chooses one of the two approaches and provides a detailed representation for the specific parts of the model that is related to the research questions while using a reduced form representation of the other approach. The first example of this method is [8]. [15] categorizes [32], [33], [34], [35] and [36] as some recent examples, which provide detailed representation of the energy sector with aggregate production functions representing one sector economy.

The method utilized in this thesis follows this third tradition. It provides a detailed energy supply model and links it to a one sector neoclassical model of economic growth within an optimization framework. Detailed representation of the energy supply sector is required in order to screen the level of GHG emissions and observe inter-fuel substitutions under alternative scenarios. On the other hand, one sector economic growth model enables this study to observe the effects of energy sector policies on major economic variables and welfare through time.

2.1.1.4 ECONOMETRIC MODELS

The common weakness of the first three modelling approaches is that they lack statistical justification for their conclusions. In addition, [15] indicates that they omit macroeconomic considerations such as unemployment, financial markets, international capital flows and monetary policy. Macro econometric models are usually considered strong enough to capture, albeit partially, these concerns. Yet, econometric models draw their conclusions based on the past data where no environmental restrictions imposed by international agreements existed. Therefore, it is very difficult for these models to capture behavioral changes and resulting substitution possibilities. [37] is an example of this category of approaches. Moreover, some top-down models such as [38] and [39] have extensions to capture some financial considerations and unemployment.

2.1.2 MODELLING ASSUMPTIONS

As environmental consequences result from human activities that increase over time, any approach dealing with this issue requires intertemporal features. Therefore, specification of time period and length of planning horizon should be determined with respect to aim of the study. As different objectives are introduced, the growth path of the model deviates from BAU scenario through the adjustment mechanisms of the model. Choice of long time units, such as five years, can lead to miss out the adjustment dynamics. On the other hand, choice of very short time units, such as one month, will not contribute to better decision making, whilst introducing computational complexities. As a result of these discussions, one year is chosen as the time unit for the model utilized in this thesis.

Choice of the length of planning horizon is another important attribute. Different types of reactions to environmental constraints are expected for different planning horizons. If planning horizon is short, economy will react to environmental constraints mainly by decreasing consumption, because these constraints will impose some restrictions on energy related activities. In the medium run, switching between fuel types will be possible to satisfy environmental concerns without economic sacrifice. In the long run, introduction of new environmentally friendly technologies is possible as there is enough time for investment. These technologies, such as CCS, are not economically competitive under BAU scenario; however, environmental constraints can make them competitive. Two types of CCS technology is investigated in this thesis, which are CCS combined with hard coal and CCS combined with lignite. As the planning horizon is extended, several types of uncertainties emerge. For instance, it becomes very difficult to predict which technologies will be used to generate electricity a century later [15]. Given these concerns, this study, which uses year 2012 as base, makes predictions until year 2038. Actually, the mathematical model is run up until year 2040; however, results regarding last two years are not presented due to end of horizon distortions.

Another attribute to consider is the geographical coverage of the approach, which can be either global or regional. As the global climate change is a result of GHGs regardless of where they are emitted, a global model is required in order to investigate the physical changes on the earth. For instance, a global model will be required in order to predict the changes in the temperature of the earth’s surface with respect to different environmental policies. Moreover, it is possible to have some feedback effects from environmental changes to economy in these models. For instance, economic productivity can decrease in relation to the global climate change and this interaction can be represented in the global models. [40] uses estimates of global environmental damage in the production function in order to incorporate regarding productivity losses.

Nevertheless, this thesis utilizes a regional model, for the aim of this study is to investigate the economic cost of environmental and foreign energy dependence restrictions for a single developing country. Working with a regional model enables a detailed representation of a specific country. The general approach proposed is calibrated to data of Turkey in order to investigate the validity of the results. Since contribution of Turkey alone to global climate change is limited, it is not possible to evaluate the physical climate change consequences because of emissions originated from Turkey. Similarly, the feedback effects from environmental changes to productivity of the country cannot be analyzed.

Level of sectoral disaggregation is another important issue which should be decided during modelling design. Representing the economy of a country with higher number of sectors increases the level of realism. On the other hand, it is known that reliability of aggregated variables is higher. Working in a dynamic framework where uncertainties are high regarding future parameters, number of sectors which is possible to represent thoroughly decreases. Therefore, static CGE models in the literature consist of higher number of sectors than dynamic CGE models. Optimization models use one aggregate economic sector in general. One exception is [41] which uses five sectors. On the other hand, considering the research questions proposed in this study, sectoral disaggregation is not required.

How capital stock accumulation behavior adapts to policy changes is also an important modelling assumption. Usually, it is assumed that new capital investments are perfectly flexible. However, change in installed capital is treated in two different ways: putty-clay and putty-putty formulations. The first formulation indicates a flexibility regarding new investments, while the second one stands for flexibility of the existing capital stock. Soft putty represents perfect flexibility while its hardened form, clay indicates no flexibility. Putty-putty formulation assumes that both the installed capital stock and new investments are able to reconfigure according to changing prices and technology availability. On the other hand, putty-clay formulation assumes that new investments are flexible while capital stock is not. Putty-putty setting can lead to misleading results with short or medium planning horizons as it assumes perfect flexibility for the existing capital. A mathematical model with putty-putty assumption can substitute existing technologies with new ones according faster than what can be achieved in reality [15]. Therefore, this study uses putty-clay approach in order to represent restrictions imposed by the availability of technological change.

Mathematical models used for energy and environmental policy analysis can also be separated into two according to how they treat future. Some models assume that all future parameters are known and the decision maker tries to achieve her goals for the entire planning horizon; defines the state of perfect foresight. In myopic models, the decision maker makes her decisions on a period by period basis with limited information about future. Therefore, models with perfect foresight assumption end up with smaller cost for emission or any other restriction [15]. This study investigates the level of economic objectives under several constraints; therefore, following most studies on energy policy in the literature perfect foresight is assumed. All the future parameters of the model such as cost and level of emission restrictions are assumed to be known in advance.

One of the most important drivers of technological change is research and development activities. As the research questions asked in this thesis are concerned with economic variables, including foreign energy dependency and environmental restrictions, the growth path of the economy is assumed to be a by-product. The adaptation of the growth rate of the economy will result partially from increasing efficiency of energy usage due to research and development activities. Some models dealing with energy-economy-environment relationship treat research and development activities endogenously. These models change the parameters of the production function with respect to endogenously decided research and development funds. This attribute is very important for studies investigating long planning horizons. Uncertainties regarding undiscovered future energy technologies are also incorporated via such methods. On the other hand, this study investigates a medium planning horizon. Therefore, technological improvements are treated exogenously.

2.2 MULTIPLE CRITERIA DECISION MAKING LITERATURE ON ENERGY AND ENVIRONMENTAL POLICIES

In designing policies regarding energy, economy and environment; it is important to consider conflicting objectives simultaneously. Otherwise, benefits obtained from one objective can be offset by other burdens since the objectives often conflict with each other. Conventional economics literature mostly relies on a single objective, which is usually the maximization of a well-defined utility function of a representative agent. If arguments of the utility function are market valued goods so that indirect utility (therefore preferences revealed), is possible to be measured, maximization of a single objective is adequate. On the other hand, this approach is doubtful for research questions investigated in this thesis since environment is a public good instead, and not a market valued one. In this case, consumers are not able to signal their attributed value to a public good through price mechanisms of a market. Therefore, it is not possible to construct a utility function with conventional methods. However, multiple criteria decision making tools are quite appropriate. By using these tools, it is possible to compare different alternatives, which can have different level of achievements in different objectives. The classification of literature used in this part mainly draws on [42] and [43] and is constructed according to methods used for energy and environmental policies. These are dominance methods; maximin, minimax methods; value measurement methods; goal, aspiration and reference level models; and outranking methods. The first five sections of this part is devoted to explanation and discussion of each of these categories and providing examples from the literature. Part six underlines the multi criteria decision making approach adopted in this study.

2.2.1 DOMINANCE METHODS

The first group of models under the classification outlined above is named as dominance methods. The method is based on identifying non-dominated alternatives. Then, using these alternatives an efficient frontier is constructed. This is the easiest and least information requiring method among all MCDM procedures because it does not need the quantification of values. For example, the tradeoff between energy system cost and level of NO_x emissions of different policies can be investigated [44]. The level of achievement in each objective can be plotted on a Cartesian coordinate system. If all of the objectives are of minimization type, the points closest to the origin defines the set of pareto optimal solutions and efficient frontier is composed of the straight line segments connecting these points.

2.2.2 MAXIMIN, MINIMAX AND MAXIMAX METHODS

The second group consists of maximin, minimax and maximax methods. Maximin and minimax methods are convenient when the decision maker is risk averse and pessimistic about uncertainties. In maximin method, the worst probable outcome of each alternative is defined. Then, the alternative with the best poorest probable outcome is chosen. In addition, minimization of the maximum regret of not choosing an alternative in minimax method is attempted. On the other hand, maximax method is used when the decision maker is risk seeking or when it is not important which attribute is used. In order to be able to use these approaches, different objectives should be comparable. Therefore, this group of approaches is not appropriate for appraisal but most commonly used for analysis of stochastic systems.

These methods are quite appropriate for analysis of physical benefits of GHG control policies for two reasons. Firstly, high level of uncertainties exists for the evaluation of physical benefits resulting from specific GHG mitigation policies. Secondly, climate policies are usually designed in order to prevent the worst outcome, which is the irreversible climate change. An example of this method can be seen in [45]. In addition, [46] uses this method to deal with uncertainties on timing and level of emissions. However, in order for a study in energy-economy-environment field to utilize these advantages, quantification of physical changes is required. As this study omits this module for reasons explained in 2.1.2, this group of approaches is not appropriate for this study.

2.2.3 VALUE MEASUREMENT METHODS

The third category is called value measurement methods. Multi attribute value theory is one of the methods in this category, which assigns weights to each attribute. Then, weighted sum of each alternative is summed up in order to obtain a final score [47]. Multi attribute utility theory is an extension which also includes risk preferences [48]. Another method in this category is the analytical hierarchy process. In this approach, the problem is divided into decision elements, which is also divided into subgroups. Then, weights are assigned to each subgroup by pairwise comparison of decision makers. Lastly, the weighted sum of achievements of each alternative is compared to obtain the best alternative. Although this category of models is easy to implement, it is difficult to define weights [48].

One of the widely used applications of multi attribute utility theory is assigning environmental quality a monetary value, which is called as willingness to pay. This value is evaluated by polls and statistical studies such as regression analysis as in [49]. In this approach, environmental quality is modeled as a separate consumption good whose value is indicated by the value of the willingness to pay. However, reliability of willingness to pay estimation can be problematic as people tend to attribute higher value for environment while answering a questionnaire than what they are ready to pay. Besides, the policies required for prevention of irreversible environmental damages can be much more different than society’s preferences in terms of cost.

2.2.4 OUTRANKING METHOD

The fourth category of models is outranking models, which sorts alternative options by pairwise comparison. Each alternative is compared for each attribute. Then, a decision on if one of the alternatives beats the other is made, by using preference information and comparison results. Most commonly used outranking methods in energy and environmental studies are ELECTRE III [50] and PROMETHEE [51]. ELECTRE III method tries to find some concordance and discordance indices by using some thresholds for comparing alternatives. Based on these indices, alternatives are outranked. One example which uses ELECTRE III in energy and environmental decision making is [52]. On the other hand, PROMETHEE method uses value functions, such as weighted sum of attributes, to compare alternatives in pair. Then, results of pairwise comparisons are used to construct a ranking of alternatives. Application of this approach to energy problems can be seen in [53]. In general, outranking methods are used for initial screening process, which eliminates unacceptable alternatives, instead of tools to obtain final results [43].

2.2.5 GOAL, ASPIRATION AND REFERANCE LEVEL MODELS

The last category defines goal or aspiration and reference level models. There are three widely used methods in this category: goal programming, STEM and TOPSIS.

In goal programming, a level of required achievement is defined for each objective. Then, weighted sum of the level of underachievement is minimized. It is also possible to consider underachievement in different objectives lexicographically when different objectives have a hierarchy among them. One advantage of goal programming in terms of energy and environmental decision making is that it is possible to represent physical quantities in the objective function explicitly instead of damage or benefit estimates [54]. In [55], the tradeoffs between market valued and non-market valued attributes such as environmental concerns are investigated.

STEM method [56] is an interactive approach which is based on the relative distance of alternatives to ideal point. By using *tchebycheff* norm, deviation from ideal point is calculated. The proposed solution is asked to the decision maker for evaluation. Then, unsatisfactory objectives are improved by changing weights and sacrificing from other objectives. This process is repeated iteratively up until a satisfactory solution is obtained. The main weakness of this method is that it can end up with a dominated solution. [57] is an example of this method used for rural energy planning. On the other hand, TOPSIS method [58] uses closeness to ideal and anti-ideal points. It evaluates relative distance to ideal point for each alternative.

2.2.6 MULTI CRITERIA DECISION MAKING APPROACH ADOPTED IN THIS STUDY

Four of the abovementioned categories require an appraisal model in order to compare non-dominated solution alternatives. However, the modeler is not the decision maker in most of the cases for energy and environmental policy making. Therefore, it is better to represent the consequences of alternatives to the decision maker instead of suggesting one solution. Given the alternatives and their tradeoffs, the decision maker can choose the best policy [22]. Therefore, this study belongs to the dominance methods. In this paper, efficient frontier is generated for three objectives. Then, comments on the decision space are provided in order to indicate how different level of achievements is obtained in different objectives.

Multiple criteria decision making approach is used mostly for appraisal of specific energy related projects, and not for country-wide policy decisions. For instance, whether to construct a power plant at a specific site area is evaluated considering economic cost, technical attributes, environmental concerns, social acceptability, regional job creation and safety. The studies which are designed to answer country-wide energy policy decisions are usually weak to represent the impact of the energy sector to the overall economy. These studies consider the cost of energy sector as the economic attribute of energy policies without considering its impact on the functioning of the economy. In this study, tradeoffs between different objectives are indicated by using a mathematical model which represents the interactions between energy sector and economic outcomes. This study is expected to introduce the generation of an efficient frontier in energy-economy-environment policy making.

It is also possible to use weighted sum approach by changing weights while considering environmental concerns and economic welfare. However, this approach-only generates supported efficient solutions, omitting unsupported efficient solutions. ε-constraint approach is capable of capturing all efficient solutions.

Although it is beyond the scope of this study, an area that multiple criteria decision making tools are powerful and widely used is group decision making. Since valuation of non-market valued goods differs among separate agents of the society, group decision making is an appropriate tool for policy making processes related with energy, economy and environment.

CHAPTER 3

GENERAL APPROACH

This chapter presents the general approach proposed to the problem by both explaining the mathematical model and generation of the efficient frontier. The macro module uses a neoclassical growth approach which is based on production and consumption of a single type of good. The production function uses several factors of production one of which is energy aggregate. Level of supply for different type of energy resources is determined in energy module considering technological constraints. Lastly, environment module calculates the amount of GHGs emitted because of energy generation and consumption activities. The projections obtained are taken as BAU scenario. Then, restrictions on level of GHG emissions and foreign energy dependence are imposed in order to generate the efficient frontier. The first part of this chapter presents the mathematical model used in this study while the second part discusses generation of the efficient frontier.

3.1 MATHEMATICAL MODEL

The constraints of the mathematical model used in this study can be grouped into three parts, which are called the macro, energy and environment modules. In this subsection, the mathematical model will be explained with an emphasis on modelling attributes.

3.1.1 MACRO MODULE

The objective of the model is maximization of utility. This utility function is the discounted logarithm of the consumption aggregate. Consumption aggregate consists of two variables, namely consumption of foreign goods (C_t^F) and consumption of domestic goods (C_t^D) at each time period. They are aggregated by a cobb-douglas type of function, whose share parameters are scf and scd. The utility function is constructed such that it accounts for both the consumption in and after the planning horizon. After the end of the planning horizon (indicated with index T), it is assumed that the consumption level of the last year, will increase with a post horizon growth rate, g, up until infinity. The logarithm of consumption aggregate is then discounted with annual discount rate, δ. Δ_t represents the compounded discount rate for year t. The objective function of the model is given in equation 12.

$$\max \sum_{t=t_0}^{T} \Delta_t [\log(C_t^{F^{scf}} C_t^{D^{scd}})] + \frac{\Delta_{T+1} *(1+g)}{1-\frac{(1+g)}{(1+\delta)}} \log\left(C_T^{F^{scf}} C_T^{D^{scd}}\right) \qquad (12)$$

The objective function only considers economic welfare which is represented by consumption aggregate. One way to incorporate environmental concerns is to subtract level of GHG emissions multiplied by a constant which represents willingness to pay from consumption. However, this approach is weak as it is difficult to determine the preferences of a society for value of emissions abatement as indicated in Chapter 2. Therefore, level of GHG emissions is considered explicitly in this study.

The production function of the model has a nested structure, which can be seen in Figure 3.1. Firstly, capital and labor are combined with a Cobb-Douglas production function to obtain value added. Similarly, four types of energy goods - electricity, petroleum, natural gas and solid fuels, are aggregated by a Cobb-Douglas type of function. Then, value added and energy aggregate are connected by a constant elasticity of substitution function with an elasticity value of 0.4. Lastly, intermediate goods are combined with energy-value added aggregate to obtain final output.

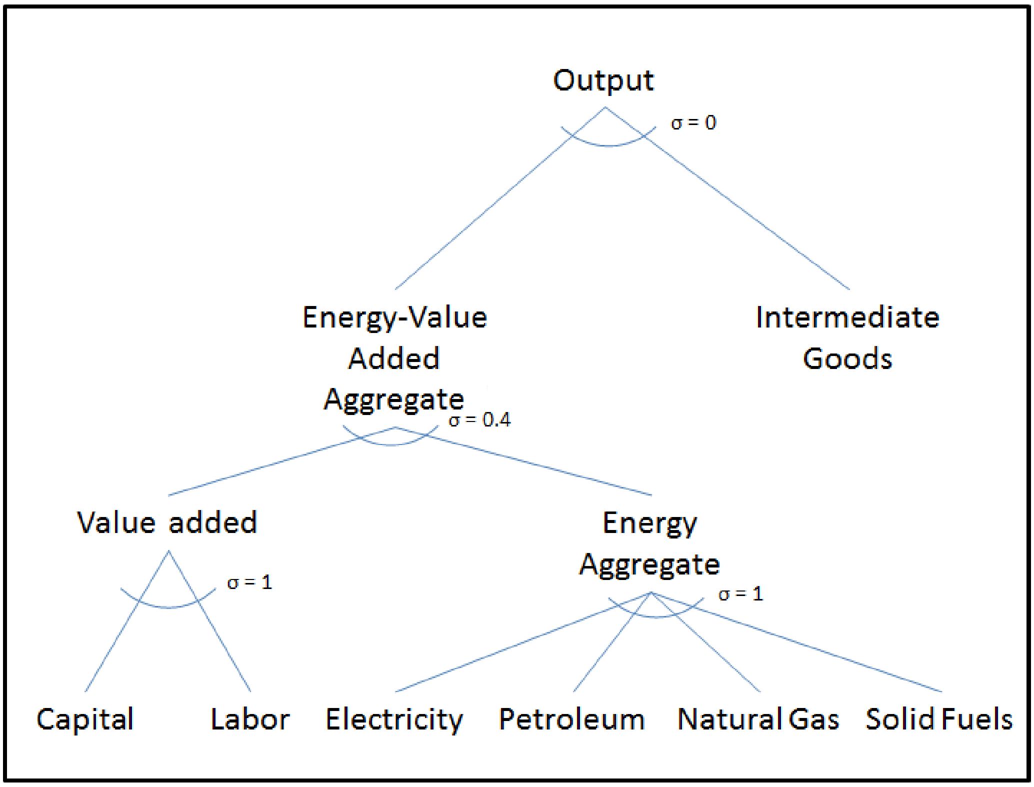

Figure 3.1. Production Nest

Equations (13)-(21) are to represent production structure of the model. Variables Y, K and L represent output, capital stock and labor force respectively. Factors of production regarding energy sector are represented as E, P, N and S, which stands for electricity, petroleum, natural gas and solid fuels respectively. As putty-clay formulation is used, it is important to separate between incremental values and surviving stocks so that letter N is added to each variable to indicate incremental values. Equations (13) and (14) define production nest mentioned in Figure 3.1. sk, sl, se, sp, sng and ss are share parameters for corresponding cobb-douglas production functions. γ_t^1 is a scale parameter for energy and value added aggregate while γ_t^2 parameter is to indicate ratio of intermediate goods to energy-value added aggregate. The ratio γ_t^1/γ_t^2 is a constant value for each time period and values of both parameters increase between consecutive time periods to represent exogenous technological improvements. Parameter ρ determines parameter σ, which is elasticity of substitution between value added and energy inputs, with equality $\sigma = 1/(1-\rho)$. This parameter is an important one regarding research questions in this study. Imposed restrictions on emissions or foreign energy dependence will affect energy sector so that ease of substitution between value added and energy aggregate is critical in terms of satisfying these restrictions with limited sacrifice from economic welfare. After defining increment in output in equations (13) and (14), equation (15) determines level of output by summing increment in output with output because of surviving stocks from previous year. Similar formulation for other factors of production is presented in equations (16)-(21). The parameter λ used in these equations is to indicate ratio of surviving stocks from year to year. Increase in labor force is equated to population projections of Turkey.

$$YN_t = \gamma_t^1\left[\alpha\left(KN_t^{sk}LN_t^{sl}\right)^{\rho} + (1-\alpha)\left(EN_t^{se}PN_t^{sp}NN_t^{sng}SN_t^{ss}\right)^{\rho}\right]^{1/\rho} \qquad \forall t \quad (13)$$

$$YN_t = \gamma_t^2 INTN_t \qquad \forall t \quad (14)$$

$$Y_t = YN_t + \lambda\, Y_{t-1} \qquad \forall t - \{t_0\} \quad (15)$$

$$K_t = KN_t + \lambda\, K_{t-1} \qquad \forall t - \{t_0\} \tag{16}$$

$$E_t = EN_t + \lambda\, E_{t-1} \qquad \forall t - \{t_0\} \tag{17}$$

$$P_t = PN_t + \lambda\, P_{t-1} \qquad \forall t - \{t_0\} \tag{18}$$

$$N_t = NN_t + \lambda\, N_{t-1} \qquad \forall t - \{t_0\} \tag{19}$$

$$S_t = SN_t + \lambda\, S_{t-1} \qquad \forall t - \{t_0\} \tag{20}$$

$$INT_t = INTN_t + \lambda\, INT_{t-1} \qquad \forall t - \{t_0\} \tag{21}$$

As it can be seen from the production structure of the mathematical model, variables representing energy supply contribute to gross output in an aggregate manner. The disaggregation regarding the energy sector is in the supply side while the demand side is aggregated as in other economic activities.

The output generated is distributed between costs of energy input (EC), intermediate goods used (INT) and gross domestic product (GDP). Then, gross domestic product is distributed between investment (INV) and consumption (C) considering current account balance, which is exports (X) subtracted by imports (M) at each year. These restrictions can be seen in equations (22)-(23). Moreover, investments are transformed into capital increment according to equation (24). Capital increment is calculated by weighted sum of last two years investment in order to represent time lag between investment and capital formation.

$$Y_t = GDP_t + EC_t + INT_t \qquad \forall t \tag{22}$$

$$GDP_t = C_t + INV_t + X_t - M_t \qquad \forall t \tag{23}$$

$$\mathrm{KN_t} = \frac{1}{3}\mathrm{INV_t} + \frac{2}{3}\,\mathrm{INV_{t-1}} \qquad \forall \mathrm{t} - \{\mathrm{t_0}\} \qquad (24)$$

The macroeconomic variables are also separated as domestic and foreign in order to represent restrictions on foreign exchange availability and foreign energy dependence. Domestic and foreign components of each variable are indicated with superscripts D and F. Equations (25)-(27) are used to represent aggregation of foreign and domestic investment, consumption and energy cost. Equation (28) determines the share of imported intermediates, shown with parameter θ, among intermediate goods used in the production function.

$$\mathrm{INV_t} = \mathrm{INV_t^D} + \mathrm{INV_t^F} \qquad \forall \mathrm{t} \qquad (25)$$

$$\mathrm{C_t} = \mathrm{C_t^D} + \mathrm{C_t^F} \qquad \forall \mathrm{t} \qquad (26)$$

$$\mathrm{EC_t} = \mathrm{EC_t^D} + \mathrm{EC_t^F} \qquad \forall \mathrm{t} \qquad (27)$$

$$\mathrm{INT_t} = \theta\,\mathrm{INT_t^F} \qquad \forall \mathrm{t} \qquad (28)$$

Level of total imports is indicated as summation of foreign investment, imported intermediates, foreign energy cost and imported consumption goods in equation (29) while inequality (30) stands for current account balance. Some level of foreign account deficit is allowed at each time period, which is determined as some percentage of corresponding year’s gross domestic product. Turkish economy has been witnessing foreign account deficit for many years, which is also true for the base year used in this study. Therefore, foreign account deficit is allowed not to introduce a macroeconomic shock to the model.

$$\mathrm{M_t} = \mathrm{INV_t^F} + \mathrm{INT_t^F} + \mathrm{EC_t^F} + \mathrm{C_t^F} \quad \forall \mathrm{t} \tag{29}$$

$$\mathrm{M_t} \leq \mathrm{X_t} + \mu\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{30}$$

Another block of restrictions imposes some restrictions on level of foreign, domestic and total investment. Levels of those variables are expected to remain within some percentage of gross domestic products of corresponding years. Therefore, constraints (31)-(36) are introduced with parameter τ, which determines allowable range of GDP for investment.

$$\mathrm{INV_t} \leq \tau^{\mathrm{T}}_{\mathrm{High}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{31}$$

$$\mathrm{INV_t^D} \leq \tau^{\mathrm{D}}_{\mathrm{High}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{32}$$

$$\mathrm{INV_t^F} \leq \tau^{\mathrm{F}}_{\mathrm{High}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{33}$$

$$\mathrm{INV_t} \geq \tau^{\mathrm{T}}_{\mathrm{Low}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{34}$$

$$\mathrm{INV_t^D} \geq \tau^{\mathrm{D}}_{\mathrm{Low}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{35}$$

$$\mathrm{INV_t^F} \geq \tau^{\mathrm{F}}_{\mathrm{Low}}\, \mathrm{GDP_t} \quad \forall \mathrm{t} \tag{36}$$

As the utility function of the model uses level of consumption in last year to represent post horizon utility, making investment has no point at the end of the planning horizon. Since increasing capital stock has no effect to increase consumption level after the end of planning horizon, the model prefers to consume as much as possible instead of investing. This problem is called as end of horizon distortions. In order to eliminate this problem, the results regarding last two year are not presented and investment level for the last year of planning horizon is fixed relative to level of gross domestic product as shown in equation (37).

$$\mathrm{INV}_T = \tau_{High}^{T}\, \mathrm{GDP}_T \qquad (37)$$

3.1.2 ENERGY MODULE

The energy module includes the set of equations which represents technological availability and conversion of energy activities in addition to estimation of energy activity costs. The energy module consists of four blocks of equations. The first block, indicated by equations (38)-(41), establishes supply and demand balance for each time period. Variables S_t, P_t, N_t and E_t represent demand for solid fuels, petroleum, natural gas and electricity for each time period t while variables dNE and dE indicate supply of non-electric and electric resources respectively. Index q represents different energy resources while setS, setP, setN and setE represent non-electric solid fuel, non-electric petroleum, non-electric natural gas and electricity generation technologies. Sets used in energy module are listed in Table 3.1.

$$S_t = \sum_{q \in setS} dNE_{qt} \quad \forall t \qquad (38)$$

$$P_t = \sum_{q \in setP} dNE_{qt} \quad \forall t \qquad (39)$$

$$N_t = \sum_{q \in setN} dNE_{qt} \quad \forall t \tag{40}$$

$$E_t = \sum_{q \in setE} dE_{qt} \qquad \forall t \tag{41}$$

Table 3.1. List of available energy generation technologies of each set used

Set Name	**Technologies Included**
SetS	Domestic Coal, Imported Coal, Lignite, Wood
SetP	Domestic Petroleum, Imported Petroleum
SetN	Natural Gas
SetE	Hydro-Dam, Hydro-River, Lignite, Petroleum, Hard Coal, Natural Gas, Nuclear, Renewables, CCS-Coal, CCS-Lignite
SetFF	Imported Coal, Imported Petroleum, Lignite, Natural Gas, Domestic Coal, Domestic Petroleum, Wood
SetBOTH	Imported Coal, Imported Petroleum, Lignite, Natural Gas
SetPotential	Hydro-Dam, Hydro-River, Renewables
SetReserve	Lignite, Domestic Coal, Domestic Petroleum
SetDNE	Domestic Coal, Domestic Petroleum, Lignite, Wood
SetDE	Lignite, CCS-Lignite
SetFNE	Imported Coal, Imported Petroleum, Natural Gas
SetFE	Imported Petroleum, Imported Coal, Natural Gas, CCS-Coal

The second block of equations calculates total use of fossil fuels for each fossil fuel resource and each time period. In addition, this block imposes resource availability on usage of these resources. They are presented in equations (42)-(43). setBOTH includes resource types which can be used for both electricity generation and non-electric consumption while setFF indicates set of all fossil fuels including wood. Parameter $\mathrm{conv_q}$ stands for thermodynamic efficiency of generating electricity from resource q.

$$\mathrm{FF_{qt} = conv_q\, dE_{qt} + dNE_{qt}} \quad \forall \mathrm{t}, \mathrm{q} \in \mathrm{setBOTH} \tag{42}$$

$$\mathrm{FF_{qt} = dNE_{qt}} \quad \forall \mathrm{t}, \mathrm{q} \in (\mathrm{setFF} \backslash \mathrm{setBOTH}) \tag{43}$$

While equation (44) imposes reserve availability restrictions for domestic resources, which is denoted with Reserve parameter, equation (45) indicates no electricity more than natural potential of the country is produced each year. Natural potential of the country is denoted with parameter Potential for each resource type.

$$\sum_{\mathrm{t=t_0}}^{\mathrm{t=T}} \mathrm{FF_{qt}} \leq \mathrm{Reserve_q}\ \mathrm{q} \in \mathrm{SetReserve} \tag{44}$$

$$\mathrm{dE_{qt}} \leq \mathrm{Potential_q}\ \ \mathrm{q} \in \mathrm{SetPotential}\ \forall \mathrm{t} \tag{45}$$

Third block is to indicate retirement and capacity increment of electricity generating units. Variable newE_{qt} represents capacity increase because of investments for each time period and each resource. In equation (46), straight line depreciation method is used for retirement of existing electricity generation capacity with respect to working life of each resource, which is represented by parameter $\mathrm{LifeTime}_{q}$.

$$\mathrm{dE}_{qt} = \mathrm{dE}_{q(t-1)} + \mathrm{newE}_{qt} - \frac{1}{\mathrm{LifeTime}_q} \mathrm{dE}_{qt_0} \quad \forall t/\{t_0\} \qquad (46)$$

$$\mathrm{newE}_{qt} \leq \mathrm{IncUP}_{qt}\, \mathrm{dE}_{q(t-1)} \quad \forall t - \{t_0\},\ q \in \mathrm{setE} \qquad (47)$$

$$\mathrm{newE}_{qt} \geq \mathrm{IncLOW}_{qt}\, \mathrm{dE}_{q(t-1)} \quad \forall t - \{t_0\},\ q \in \mathrm{setE} \qquad (48)$$

Equations (47) and (48) are to impose some restrictions on electricity generation capacity increment in order to indicate some technical constraints. For instance, it is impossible to double the hydroelectric electricity generation capacity of a country in one year as construction of a power plant requires some time. The parameters of technical constraints will be explained in the next chapter with their reasoning.

Last block of equations in energy module is to evaluate domestic and foreign costs regarding energy generation activities. There are three types of costs, which are investment, fuel and operating maintenance costs. These are represented with parameters ci, cf and co for each resource type and time, respectively. Moreover, parameter τ_{qt} is used to represent foreign share of any investment cost. Costs regarding electricity are multiplied with a coefficient, $\mathrm{coef}_{T\&D}$, to represent losses because of transmission and distribution activities.

$$EC_t^D = \sum_{q\,\in SetDNE} cf_{qt}\, dNE_{qt} + coef_{T\&D}\left\{\sum_{q\in SetDE} cf_{qt} conv_q\, dE_{qt} + \sum_{q\in setE}\left(co_{qt} + \left(1-\tau_{qt}\right)ci_{qt}\right)dE_{qt}\right\} \quad \forall t \tag{49}$$

$$EC_t^F = \sum_{q\,\in SetFNE} cf_{qt}\, dNE_{qt} + coef_{T\&D}\left\{\sum_{q\in SetFE} cf_{qt} conv_q\, dE_{qt} + \sum_{q\in setE} \tau_{qt}\, ci_{qt}\, dE_{qt}\right\} \quad \forall t \tag{50}$$

In addition, two more restrictions are added to energy module. The first one represents technical restrictions on setting up new oil wells. Equation (51) indicates that domestic petroleum supply cannot increase more than 10% of previous year's production. The equation (52) restricts usage of wood as energy supply not to harm environment.

$$\mathrm{dNE}_{\mathrm{Domestic\ Petroleum,t}} \leq 1.1\ \mathrm{dNE}_{\mathrm{Domestic\ Petroleum,(t-1)}} \quad \forall \mathrm{t} - \{\mathrm{t}_0\} \tag{51}$$

$$\mathrm{dNE}_{\mathrm{Wood,t}} \leq 5000 \quad \forall \mathrm{t} \tag{52}$$

3.1.3 ENVIRONMENT MODULE

The last module is environmental module which is used to estimate level of GHG emissions because of energy generation and consumption activities. Only three of the GHGs, which are CO_2, CH_4 and N_2O, are investigated in this study as they constitute more than 99% of total CO_2 equivalent emissions for Turkey [26]. Then the levels of emissions of these three gasses are represented in CO_2

equivalent emissions unit so that total emissions are calculated in single unit measure. Level of emissions are calculated by multiplying energy generation and consumption activities with fixed coefficients so that level of GHG emission are simply a linear transformation of activity level decided in macro economy and energy modules. Although it is difficult to represent level of CH_4 and N_2O emissions in fixed proportions with activity levels as they differ between economic sectors [3], it is common practice to use fixed proportions because of measurement difficulties and costs [27]. In addition, this study is based on single economic sector so that use of fixed proportions is expected to be an appropriate approximation.

Emission level of each GHGs for each time period ($\mathrm{Emission}_{g,t}$) is calculated in (53). In equation (53), index gg represents three GHGs while parameter ef indicates level of emission per unit usage of fossil fuel q. Then, total level of GHGs emitted during planning horizon is calculated in (54).

$$\mathrm{Emission}_{gg,t} = \sum_q \mathrm{ef}_{q,gg}\ \mathrm{FF}_{q,t} \quad \forall gg, t \tag{53}$$

$$\mathrm{TotalEmission} = \sum_t \sum_{gg} \mathrm{Emission}_{gg,t} \tag{54}$$

The macro economy module and energy module are integrated through energy cost and level of energy usage variables. However, environmental module is just to screen level of GHGs resulted from variables of energy module. It has no feedback mechanism to other modules because of geographical coverage of the study. GHGs emitted within a single country, which is at size of Turkey, is not enough to create significant global impact, which can affect economic life.

3.2 GENERATION OF THE EFFICIENT FRONTIER

The mathematical model proposed in the previous section considers economic welfare only which is measured by a function of consumption. However, the research questions asked in this study also requires consideration of level of GHG emissions and foreign energy dependence. Those objectives which are not valued by the market are accounted by imposing some restrictions on their levels so that the efficient frontier is obtained.

Firstly, only two objectives, which are maximization of economic welfare and minimization of total GHGs emitted, are considered. By imposing different level of restrictions on $\mathrm{TotalEmission}$ variable, efficient frontier is generated. In inequality (55), BaseEmission parameter indicates the total level of CO_2 equivalent emissions during the planning horizon evaluated in BAU scenario. It excludes the emissions of last two years similar to other variables due to end of horizon distortions. $\mathrm{EmissionStep}$ and ω parameters are used to generate efficient frontier. By changing the value of parameter ω from 0 to different integers, efficient frontier is constructed.

$$\mathrm{TotalEmission} \leq \mathrm{BaseEmission} - \omega\,\mathrm{EmissionStep} \qquad (55)$$

In this way, quantitative tradeoffs between the two objectives are captured. Then, how generated points in efficient frontier are achieved is investigated. The reactions of energy usage and macroeconomic variables to different levels of imposed restrictions are investigated. There are two basic reactions to an environmental restriction. Firstly, the model can decrease its energy usage. It tries to substitute value added for energy aggregate. In this reaction, substitution parameter between value added and energy aggregate is of utmost importance. This substitution means decreasing energy intensity of the economy. Secondly, the model can substitute environmentally friendly energy resources instead of existing ones. As environmentally friendly energy resources are more expensive than current ones, this requires a higher amount of investment and ends up with decreased consumption which is a sacrifice from economic welfare objective. In this reaction, cost of environmentally friendly energy sources is very important. Use of both reactions is discussed quantitatively in detail.

Secondly, the third objective, which is minimization of foreign energy dependency, is investigated. Foreign energy dependency is measured as the ratio of foreign to total energy cost in the planning horizon excluding last two years. All three objectives are considered two by two in order to generate some points on the efficient frontier by using the approach followed in the first part. Further investigation is performed for some chosen regions that perform satisfactorily in all three objectives. Then, regions where two of the three objectives are not conflicting are indicated. Moreover, the reasons of conflict or reconciliation between objectives are investigated in the decision space.

As it can be observed from the equations of the mathematical model, perfect foresight is assumed. All the technical parameters of the energy sector, economy and level of emission restrictions are assumed to be known by the decision maker at the beginning of the planning horizon. This approach disregards uncertainties on parameters. For this reason, sensitivity analysis is conducted on most critical parameters.

CHAPTER 4

PARAMETERS AND DATA USED IN THE MATHEMATICAL MODEL

The modeling approach outlined in the previous chapter is applied to Turkey in this study. Data used for this purpose can be separated into three groups: the first group consists of the variables which indicate the macroeconomic and energy sector of the country as of 2012. As the outcome of a study is heavily dependent on the base year under the modelling approach used in this study, how base year variables are obtained is explained in detail. The second group consists of technical parameters. Parameters used in utility or production functions fall in this category. In addition, energy sector cost parameters are also categorized in this group. Some of these parameters are taken from literature while some of them are calibrated according to base year data. The last group comprises of other data used in the model.

4.1 BASE YEAR DATA

Data of the base year of the model can be separated into two: macroeconomic variables and energy variables. The first part of this section explains the macroeconomic variables while the second one presents energy balance of the base year.

4.1.1 MACROECONOMIC VARIABLES

How the macroeconomic variables regarding the base year are obtained is explained in this section. All the monetary values are presented in 2012 Turkish Liras. Total consumption and investment values are obtained from [59] while their foreign parts are obtained from [60]. Consumption of domestic goods and investment on domestic capital are calculated by simply subtracting foreign components from aggregate ones. Their values are listed in Table 4.1.

Table 4.1. Consumption and Investment Values in Base Year in Millions of 2012 Turkish Liras

Variable Name	**Symbol in the Model**	**Value**
Consumption	C	1,204,705
Consumption of Imported Goods	C^F	48,070
Consumption of Domestic Goods	C^D	1,156,636
Investment	INV	287,121
Investment via purchases of Foreign Goods	INV^F	61,080
Investment via purchases of Domestic Goods	INV^D	226,042

Source: [59], [60] and the author's calculations

Energy is assumed as an intermediate good in this study. Therefore, its cost in base year is required among macroeconomic variables. Foreign and domestic components of energy cost for the base year are calculated according to (49) and (50). The construction of the cost parameters and energy use quantities are explained in the next section. Energy cost is calculated with the same set of equations for each year. Therefore, energy cost for the base year is also calculated explicitly instead of obtaining it by using input output tables of Turkey. In this way, internal validity of the model is established. Energy cost values are given in Table 4.2.

Table 4.2. Energy Cost Values in Base Year in Millions of 2012 Turkish Liras

Variable Name	**Symbol in the Model**	**Value**
Energy Cost	EC	100,464
Foreign Energy Cost	EC^F	90,682
Domestic Energy Cost	EC^D	9,782

Source: [41], [63], [64], [66] and the author’s calculations

The variables to represent the interaction of the economy with rest of the world are import and export values. Export value for the base year is taken from [60]. On the other hand, value of imports is calculated internally by summing up imports for investment, imported intermediates and consumption of foreign goods. Similar to energy cost values, this calculation is performed in order to establish internal validity. Gross domestic product value which is also equal to value added of the country is calculated by subtracting the import value from the summation of consumption, investment and exports. Then, total output value is computed by summing gross domestic product, value of intermediates and the energy cost. These values can be seen in Table 4.3.

Table 4.3. Values of Some Macroeconomic Variables in Base Year in Millions of 2012 Turkish Liras

Variable Name	**Symbol in the Model**	**Value**
Exports	X	274,493
Imports	M	424,095
Gross Domestic Product	GDP	1,342,225
Output	Y	2,857,670

Source: [60] and the author’s calculations

The foreign component of the value of intermediates is also required to thoroughly represent the production structure of the economy. However, the latest input output tables of Turkey are published in 2002 [61]. Although it is widely believed that the structure of the economy has changed significantly since then, the 2002 input output tables are used in this study. The ratio of the value of intermediates to value added is calculated as 1.129. Using this value and gross domestic product presented above, total value of intermediate goods for base year is calculated. Imported part of intermediate goods is taken from [60]. Intermediate goods calculated above include expenses for energy. However, energy activities are treated separately in this study. Therefore, value of intermediate goods and imported intermediate goods are calculated by excluding energy cost and foreign energy cost. Their values are given in Table 4.4.

Table 4.4. Selected Macroeconomic Variables in Base Year in Millions of 2012 Turkish Liras

Variable Name	**Symbol in the Model**	**Value**
Total Intermediates	Tot-Int	1,515,445
Imported Intermediates	Tot-Imp-Int	314,947
Intermediates (excluding energy)	INT	1,414,981
Imported Intermediates (excluding energy)	INTM	224,264

[60], [61] and the author’s calculations

Some of the abovementioned values are published in foreign currency. Therefore, foreign exchange value taken from [62] is used to convert these values into Turkish Liras.

4.1.2 ENERGY SECTOR BASE-YEAR VARIABLES

This section presents the energy balance of Turkey in 2012. In addition, the main assumptions about energy types considered are outlined.

The assumptions on energy balance of the country, most of which are similar to [41], can be listed as follows: all the variables regarding energy are presented in thousand tons of oil equivalent (ktoe). The energy balance table of the country is obtained from [63]. Then, it is processed according to assumptions provided below.

- Energy resources asphaltite and secondary coal are added to hard coal.
- Petroleum coke is added to petroleum.
- Animal and plant waste is added to wood.
- Geothermal heat, biomass and solar heat are ignored.
- Domestic natural gas resources are ignored.
- Bunker sales, statistical discrepancy and change in stocks are proportionally distributed between domestic production and net imports.
- Primary energy used for electricity generation is taken from [63]. The difference between total supply and primary energy used for electricity generation is assumed to be used directly for non-electric purposes.
- For hard coal and petroleum, foreign and domestic parts of non-electric consumption are distributed proportionally to their total supply amounts.
- Electricity generation by solar, wind and geothermal technologies are aggregated to form renewable resources.
- International trade of electricity is ignored.

Foreign and domestic components of energy supply with respect to resource types can be observed in Table 4.5. Consumption of energy for electricity generation and for non-electricity generation purposes is presented in Table 4.6. Table 4.6 also illustrates domestically supplied and imported parts of non-electricity consumption.

Table 4.5. Domestic and Foreign Components of Energy Supplied by Resource Types in ktoe

Resource Type	**Domestic Production**	**Imports - Exports**	**Total Supply**
Hard Coal	1655	19406	21061
Lignite	15433	0	15433
Wood	3465	0	3465
Petroleum	2889	38222	40911
Natural Gas	525	36849	37374
Renewables	1277	0	1277

Source: [63] and the author’s calculations

Table 4.6. Consumption of Energy for Electricity Production, Domestic and Foreign Components of Non-electricity Consumption by Resource Types in ktoe

Resource Type	**Electricity Production**	**Non-electricity Consumption**	**Domestically Supplied Non-electricity Consumption**	**Imported Non-electricity Consumption**
Hard Coal	8494	12567	1655	10912
Lignite	10066	5367	5367	0
Wood	65	3465	0	0
Petroleum	3744	37167	2689	34478
Natural Gas	20105	17269	0	17269
Renewables	1277	1277	0	0

Source: [63] and the author's calculations

Electricity generation amounts in 2012 with respect to energy resources are taken from [64], which can be seen in Table 4.7. The factor of 0.086 is used for conversion between gigawatt hour and thousand tons of oil equivalent units.

Table 4.7. Electricity Generation in 2012 by Resource Types in ktoe

Resource Type	**Generation Amount**
Hard Coal	2866
Lignite	2983
Wood	0
Petroleum	141
Natural Gas	8987
Renewables	581
Hydroelectricity	4976

Source: [64]

4.2 TECHNICAL PARAMETERS

This section is to present technical and cost parameters of the mathematical model used. Calibration methods and literature are used to obtain the parameters of the model. This section presents three parts defined according to type of parameters: parameters of functional forms used, cost parameters and technical parameters regarding energy generation technologies.

4.2.1 PARAMETERS OF PRODUCTION AND UTILITY FUNCTIONS

The utility function of the model is the one explained in Chapter 3. It consists of discounted logarithm of consumption aggregate. Therefore, two kinds of parameters are used in the utility function: the discount parameter and the share parameters of consumption aggregate. Following [41], discount parameter is assumed to be 0.9. This parameter indicates the time preference of consumption between two consecutive time periods. The consumption aggregate consists of consumption of foreign and domestic goods. They are aggregated by a Cobb-Douglas function. The share parameters used for consumption aggregate are calibrated by ratio of foreign and domestic consumption to total in 2012. The utility function consists of two parts. The first part represents utility during the planning horizon while the second one stands for post horizon utility. Since the consumption path is not determined by internal dynamics of the model after planning horizon, a fixed growth rate after this point is assumed. This rate is assumed to be 3.0%.

Production structure of the mathematical model is also explained in Chapter 3. The structure consists of nested production functions. Firstly, energy inputs are aggregated by a Cobb-Douglas type production function. Share parameters are calibrated according to base year energy expenses evaluated by the model. Secondly, capital and labor are aggregated in order to obtain value added. Share parameters of labor and capital are calibrated with respect to input output tables of 2002 [61]. Then, capital and labor aggregate are combined with a constant elasticity of substitution function. The elasticity of substitution parameter used in this function is one of the most critical parameters in the model and is taken from [16] as 0.4. The share parameter of this function is calibrated by using gross domestic product and energy cost evaluated internally by the model. The obtained energy and value added aggregate is combined with intermediate goods via a Leontief production function to obtain final output. The parameter indicating the relationship between intermediate goods and output is calibrated for the base year. On the other hand, the parameter indicating the relationship between value added and output is determined in a way to obtain a realistic growth path for the economy. Then, these parameters are multiplied by 1.01 in each year in order to represent an autonomous technological progress. Lastly, the survival factor for the putty-clay structure is assumed to be 0.975. The parameters of utility and production structures can be found in Table 4.8.

Table 4.8. Parameters of Utility and Production Functions

Parameter	**Symbol**	**Value**
Utility discount parameter	δ	0.9
Share parameter for domestic and foreign consumption	scd - scf	0.96 - 0.04
Post horizon growth rate	g	1.03
Share parameters between capital and labor	$sk - sl$	0.656 – 0.344
Share parameter between electricity, petroleum, natural gas and solid fuels	se- sp- sng- ss	0.337-0.452-0.144-0.068
Share parameter between value added and energy aggregate	α	0.93
Substitution parameter between value added and energy aggregate	σ	0.4
Survival Factor	λ	0.975
Technological improvement parameter	$\gamma_{t+1}^{1}/\gamma_{t}^{1}$	1.01
Output-value added ratio parameter	$\gamma_{t_0}^{1}$	5
Output-intermediates ratio parameter	$\gamma_{t_0}^{1}$	2.02

One of the inputs to production function, which is labor, is determined exogenously in the model. The payments to labor in base year are calculated by multiplying share of labor parameter (s_l) with estimated gross domestic product. Then, population projection of Turkey [65] is used to generate labor input for future time periods.

4.2.2 TECHNICAL PARAMETERS REGARDING ENERGY SECTOR

Technical parameters of the model regarding energy sector includes plant lives, thermodynamic efficiency of power plants, emission factors and available reserves of natural resources. Plant lives of different type of power plants, which are taken from [41], are illustrated in Table 4.9.

Table 4.9. Plant Lives of Different Power Plants in years

Plant Type	**Life**
Steam, Hard Coal	30
Steam, Lignite	30
Hydropower, Large Scale	40
Hydropower, Small Scale	40
Steam, Petroleum	30
Steam, Natural Gas	25
Renewables	25
Steam, CCS With Hard Coal	30
Steam, CCS Fueled with Lignite	30

Source: [41]

Thermodynamic efficiency of steam power plants is also taken from [66]. It represents the amount of electricity generated per one unit of primary energy used. Efficiency of steam type power plants are assumed to be 39% while the efficiency of power plants with CCS technology is assumed to be 34%.

Capacity factor of power plants is another technical attribute of different energy generation technologies. This parameter indicates the actual output of a power plant with respect to potential output. A power plant may not work continuously because of several reasons such as maintenance activities or natural restrictions. This parameter accounts for these breaks. Capacity factor is used for unit investment cost estimation which is explained in the next section. Capacity factor of different type of power plants, which are taken from [66], are listed in Table 4.10.

Table 4.10. Capacity Factor of Power plants

Power Plant Type	**Capacity Factor**
Steam, Hard Coal	0.75
Renewables	0.22
Steam, Lignite	0.75
Hydro Power, Large Scale	0.26
Hydro Power, Small Scale	0.3
Steam, Petroleum	0.75
Steam, Natural Gas	0.8
Nuclear	0.9
Steam, CCS with Lignite	0.75
Steam, CCS with Hard Coal	0.75

Source: [66]

Emission factors are the parameters that represent level of CO_2 equivalent emissions per unit of energy used. The emission factor data is obtained from [41], whose values are given Table 4.11. For CCS technology, CH_4 and CO_2 emissions per energy generated are expected to be one fifth of ordinary power plants [67].

Table 4.11. Emission factors for different fuel types in Gg/ktoe

Fuel Type	**Emitted Gas**	**Emission Factor (Gg/ktoe)**
Hard Coal	CO_2	3.3810
Petroleum	CO_2	3.0400
Natural Gas	CO_2	2.3370
Lignite	CO_2	4.1520
Lignite	CH_4	0.1205
Wood	CH_4	0.3681
All fuel types	NO_2	0.0170

Source: [41]

The last technical parameter regarding energy sector is reserve or potential data. Reserve parameter is used for depletable natural resources such as hard coal, lignite and petroleum products while potential parameter is used for renewable resources such as hydroelectricity and renewables. The reserve and potential data are taken from [63]. The proven reserves are used in this study. During reserve calculations, calorific value of lignite, petroleum products and hard coal are taken as 1750, 10500 and 6450 kilo calorie per kilogram. For renewable resources, capacity factor is used to calculate yearly electricity generation potential. Table 4.12 presents the reserve and potential levels.

Table 4.12. Reserve and Yearly Potential Parameters in ktoe

Resource Type	**Reserve/Potential**
Lignite	1,886,903
Petroleum Products	45,287
Hyrdoelectricity	11,127
Hard Coal	339,270
Renewables	8,055

Source: [63] and the author’s calculations

4.2.3 ENERGY COST PARAMETERS

There are mainly three types of cost parameters used in this study. The first one is fuel cost. This parameter represents the purchasing cost of imported fuels or extraction cost of domestic fuels. Purchasing cost of imported fuels is taken from [66]. In [66], the cost projections are published from 2012 to 2040 with a period unit of several years. The data is interpolated in order to find out the corresponding cost for each year. Table 4.13 gives the cost figures. Extraction cost of domestic fuels is taken from [41]. Since [41] uses 2003 Turkish Liras as base monetary value, GDP deflator is used to convert these values to 2012 Turkish Liras. Resulting values can be seen in Table 4.14.

The second main cost type is investment cost for power plants. These data is also obtained from [66]. Investment cost data is published in monetary value per installed capacity. However, the mathematical model used in this study uses level of energy supplied in order to estimate cost of energy in order not to use discrete variables which complicates the model. Therefore, an approximation is used for investment cost evaluation. Total energy to be generated during the whole life span of power plant is calculated by considering capacity factor and plant life. Then, investment cost of installed capacity is divided by total energy to be generated in order to estimate investment cost per energy supplied. The resulting values are given in Table 4.15. In addition, calculated investment costs are divided as foreign and domestic, according to energy generation technology. The parameters to represent foreign and domestic shares of investment cost are listed in Table 4.16.

Table 4.13. Cost Proj. for Imp. Fuels (Millions of 2012 Turkish Lira per ktoe)

Years	Hard Coal	Natural Gas	Petroleum	Years	Hard Coal	Natural Gas	Petroleum
2012	0.276	0.836	1.308	2027	0.328	0.936	1.558
2013	0.281	0.842	1.325	2028	0.330	0.943	1.575
2014	0.285	0.848	1.341	2029	0.333	0.950	1.592
2015	0.290	0.855	1.358	2030	0.329	0.957	1.632
2016	0.294	0.861	1.374	2031	0.332	0.965	1.649
2017	0.299	0.867	1.391	2032	0.334	0.972	1.666
2018	0.304	0.873	1.407	2033	0.336	0.979	1.683
2019	0.308	0.880	1.424	2034	0.338	0.986	1.700
2020	0.313	0.886	1.440	2035	0.335	1.000	1.740
2021	0.315	0.893	1.457	2036	0.337	1.007	1.757
2022	0.317	0.900	1.474	2037	0.339	1.015	1.774
2023	0.319	0.907	1.491	2038	0.342	1.022	1.791
2024	0.322	0.914	1.508	2039	0.344	1.029	1.808
2025	0.324	0.922	1.524	2040	0.341	1.043	1.848
2026	0.326	0.929	1.541				

Source: [66]

Table 4.14. Extraction Cost of Domestic Resources (Millions of 2012 Turkish Liras per ktoe)

Fuel Type	**Extraction Cost**
Hard Coal	0.623
Lignite	0.321
Petroleum	0.095
Wood	0.305

Source: [41]

Table 4.15. Investment Cost for Electricity Generation (Millions of 2012 Turkish Liras per ktoe)

Power Plant Type	**Investment Cost**
Steam, Hard Coal	0.181
Renewables	0.777
Steam, Lignite	0.181
Hydro Power, Large Scale	0.522
Hydro Power, Small Scale	0.805
Steam, Petroleum	0.181
Steam, Natural Gas	0.123
Nuclear	1.195
Steam, CCS with Hard Coal	0.843
Steam, CCS with Lignite	0.843

Source: [66] and the author’s calculations

Table 4.16. Foreign and Domestic Shares of Investment Cost for Electricity Generation

Power Plant Type	**Foreign Share in Investment Cost**
Steam, CCS fueled with Hard Coal	0.75
Steam, CCS fueled with Lignite	0.75
Steam, Hard Coal	0.75
Steam, Lignite	0.75
Hydro Power, Large Scale	0.50
Hydro Power, Small Scale	0.75
Steam, Petroleum	0.75
Steam, Natural Gas	0.75
Renewables	0.75
Nuclear	1.00

Source: [41]

The last main cost type is operating and maintenance cost for power plants. Similar to investment cost, the values obtained from [66] are used. The cost figures per installed capacity are transformed into cost per energy supplied by using similar approach to investment cost. The resulting values can be seen in Table 4.17.

Following [41], transmission and distribution cost for electricity is assumed to be 20% of the total electricity generation cost.

Table 4.17. Operating and Maintenance Cost for Electricity Generation (Millions of 2012 Turkish Liras per ktoe)

Power Plant Type	**Operating and Maintenance Cost**
Steam, Hard Coal	0.005
Renewables	0.020
Steam, Lignite	0.005
Hydro Power, Large Scale	0.012
Hydro Power, Small Scale	0.014
Steam, Petroleum	0.005
Steam, Natural Gas	0.005
Nuclear	0.036
Steam, CCS with Hard Coal	0.025
Steam, CCS with Lignite	0.025

Source: [66]

4.3 OTHER PARAMETERS

Firstly, level of foreign, domestic and total investment is restricted to be within some range of gross domestic product. The parameters defining these ranges which are taken from [41] are listed in Table 4.18. In addition, total investment in the last year is equated to 29% of corresponding year's gross domestic product in order to eliminate end of horizon distortions. As output to be produced after the end of horizon does not contribute to consumption, the solution of the model tries to spend as much as possible at the end of planning horizon. This problem is called as end of horizon distortion. This problem is tackled by fixing last year's investment value and eliminating the results of last two years.

Table 4.18. Parameters Defining Possible range of investment variables with respect to corresponding year's gross domestic product

Restricted Variable	**Lower Limit**	**Upper Limit**
Total Investment	0.22	0.29
Investment on Domestic Goods	0.15	0.21
Investment on Foreign Goods	0.05	0.09

Source: [41]

Change in amount of electricity generated is also restricted in order to represent technological restrictions. For instance, it is not possible to double hydroelectric power generation in one year; some construction period is required. The restrictions are as follows: for the first 8 years electricity generation increases from lignite, hard coal and CCS technology are assumed to be less than 10% of previous year’s electricity generation. Similar constraints are imposed on hydro power with 5%. Due to ease of construction, the same parameter is 100% for renewables. In order to represent, existing agreements with natural gas power plants, power generation from natural gas is assumed to increase at least 7.5% for the first 13 years while it is 4% between first 13 and 18 years of the planning horizon.

Foreign share of intermediate goods used is assumed to be constant and equal to its share in base year. This value is equal to 0.159.

According to evaluated values, Turkish economy witnessed current account deficit which is equal to 11% of gross domestic product in year. The same percentage of current account deficit is allowed in order not to introduce a shock to economy.

CHAPTER 5

BUSINESS AS USUAL SCENARIO PROJECTIONS AND SENSITIVITY ANALYSIS

This chapter of the thesis is devoted to presentation of the BAU scenario projections and of the sensitivity analysis performed. The BAU scenario tries to maximize economic welfare which is measured by a function of consumption level. It pays no attention to foreign energy dependence or environmental concerns. Then, the most critical and uncertain parameters that can affect the outcome of the study are chosen and sensitivity analysis is conducted on these parameters. It is expected to see the effects of uncertainties in this way. This chapter consists of two parts. The first part presents the BAU projections and provides some insights about the results while the second part discusses the result of sensitivity analysis.

5.1 BUSSINESS AS USUAL SCENARIO PROJECTIONS

This part explains the results of the BAU scenario. The growth path of the macroeconomic and the energy sector variables, as well as the emission level path are provided. However, it is useful to make some remarks on projections before presenting the results. First of all, the power of the modelling framework used in this study is not in representing the functioning of economy and forecasting economic growth as underlined in Chapter 2. The strength is more in accounting for the relative changes of economic welfare and energy supply in response to the imposed restrictions. Secondly, parameters used in the model are obtained by calibrating the base year data or by using results from the literature. Only a single parameter, the scale parameter between energy-value added aggregate and output, ($\gamma_{t_0}^{1}$), is chosen arbitrarily as explained in Chapter 4. This parameter value is chosen so that a realistic average yearly gross domestic product increase is obtained. The weakness of projecting realistic base results for macroeconomic variables is alleviated in this way. Once the BAU scenario results are obtained realistically, relative changes of imposed restrictions are investigated. Studies in the literature, which belong to the same family with this study, use upper and lower bounds on final energy supply. Realistic growth paths of energy variables are tried to be obtained in this way. These restrictions are not used in this study. It is believed that the cost structure and marginal productivity of energy inputs should decide the level of energy supply activities alone. Therefore, the outcome of the BAU scenario indicates what can be achieved given the cost structure instead of indicating realistic projections of the energy sector. Trying to obtain realistic results for macroeconomic variables while letting activity analysis framework determine energy sector variables seems contradicting at first glance. However, this fact results from trying to integrate economics and engineering approaches. This model shows how the energy supply should be constructed to optimize the objective function if we ignored all the other concerns.

The mathematical model, which is represented in equations (12)-(54), is a nonlinear optimization model consisting of 1,893 equations and 1,747 decision variables. Although all other constraints are linear, the problem is not a convex optimization problem because of the structure of equations (12) and (13). Due to these equations, global optimality of solutions is not guaranteed. The mathematical model is coded in GAMS environment [67] and CONOPT [68] solver is used to obtain solutions. Although global optimality is not guaranteed, the solutions under various conditions give smooth and consistent results, indicating that solutions are likely to be close to optimal. Solution time for all the scenarios studied take less than a few seconds of CPU time.

The projections of several macroeconomic variables for some years can be seen in Table 5.1. Average growth rates of gross domestic product, consumption, investment, imports, and exports are 3.6%, 3.3%, 4.8%, 7.7%, and 9.0%, respectively, which seems reasonable.

Table 5.1. Projection of Main Macroeconomic Variables in Millions of 2012 TL

	2012	**2020**	**2030**	**2038**
GDP	1,342,225	1,635,921	2,478,438	3,343,093
Consumption	1,204,705	1,350,567	2,046,123	2,759,956
Investment	287,121	474,417	718,747	969,497
Imports	424,095	1,025,780	2,114,240	2,876,878
Exports	274,493	836,717	1,827,808	2,490,518

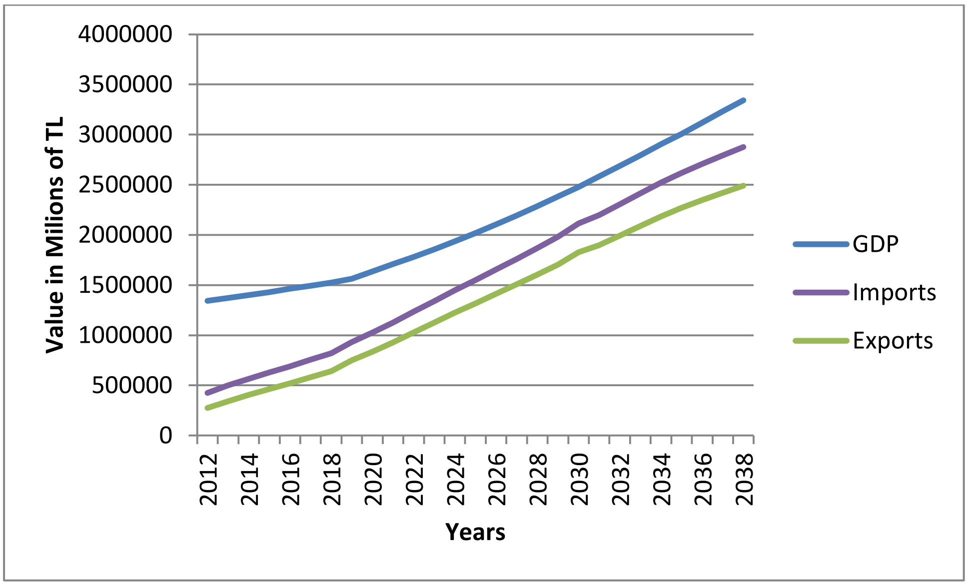

Figure 5.1. Projections of GDP, Output, and Imports

The trajectories of imports and exports are quite similar because of the current account balance constraints, which are always binding. The trajectories of consumption and investment variables can be seen in Figure 5.2. The spikes in year 2019 are because of restriction relaxations on energy sector. Similar spikes can also be seen in GDP. Up to this year, increases in electricity generation are limited in order to represent time requirement for capacity building. After this year, the model is free to increase electricity generation capacity freely. This fact indicates how technical restrictions on energy sector prevent reaching the full potential of the economy.

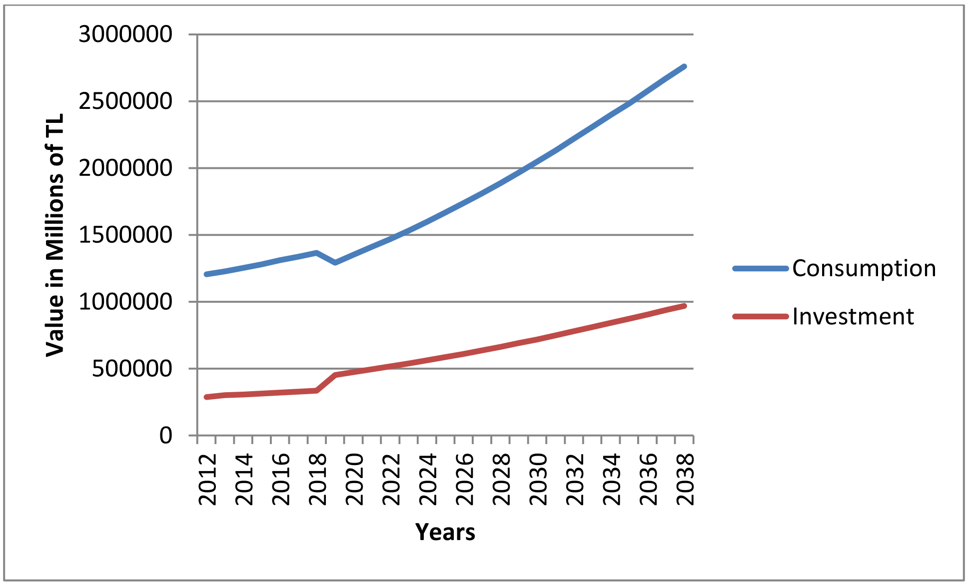

Figure 5.2. Projections of consumption and investment variables

Final energy usage values for some selected years can be seen in Table 5.2 and they are graphed in Figure 5.3. Average yearly growth rates of solid fuels, petroleum, natural gas, and electricity are 12.4%, 11.0%, 11.7%, and 13.6%, respectively. Again, the relaxation on electricity generation capacity building restrictions can be observed in year 2019.

Energy demand projections proposed in this study are higher than governmental projections. For example, average electricity demand growth rate until 2023 is cited as 5.8% per year in [70], as opposed to the projections of 13.6% of this study. As explained at the beginning of this chapter, no restrictions on growth paths of energy variables are imposed in this study so that only cost structure and marginal productivity of energy goods determined the demand for energy goods. Therefore, the energy supply projections of this thesis underline what can be achieved instead of forcing realistic results.

Table 5.2. Final Energy Usage in ktoe

	2012	**2020**	**2030**	**2038**
Solid Fuels	21,334	127,374	267,973	381,281
Petroleum	37,167	184,838	368,119	498,729
Natural Gas	17,269	94,912	195,769	271,131
Electricity	20,535	88,168	333,025	522,048

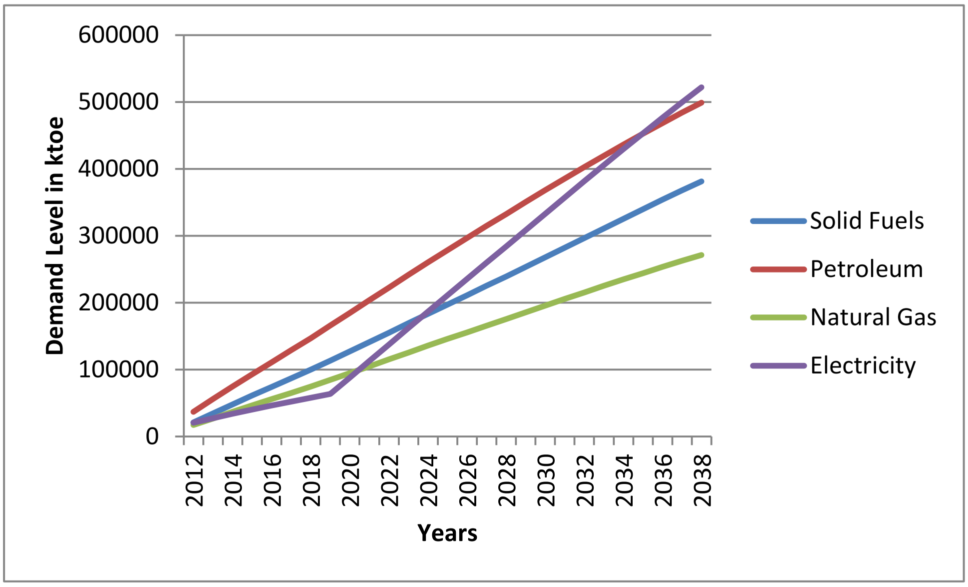

Figure 5.3. Final Energy Demand Level in ktoe

The electricity supply levels with respect to resource types can be seen in Table 5.3. An obvious observation on these values is the massive increase in solid fuels. The model satisfies almost all electricity generation requirements by using solid fuels. Hydro power and renewables also have cost advantages and are preferred. However, they reach their natural potentials before 2020 and no increments can be observed afterwards. They do not reach their natural limits sooner because there are technical constraints which restrict the level of electricity generation capacity increments. Natural gas is another resource preferred by the model especially at the initial stages of the planning horizon. Then, increments in natural gas are also substituted by solid fuels. Lastly, electricity generation by using petroleum is not preferred. Existing capacities simply depreciate and no investments are made in this technology.

The fact that solid fuels and natural gas resources are preferred for electricity generation also results in environmental problems because they are the most GHG emitting resources. Limited natural capacity of renewable resources and hydro power makes environmental decision making a more conflicting objective with economic welfare.

Table 5.3. Electricity Generation Level by Resource Types in GWh

	2012	**2020**	**2030**	**2038**
Solid Fuels	68,013	305,528	2,893,270	5,125,093
Renewables	6,760	93,662	93,662	93,662
Hydro Power	57,865	129,388	129,388	129,388
Natural Gas	104,499	495,427	755,403	721,963
Petroleum	1,639	1,202	655	218

It is necessary to discuss the unrealistic increases in solid fuel usage. As indicated before, this option is the most beneficial option in terms of the utility function, given the parameter specifications of the model. Therefore, solid fuels are preferred mostly for electricity generation by comparing only marginal productivity and marginal cost of alternatives in addition to some natural restrictions.

Whether to set up a nuclear reactor or not has been a controversial issue in Turkey. It is in government's agenda to set up two nuclear reactors, each of which has a 4800 MW of capacity. The nuclear reactors consist of four units. Each of them has a capacity of 1200 MW. The first nuclear reactor is planned to start service between 2020 and 2023 by opening one unit each year. The second one is scheduled to start service between years 2025 and 2028, in a similar manner. In this study whether to launch the nuclear program or not is also investigated. For this purpose, some of the model parameters are forced to take appropriate values so that the nuclear program is launched. The resulting objective function value without the nuclear program was lower than that with the nuclear program, as expected. It is not preferred to set up nuclear reactors in terms of increasing economic welfare.

The fact that the final energy demand variables grow faster than investments indicates that the model prefers to increase its output by using a higher amount of energy to capital ratio. The energy intensity of the economy is demonstrated in Figure 5.4. The value presented is calculated by dividing the total primary energy usage by the GDP of the corresponding year. Average yearly growth of primary energy usage and GDP are 12.0% and 3.6%, respectively. Therefore, energy intensity of the economy increases substantially. Rate of increase decreases and converges to some value which may indicate that the optimal value-added energy ratio is obtained in time. The substantial increase in primary energy usage also leads to a very high level of GHG emission increase. The growth path of total GHG emissions can be seen in Figure 5.5.

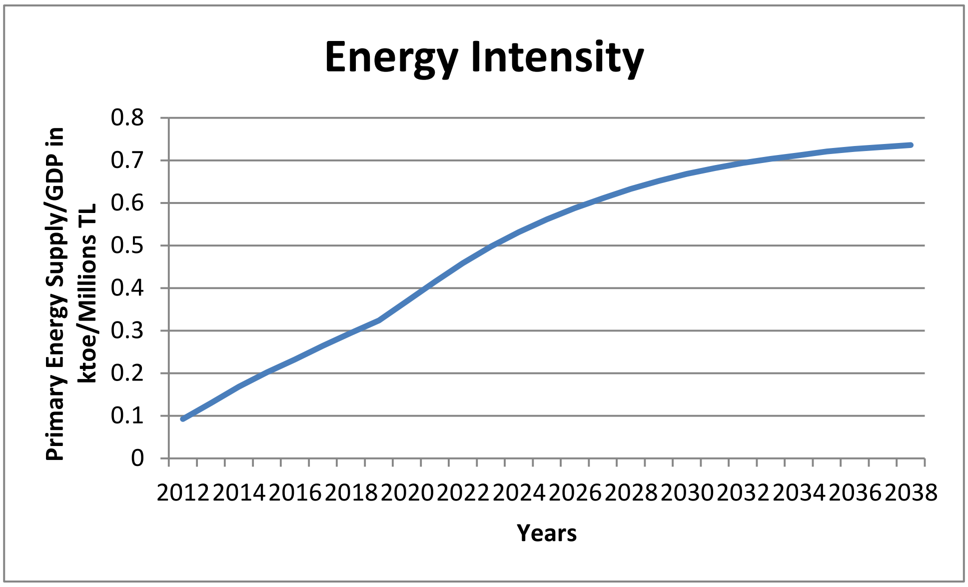

Figure 5.4. Energy intensity of the economy in ktoe/millions of TL

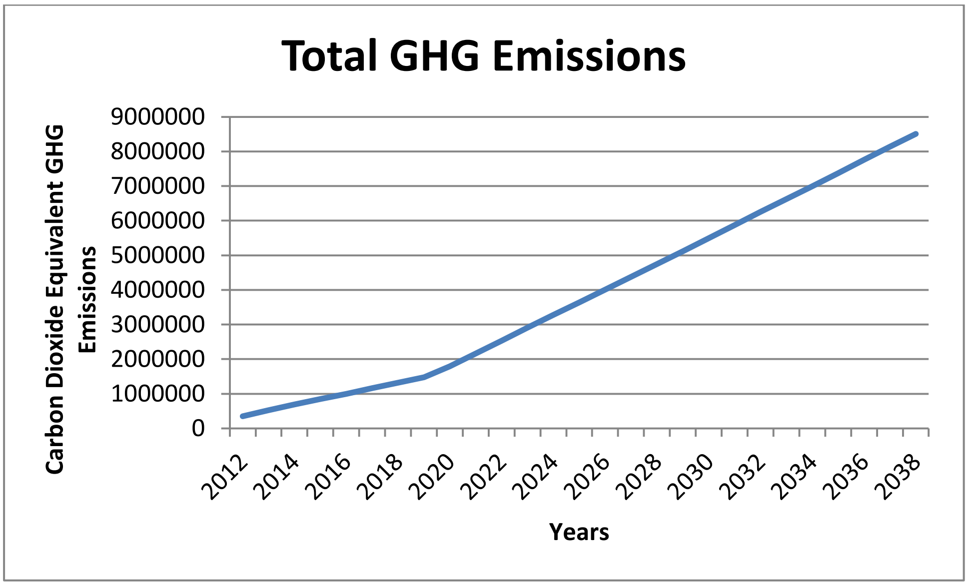

Figure 5.5. Growth path of total GHG emissions in CO_2 equivalent Gg

The last thing to check about the results of the mathematical model is the end of horizon distortions. The model could prefer to consume all its output instead of making any investments in the last periods of the planning horizon. This is because the production after the planning horizon will not be performed according to mathematical models. In order to resolve this problem, investment level of the last year in the planning horizon is set to some percentage of the GDP. In addition, results regarding the last two years are not presented. In order to understand whether these precautions worked or not, the model is run until 2038. The results obtained are compared with the model which is run until 2040. The relative change regarding main macroeconomic variables; which are GDP, consumption, investment, imports, energy cost; deviated less than 1%. Therefore, it is concluded that the end of horizon distortions do not cause important problems.

5.2 SENSITIVITY ANALYSIS

There are four critical model parameters that can affect the results of this kind of models in general. They are, substitution parameter between value-added and energy aggregate (σ), discount parameter of the utility function (δ), the parameter representing surviving stocks in the putty-clay structure (λ), and the parameter representing autonomous technological improvements. Among these, autonomous technological improvement parameter is especially important in studies that try to forecast growth paths of macroeconomic variables. As this parameter is used as a direct multiplier in the production function, it has almost proportional impact on most macroeconomic variables. On the other hand, this study specifies its parameters so that an exogenously determined growth path of GDP is obtained. Then, relative impacts of some restrictions are investigated. As this parameter has a limited impact on the pattern of the production structure, it is not very important for this specific study. This subsection presents sensitivity analysis results conducted on other three parameters.

5.2.1 SUBSTITUTION PARAMETER BETWEEN VALUE-ADDED AND ENERGY AGGREGATE

The production structure of the mathematical model used indicates the aggregation of value added and energy composite by a constant elasticity of substitution (CES) function. The substitution parameter of the CES function, which determines the ease of substitution between its factors of production, can be crucial for this study for two main reasons. Firstly, it can affect the pattern observed in the production structure in the BAU scenario. More specifically, decisions of the model to use more capital or energy composite can change depending on the value of this parameter. Secondly, the outcome of scenario analysis can change depending on the specification of this parameter. As more environmental restrictions are introduced, the model will try to substitute value added for energy. Therefore, the more the ease of substitution between value added and energy composite is, the less the cost of environmental restrictions are. Especially for the second reason, this parameter is the most critical one in terms of research questions of this study. In this part, sensitivity of the BAU scenario projections to substitution parameter will be investigated. Sensitivity of the constructed efficient frontier will be explored in the next chapter.

Changing the value of substitution parameter without any change in other parameters causes very different growth paths of macroeconomic variables. For instance, average yearly growth rate of GDP can change substantially. However, the same calibration procedure is followed for each different parameter specification. Scale parameter of the Leontief function between energy - value added composite and gross output is specified such that average yearly growth rate of GDP is approximately equal to the BAU scenario result.

Basic value of this parameter is taken as 0.4 as explained in Chapter 4. Two other values, 0.2 and 0.6, are also used in order to observe the responses of the model results. These values are the extreme values seen in the literature. After calibrating the models for each of these variables to obtain 3.6% annual GDP growth increase, the results are compared. The changes in gross output and consumption variables relative to the BAU scenario for each value can be seen in Figures 5.6 and 5.7.

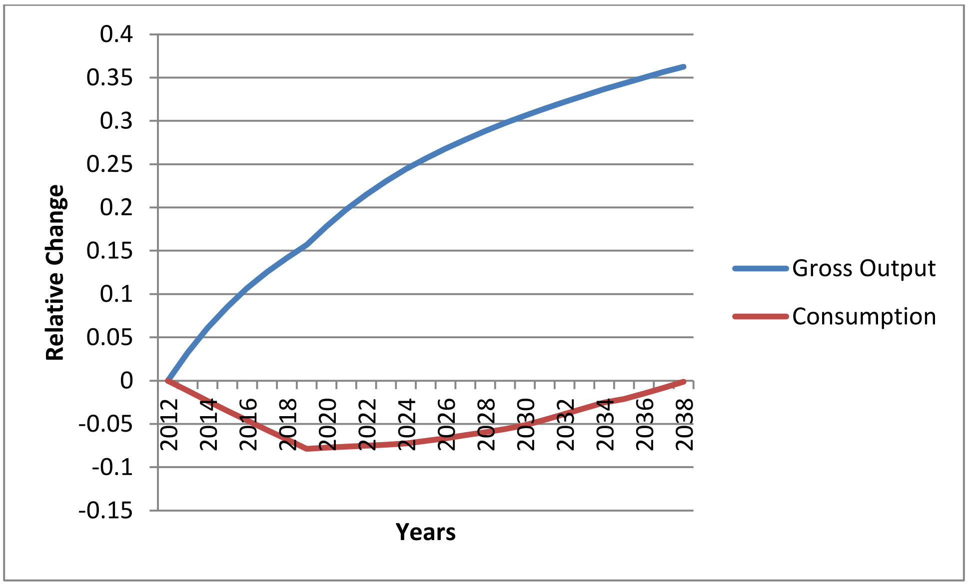

Figure 5.6. Change in gross output and consumption with σ=0.2 relative to σ =0.4

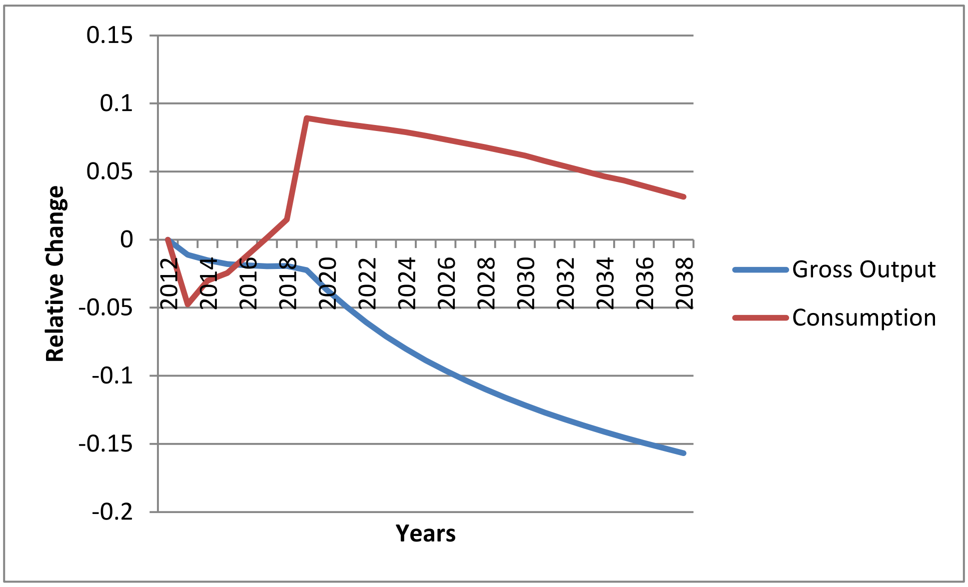

Figure 5.7. Change in gross output and consumption with σ=0.6 relative to σ =0.4

Gross output presented in Figure 5.6 and 5.7 is not GDP but it also includes energy cost and cost of intermediates. It is seen that when the value of substitution parameter is low, lower consumption levels are obtained in spite of higher gross output values. This is because of the inefficient high usage of the energy factor. Although the gross output level is higher, most of it is spent as cost of energy goods. When sigma value is higher, the situation is reversed as can be seen in Figure 5.7.

In both cases, GDP, investment and consumption values do not change more than 10% in any year. This is expected as a result of calibrating the model according to an exogenously determined growth rate of GDP. However, energy usage of the model changes substantially with the substitution parameter. Up to 90% yearly increases in terms of final energy usage are observed by changing substitution parameter value to 0.2. When it is 0.6, the corresponding decreases are up to 50%. As a result, substitution parameter affects the production pattern of the model although it doesn’t affect consumption variable much.

5.2.2 PARAMETER REPRESENTING THE SURVIVING STOCKS IN EACH YEAR

The parameter representing the surviving stocks of the putty clay structure determines speed of adjustment. This parameter indicates the ratio of existing factor of production which should remain the same in the next period. Therefore, the model has a wider room for change when the value of this parameter is lower. In this part, sensitivity analysis is conducted on the putty clay parameter for energy inputs. The base value used for this parameter is 0.9675 as explained in Chapter 4. The values of 0.9625 and 0.9725 are experimented with in this section. The relative changes of GDP, gross output and consumption can be seen in Figures 5.8 and 5.9.

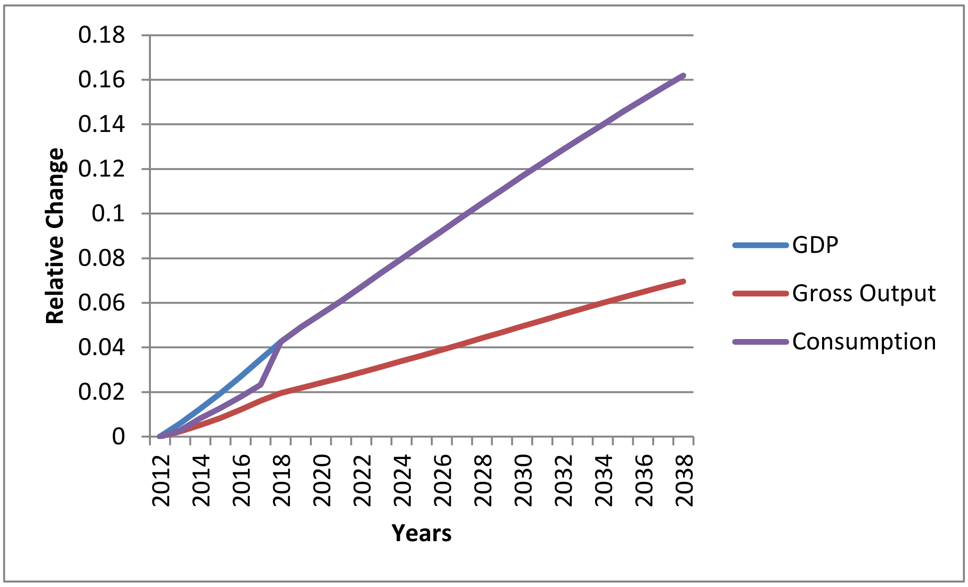

Figure 5.8. Relative changes in gross output, GDP and consumption when λ=0.9625

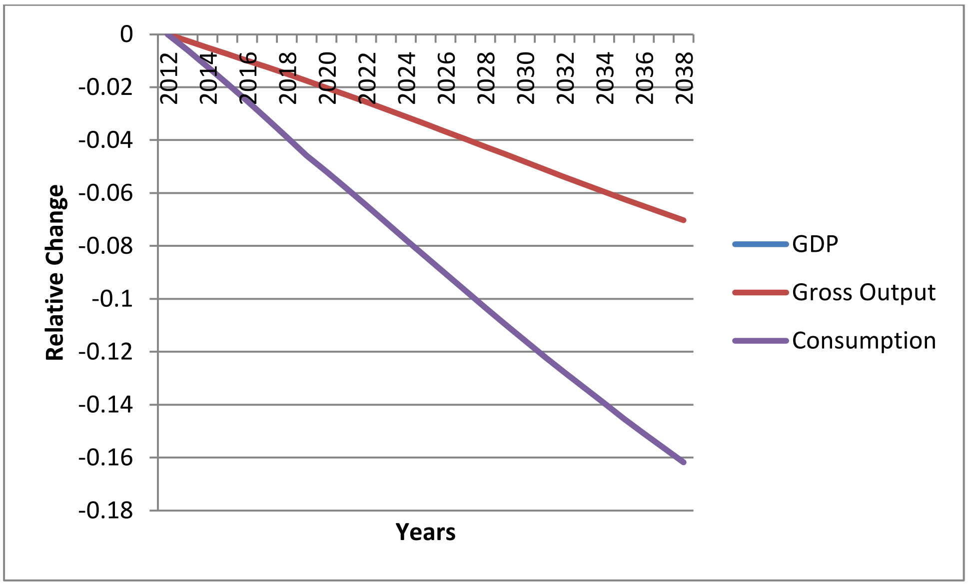

Figure 5.9. Relative changes in gross output, GDP and consumption when λ=0.9725

As the value of this parameter decreases, energy sector converges from base year values to optimal patterns easily. Therefore, gross output, GDP and consumption values increase. Higher amount of increases in GDP and consumption than gross output in Figure 5.8 implicitly indicates a more productive energy input usage. Figure 5.9 shows the same situation but reversed when the value of this parameter increases. It is also necessary to indicate that model results are sensitive to this parameter and correct parameter specification is required for correct results.

5.2.3 UTILITY FUNCTION DISCOUNT PARAMETER

The utility function consists of discounted sum of a non-decreasing function of consumption. The discount parameter indicates the valuation of next period's consumption with respect to the current one. As the value of this parameter decreases, near future consumption variables gain importance in the utility function. As a result, the model tends to increase the level of near future consumption variables instead of investment. The discount parameter is the main parameter that defines investment and consumption decisions in a typical neoclassical growth model.

There is one more set of parameters that restrict investment decisions in this study. Total, foreign and domestic investment variables are restricted to be within some ratio of GDP. Therefore, discount parameter determines the level of investment variables within indicated limits. If the discount parameter value is very low so that the utility function forces to invest less in the near future, these restrictions will prevent investment level to fall below certain values. If the parameter's value is high, the same block of restrictions prevents investments to be above certain limits. The base value used for discounting purposes is 0.9. If this value is not between 0.83 and 0.93, all the investment decisions are determined by restrictions on total, foreign and domestic investments. Beyond this range, the value of the discounting parameter is not effective. Sensitivity analysis is conducted by using these extreme values for the discounting parameter. Relative changes of GDP, gross output and consumption can be seen in Figures 5.10 and 5.11.

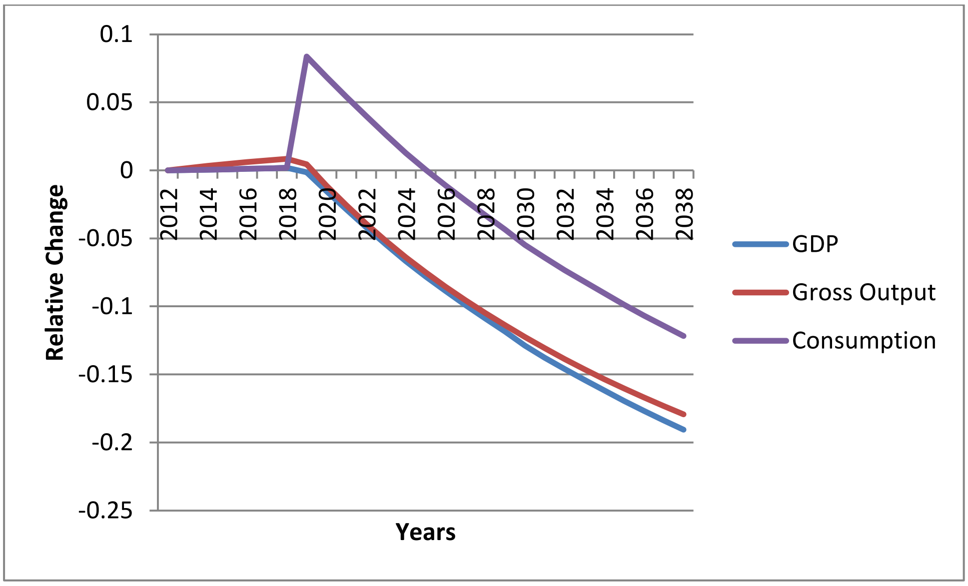

Figure 5.10. Relative Change in GDP, Gross Output and Consumption when δ=0.83

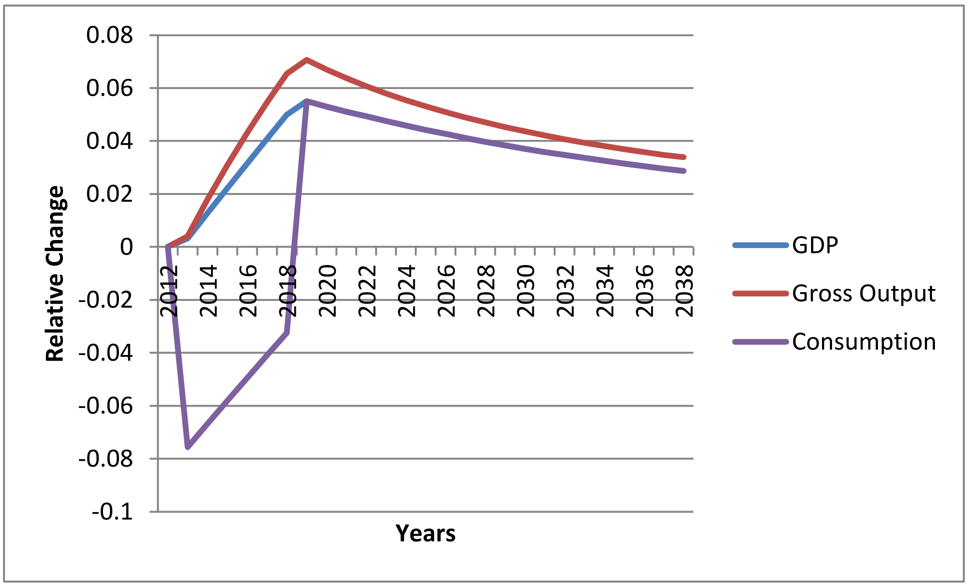

Figure 5.11. Relative Change in GDP, Gross Output and Consumption when δ=0.93

As it can be seen in Figure 5.9, mathematical model tries to substitute near future consumption for distant one. The reason of similar trend with BAU scenario until 2019 is that the model prefers to invest less until 2019 in the BAU scenario too. As a result, it is not possible to consume any more until that year. The choice of BAU scenario to invest less is again most probably related with restrictions on energy sector until that year. Relative changes are below 20% in any year.

When the value of discount parameter is increased, near future consumption is substituted with investments so that GDP increases. As a result, distant future consumption levels increase. However, relative change in consumption or GDP never surpasses the value of 5% as seen in Figure 5.10.

It is possible to conclude that the impact of utility function discount parameter on the results of the study is restricted because of other restrictions imposed on investment variables.

CHAPTER 6

SCENARIO ANALYSIS

This chapter of the thesis is devoted to the presentation of scenario analysis. The impact of environmental restrictions, world fuel price changes and foreign energy dependency restrictions on economic welfare are investigated in this chapter. The objective space of the problem is searched under various scenarios to discover possible levels of achievements in terms of the objectives of the problem. The decision space of the problem is also investigated. The reactions of macroeconomic and energy sector variables to imposed restrictions are presented so that the way given levels of achievements are obtained in different scenarios is discovered. This chapter is organized in three sections. The first section analyzes the environmental restrictions while the second demonstrates the economic impact of changing world fuel prices. Lastly, the third objective which is the minimization of foreign energy dependence is incorporated to analysis.

6.1 ENVIRONMENTAL RESTRICTIONS

Achievement of environmental concerns conflicts with maximization of the utility function of the model. As different levels of environmental constraints are imposed to the model, level of energy sector activities are also restricted since level of GHG emissions is simply a linear transformation of energy activities. Therefore, the model will be forced to switch to more costly energy activities or decrease its level of energy usage. As a result, the optimal growth path of macroeconomic variables will be disturbed which will result in a decreased utility level.

The main purpose of this scenario analysis is the determination of economic welfare losses resulting from GHG mitigation objectives. Efficient frontier is generated by the ε-constraint approach. Utility is maximized for different levels of GHG emission restrictions. However, the objective function of the model is utility, which is an abstract concept. It is not easy to interpret the level of economic welfare that a specific level of utility corresponds to. Since utility function is closely related to the consumption level, the latter values corresponding to different utility levels are used as an approximation of economic welfare. For this purpose, the vector of consumption values in the BAU scenario is used. The consumption vector is multiplied with different scalar values between 0 and 1. The obtained vectors are substituted into the utility function. Different levels of utilities corresponding to different average consumption levels are calculated in this way. For instance, the utility function value which corresponds to the consumption level of 5% less than BAU scenario on the average is obtained. This consumption mapping is used to demonstrate different utility values obtained in different scenarios. In this way, it is possible to represent change in economic welfare in terms of average consumption change.

The efficient frontier obtained can be seen in Figure 6.1. The values shown in the graph are relative consumption and total emission levels relative to the BAU scenario. It is possible to decrease BAU emission levels by 30% with a 1% average yearly consumption decrease approximately. Similarly, 40% emission reductions are possible with 2% yearly consumption decrease. As the level of emission restrictions increase further, the model is not able to use substitution possibilities in order to decrease emissions without a substantial economic sacrifice. Increasing restrictions further cause catastrophic economic consequences.

It is useful to note that abovementioned average consumption decreases are relative to the BAU scenario projections. In BAU scenario, consumption level increases 3.3% annually on the average. Therefore, the mentioned decreases are not absolute but relative to the increased level of consumption of the BAU scenario. Roughly speaking, 1% decrease, for example, reduces the 3.3% increase of the BAU scenario slightly more than 1%. Hence, there still is a net increase in the consumption.

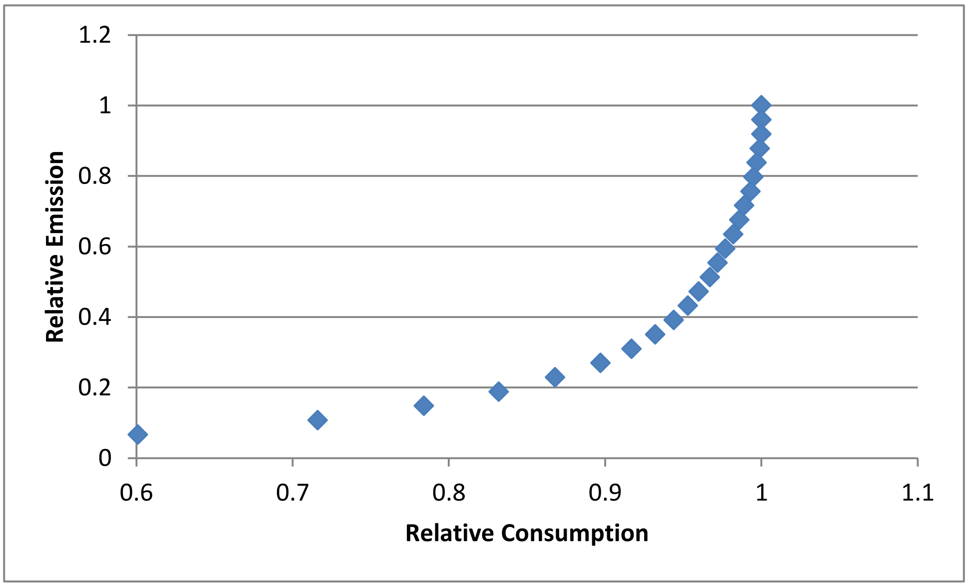

Figure 6.1. Average consumption and total emission levels relative to the BAU scenario

It is useful to note that the above-mentioned emission restrictions are relative to the BAU scenario projections. The emission levels in the BAU scenario are already very high as explained in Chapter 5. If the emission level is forced to its 2012 value, the total emission level would be approximately 8% of the BAU scenario. This restriction causes a 35% average consumption decrease for each year relative to the BAU scenario, which is a massive burden.

Level of total final energy demand with respect to the relative emission level is given in Figure 6.2. As the level of emission restrictions increase, all kinds of total final energy demand decreases. The rate of decline in solid fuels and electricity is very high while demand for petroleum and natural gas remains almost constant at the low levels of restrictions. This result is reasonable because solid fuels are the most emission-intensive resource types. In addition, decreasing the use of electricity is also reasonable considering the fact that most of the electricity supply is generated by using solid fuels. Although natural gas and petroleum are also emission generators, they are more environmentally friendly compared to solid fuels. As a result, the share of natural gas and petroleum increases. After, the emission level falls below 70% of its value with the BAU scenario, the rate of decline in petroleum and natural gas also increases. Between 70% and 40%, demand for all resources decrease at approximately the same rate. After 40%, rate of decline in all energy types increases. It is especially very high in petroleum products. In total, extreme GHG restrictions result in massive energy consumption decreases. The almost linear relationship between total energy demand and emission levels is expected considering the calculation of GHG emission levels.

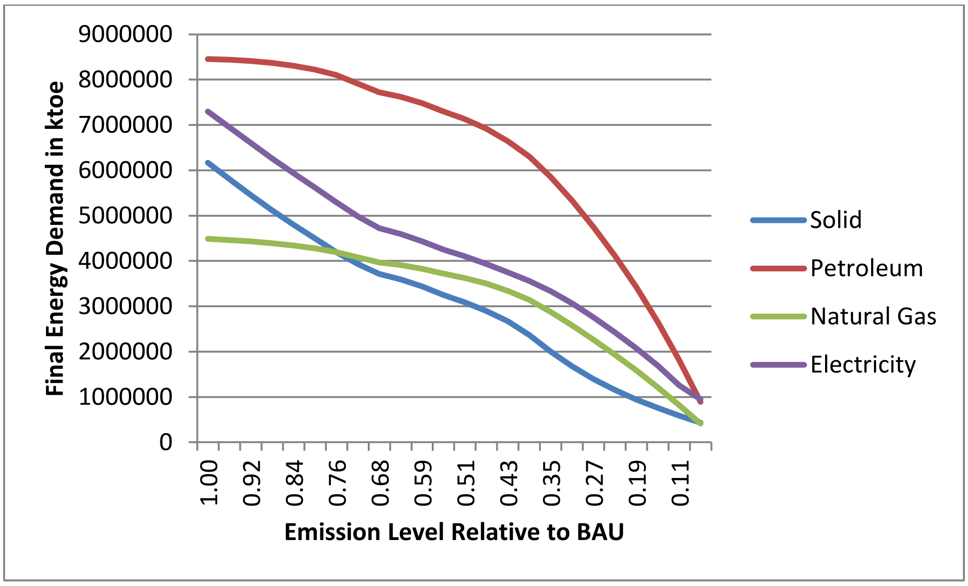

Figure 6.2. Final energy demand (ktoe) with respect to relative emission level

There are two possible reactions of energy sector variables to the imposed GHG restrictions. The first one is decreasing the levels of energy activities while the second one is substitution of GHG emitting resource types with more environmentally-friendly technologies. In order to investigate the substitution responses to restrictions, the following procedure is adopted. Firstly, it is assumed that final demand for all energy types decrease proportional to total energy demand as GHG restrictions are introduced. Then, these calculated values are subtracted from projected final energy usages. The obtained results indicate pure substitution impact of GHG restrictions, which can be seen in Figure 6.3. The graph underlines the substitution amounts after considering energy demand decreases. It is seen that solid fuels and electricity is substituted with petroleum and natural gas at different amounts for different levels of GHG restrictions. Substitution amounts increase until approximately a 30% decrease in the emission level (i.e., 70% of the BAU level). Then, it remains almost constant between 70% and 40% of the BAU level. After 40% of the BAU level, even the emissions from natural gas and petroleum are not tolerable so that substitution amounts return back to zero level. It is also possible to observe that some amount of solid fuel demand is substituted by electricity at around 30% of the BAU emission level.

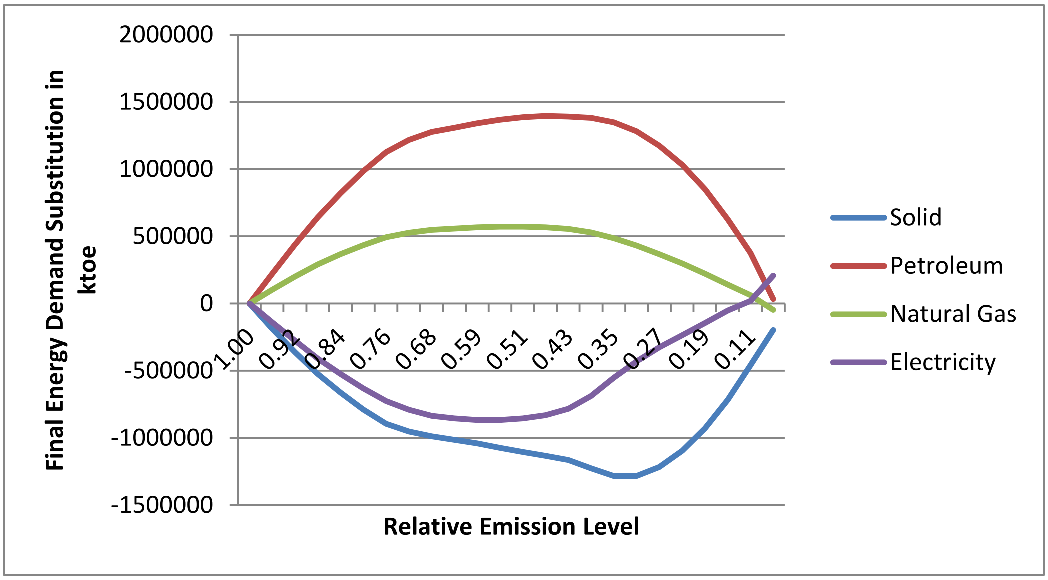

Figure 6.3. Pure final energy demand substitution impact of GHG restrictions

Total electricity supply amounts by technologies with respect to emission levels can be seen in Figure 6.4. Since clean technologies such as hydro power and renewables reach their natural limits even in the BAU scenario, they are not responsive to emission restrictions. Because of its high cost, petroleum is not preferred under any scenarios. An obvious observation is the massive decrease in solid fuel usage. This is expected because is the solid fuels are the main GHG emitting resources. The level of natural gas usage remains almost constant until 40% emission level relative to BAU. After that point, the emissions resulting from natural gas fired power plants are also intolerable due to emission restrictions and level of their usages decrease too. Carbon capture and storage is an interesting technology. It is economically not competitive in the BAU scenario because it is expensive in terms of investment, operating and maintenance costs. In addition, its thermodynamic efficiency is low compared to ordinary steam power plants as discussed in Chapter 4. However, emissions are reduced by 80% compared to ordinary steam power plants. The outcome of this study indicates that CCS technology is economically competitive below 70% of emission level relative to BAU. In addition, it is the main method of mitigation considering limited natural resource availability of clean technologies. However, decreasing the amount of emissions to 70% of the BAU level corresponds to approximately 1% yearly consumption sacrifice relative to BAU. This fact points out that CCS technology is economically competitive only after substantial amount of economic burden so that the use of CCS technology is not realistic with its current cost structure.

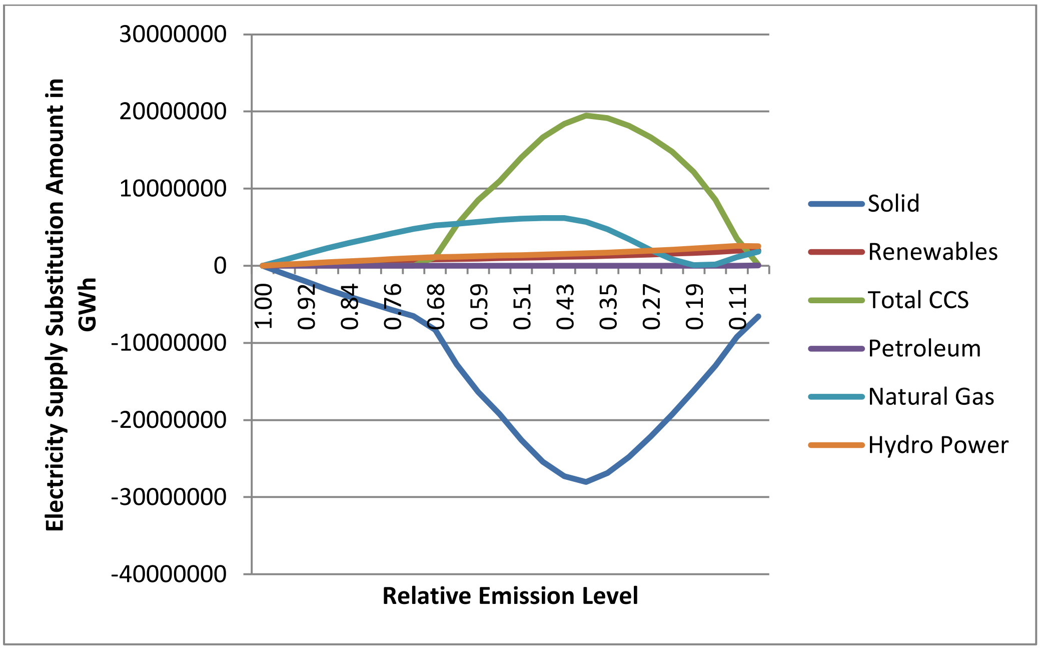

Figure 6.4. Total electricity supply amounts with respect to relative emission levels

The same procedure with the final energy demand is followed in order to obtain pure substitution amount among technologies. The results can be seen in Figure 6.5. As mentioned before, CCS technology is the main substitution possibility in terms of GHG mitigation purposes. In addition, some amount of solid fuels is substituted by natural gas especially until 40% emission level relative to BAU. Although use of renewables and hydro power do not change with environmental restrictions, they indicate some level of substitution in Figure 6.5. This problem is due to imperfections of the approach adopted in order to determine level of substitution.

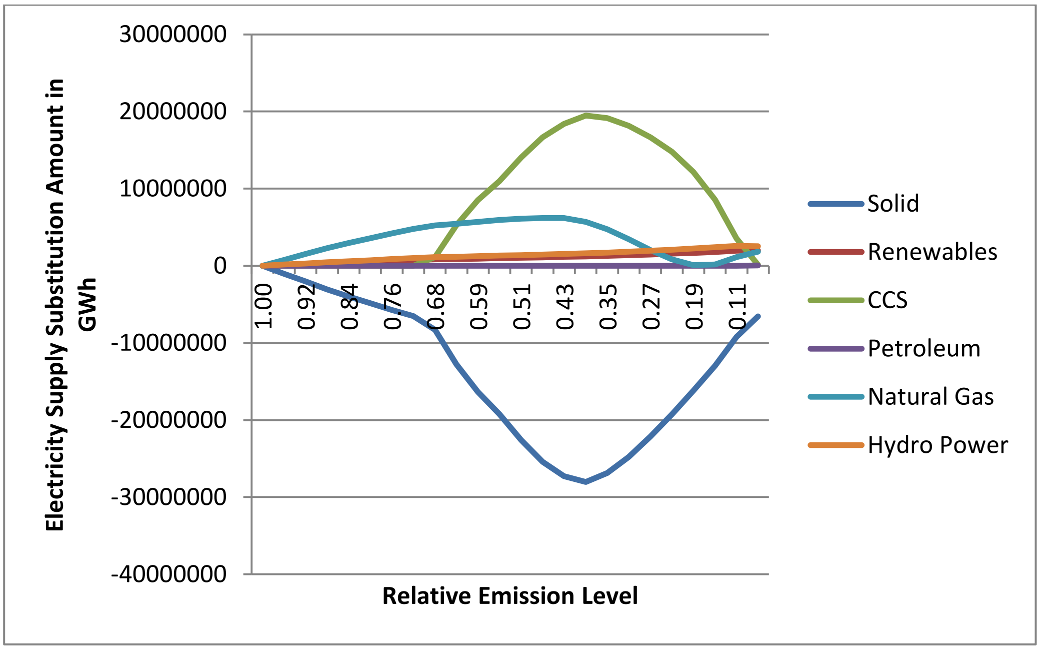

Figure 6.5. Pure electricity supply substitution impact of GHG restrictions

It was mentioned that projections of BAU scenario energy demand are higher than government projections. However, average growth rate of energy demand variables matches government projections with imposed environmental restrictions. For example: electricity demand growth rate is 5.9% when total emission level is decreased to 10.7% of the BAU level. On the other hand, this emission decrease leads to a massive economic cost which is 28% of consumption decrease relative to BAU annually.

The reactions of the supply side of the energy sector to environmental restrictions are underlined in this thesis. It is also possible to satisfy environmental restrictions with changes in the demand side of the energy sector. For instance, higher efficiency in heating and transportation activities can contribute to lower energy usage. However, these activities are not represented separately in this study. Instead, substitution of value added for energy aggregate in the production function represents energy demand adjustments. As discussed in Chapter 5, the substitution parameter between energy value-added aggregate is very important for the outcome of this study. Higher elasticity values make it easier to substitute value added for energy so that cost of environmental restrictions can be decreased. For this reason, sensitivity analysis is conducted on the substitution parameter by using 0.2 and 0.6 values. Similar to the procedure in Chapter 5, other model parameters are calibrated so that 3.6% average yearly growth rate for GDP is obtained. Instead of imposing restrictions relative to the BAU scenario, the same level of GHG restrictions is imposed to all parameter settings so that results are comparable. Utility values obtained are compared based on the consumption mapping generated from the BAU scenario of the base case. The results can be seen in Figure 6.6.

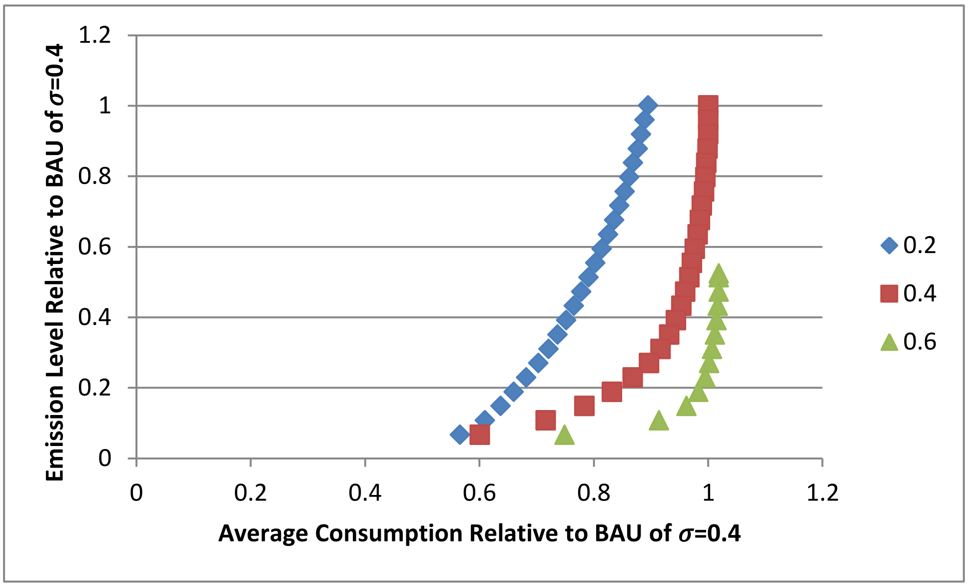

Figure 6.6. Sensitivity analysis of the efficient frontier with respect to energy value-added substitution parameter

As anticipated, obtaining the same level of emission level is more costly when substitution parameter decreases. For instance, decreasing total emission level to approximately 70% of the BAU scenario of base parameter settings, decreases average consumption values by 1% when σ = 0.4. The same consumption decrease is 15% when σ = 0.2. Total emission level when substitution parameter takes the value of 0.6 is only 55% of emissions in the base model. In addition, average consumption values increase by 1.9%. In that case, 22% of emissions relative to the BAU scenario of base parameter settings is reachable with less than 1% average consumption decrease relative to the BAU scenario of base parameter settings. These results indicate the importance of this specific parameter in terms of the outcome of the study. Incorrect estimate of this parameter ends up with misleading results.

There are two main ways of satisfying environmental restrictions. The first one is the adaptation of energy supply options. This can be accomplished by inter-fuel substitution. It is seen that solid fuels are substituted by natural gas and petroleum, which are cleaner fuels. However, they are also GHG emitting energy resources. Therefore, mitigation level obtained in this way is limited. Another energy supply adaptation method is switching to environmentally friendly electricity generation activities, which are CCS, hydro power and renewables. On the other hand, contributions of these is again limited. Natural potential for hydro power and renewables is limited while CCS is a very expensive technology as underlined before. As a result, energy supply adaptation options have limited contribution to satisfying environmental restrictions. The second way of satisfying environmental restrictions is substituting value added for energy inputs. As explained, substitution effect is the main driver of coping with environmental concerns for Turkey because of limitations in energy supply options. This fact also points out the importance of demand side management policies for Turkey.

6.2 WORLD FUEL PRICE CHANGES

How the model results are affected from world fuel price changes is another research question investigated in this study. The growth path of world fuel prices are taken from the current policies scenario of [65]. The scenario is constructed on the assumption that all countries continue their existing policies on environmental issues and this scenario is the main one used in this study. On the other hand, there are two other scenarios proposed in [65]. The first one is new policies scenario. New policies scenario is based on the assumption that new policies on environment, which are proposed by international agreements, come into force. Actually, it is not certain that these policies will come into force as there are institutional restrictions on legislation procedures of each country. The second one is named as 450 scenario. This scenario is based on the assumption that policies required to limit increase in earth surface temperature by 2 centigrade degrees with 50% possibility are adopted. The changes in world fuel prices relative to current policies scenario can be seen in Figure 6.7.

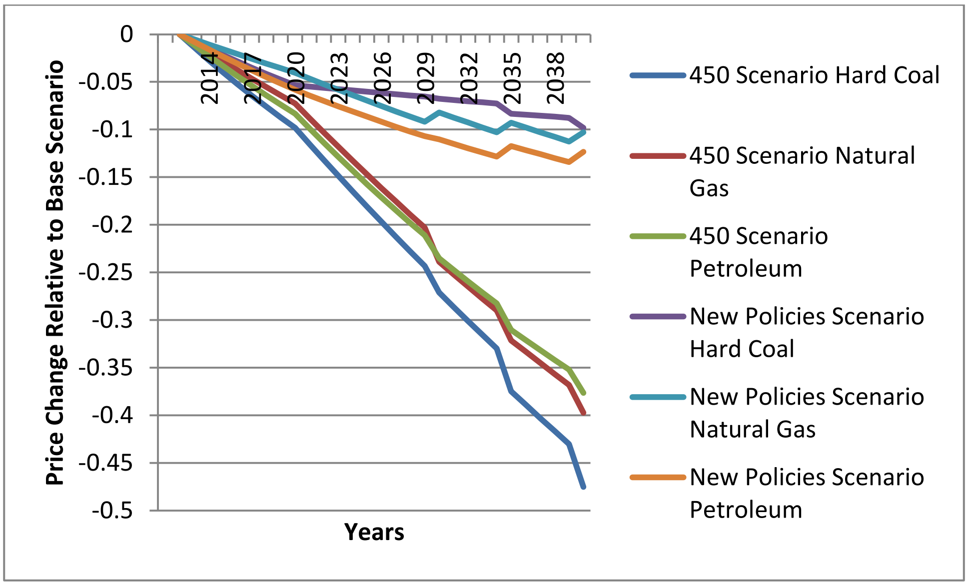

Figure 6.7. Relative changes in world fuel prices

As it can be seen in Figure 6.7, both scenarios indicate lower energy prices relative to the current policies scenario. Especially in 450 Scenario, almost 50% cost decreases are anticipated until year 2040. The relative changes in GDP, investments and consumption paths for both scenarios can be seen in Figures 6.8 and 6.9. It is seen that cheaper world fuel prices lead to investing more. Although the consumption level decreases at initial stages, it increases substantially in the distant future. Almost one to one changes in main macroeconomic variables with respect to fuel price changes indicate how important world fuel prices are for the economy.

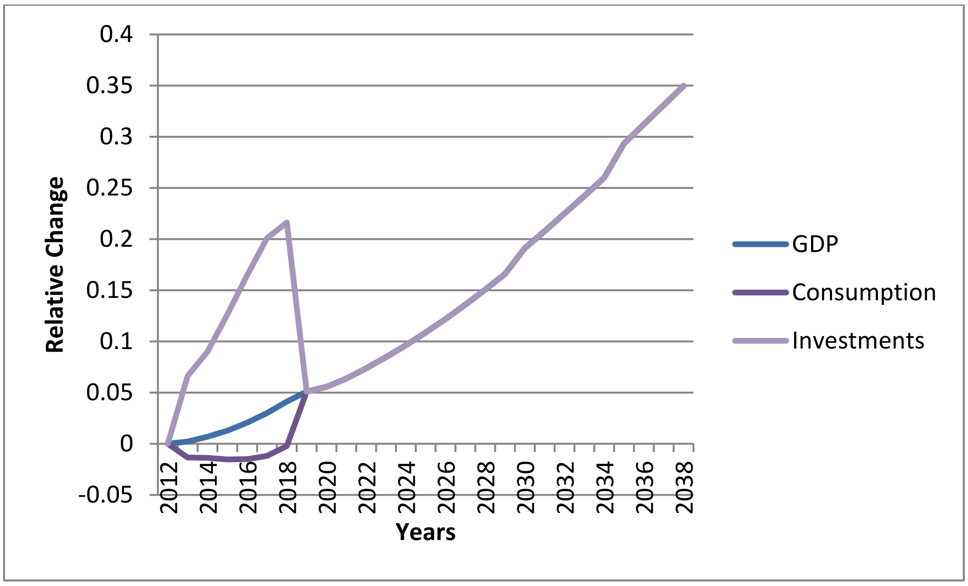

Figure 6.8. Relative changes in GDP, consumption and investment variables resulting from 450 Scenario

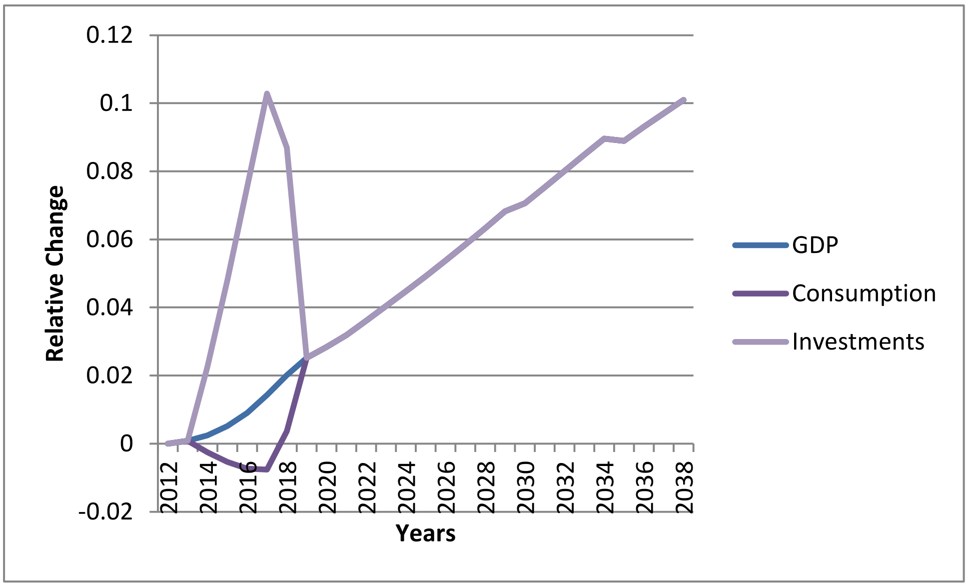

Figure 6.9. Relative changes in GDP, consumption and investment variables resulting from New Policies Scenario

6.3 ANALYSIS OF FOREIGN ENERGY INDEPENDENCE OBJECTIVE

The supply security is another important issue in energy policies. In order to establish supply security, countries try to supply their energy needs by domestic resources. The level of foreign energy dependency is measured by the ratio of total foreign energy cost to total energy cost during the planning horizon.

The most dirty primary energy resources in terms of climate change are hard coal, lignite, natural gas and petroleum. Among these primary energy resources, all of the natural gas and most of the hard coal and petroleum demand are imported while all of the lignite demand is supplied domestically. As environmental restrictions are introduced, the reaction of primary energy demand can be seen in Figure 6.10. It is seen that demand for hard coal, petroleum and natural gas decrease with increasing GHG emission restrictions. However demand for lignite remains constant until 31% of emission restrictions. The mathematical model does not prefer to sacrifice from lignite usage in spite of the fact that it is a dirty primary energy resource. The reason behind this fact is low cost of lignite. While trying to maximize economic welfare, lignite is the last dirty primary energy type to sacrifice. Other primary energy resources, which are hydroelectricity renewables and wood, remain at their levels in BAU scenario because of natural limitations although the model requires them more with environmental restrictions.

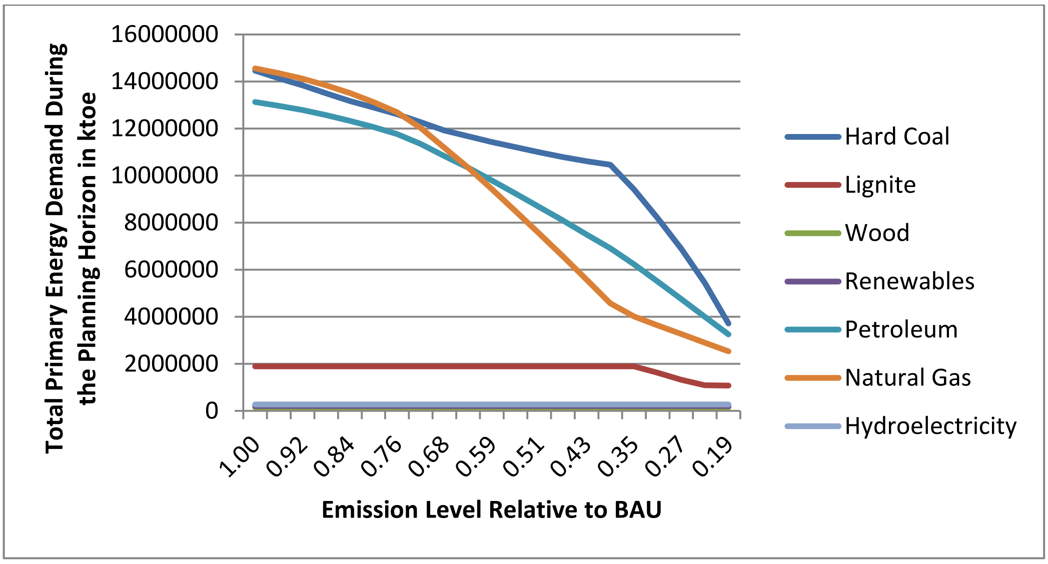

Figure 6.10. Reaction of Primary Energy Demand to Environmental Restrictions

Since lignite is supplied domestically while hard coal, petroleum and, natural gas are imported heavily; decreasing foreign energy dependence objective shows a close relationship with decreasing GHG emissions until 31% of emission level. Foreign energy dependence increases with decreasing GHG emissions between 31% and 23% of emissions. In this interval, the model has to decrease lignite demand in order to cope with severe environmental restrictions. After this point, lignite demand remains constant so that the two objectives are again in parallel. The foreign energy dependence objective values with imposed environmental restrictions can be seen in Figure 6.11.

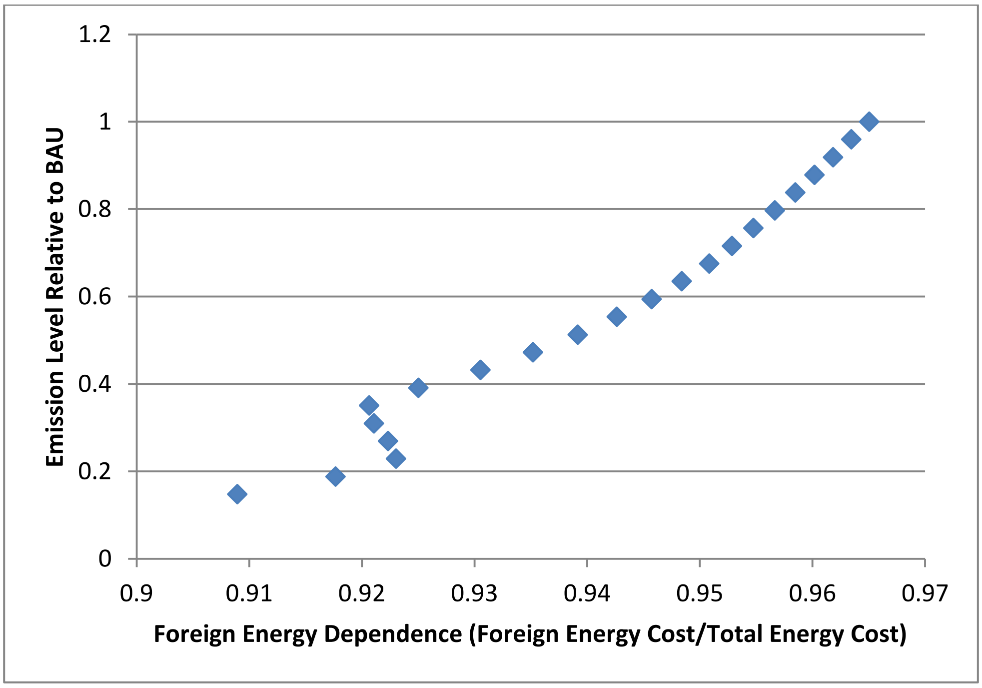

Figure 6.11. Relationship between emission and foreign energy independence objective

CHAPTER 7

CONCLUSION

It is shown that energy policy decisions are related with both environmental quality and economic welfare of a country. Energy supply security is another important issue. As a result, energy policy decisions are designed in order to satisfy several objectives, which are maximization of economic welfare, minimization of GHG emissions and minimization of foreign energy dependency.

The main purpose of this study is to develop a multi objective decision support system which combines economics and engineering perspectives. For this purpose; a detailed activity analysis model, which represent energy sector and its environmental consequences, is combined with a one sector neoclassical growth framework. By imposing different levels of restrictions on GHG emissions and foreign energy dependency, the efficient frontier is generated. Consequently, it was possible to report tradeoffs between above-mentioned objectives quantitatively. Moreover, reaction of economy and energy sector to the restrictions is investigated so that how a country meets specific goals is presented.

Literature studying energy and environmental policy analysis is based on quantification of economic burden resulting from commitment to certain international agreements such as the Kyoto protocol. On the other hand, this study explores the level of economic burden and change in energy sector for different levels of emission restrictions. Investigation of foreign energy dependency is another contribution of this thesis.

The approach presented is applied to Turkish data in order to validate the approach. The BAU scenario results indicate increasing energy intensity for the economy. The rate of increase in electricity usage increases especially after year 2019 where some of the restrictions on electricity generation are relaxed. After this year, rate of investment also increases. This fact indicates how restrictions on energy sector prevent economy to reach its full potential. Sensitivity analysis is also conducted on most critical model parameters. Substitution parameter between energy aggregate and value added with the parameter representing the surviving stocks of putty-clay structure are found to effect growth path of variables significantly. Changes in discount parameter of the utility function are less effective on model parameters as a result of other constraints on investment variables.

The efficient frontier constructed indicates that it is costly to decrease level of emissions relative to the BAU scenario given the used model parameters. 30% emission reduction is possible with a 1% average yearly consumption decrease while 40% is possible with 2% consumption reduction. Moreover, keeping GHG emissions at 2012 level causes 35% average consumption decrease relative to BAU scenario. As environmental restrictions are introduced, the model decreases its level of energy demand in order to satisfy restrictions. Inter-fuel substitutions are performed. GHG intensive resources electricity and solid fuels are substituted by less intensive resources of petroleum and natural gas. Electricity is a GHG intensive resource because the model prefers solid fuel intensive electricity generation in its BAU scenario. In terms of electricity generation, CCS is the most important technology for mitigation objectives considering the limited natural potential of renewables and hydro power.

However, it is competitive only after very significant amount of economic burden.

The cost of environmental restrictions evaluated in this study is heavily dependent on the substitution parameter between value added and energy aggregate. As ease of substitution increases, it is easier to substitute value added for energy in order to satisfy environmental restrictions without sacrifice in economic welfare. Therefore, correct specification of this parameter is of utmost importance. In addition, there is a close relationship between world fuel price changes and relative consumption path change of the economy. This result indicates the importance of world energy prices for Turkish economy.

There are two main possible future research questions for this study. The first one is generalizing the proposed approach to world-wide scale or to regional scale. This study demonstrates the level of achievements that can be obtained for economic and environmental objectives. The second research question can be the investigation of policy tools such as quotas or taxes in order to efficiently achieve these goals.

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