ANALYSIS OF CO_2 EMISSION REDUCTION, ENERGY AND ECONOMY INTERACTIONS IN TURKEY USING BUEMS-MACRO

by

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ABSTRACT

ANALYSIS OF CO_2 EMISSION REDUCTION, ENERGY AND ECONOMY INTERACTIONS IN TURKEY USING BUEMS-MACRO

Growth in the world's population and the economy, together with the rapid urbanization lead to a dramatic increase in energy demand. Among all energy sources, the most rapid consumption growth occurs in renewable energy which is followed by nuclear energy. The Turkish Ministry of Energy and Natural Resources (MENR) recently has released new projects under the Renewable Energy Resource Area (YEKA) scheme and announced intentions for three nuclear power plants by 2030. However, fossil fuels are expected to dominate the world's energy demand in the near future, although fossil fuels are the largest contributors to climate change. As a result of this, energy modeling plays a key role in climate change mitigation and has been a widely used tool for energy planning in the recent past decades. This thesis aims to take advantages of both top-down and bottom-up energy models by proposing a model which defines a linkeage between the energy, the economy and the environment for the Turkish energy system. In this regard, Boğaziçi University Energy Modeling System (BUEMS) which has been developed under a project for the Scientific Technology and Research Council of Turkey (TUBİTAK, 2018), has been calibrated according to the latest Turkish energy sector data, and is used for the bottom-up structure and the Macro model that has been proposed in this thesis is used for the top-down structure. BUEMS and Macro models are together referred to as Boğaziçi University Energy Modeling System together with a Macroeconomic Model (BUEMS-MACRO). In this study, the current energy system of Turkey is taken as a Base scenario. Based on Base scenario, different policy scenarios have been carried out for both BUEMS and BUEMS-MACRO model and the results of policy scenarios are compared with the Base scenario.

ÖZET

BUEMS-MACRO KULLANARAK TÜRKİYE’DE CO_2 EMISYON AZALTIM, ENERJİ VE EKONOMİ ETKİLEŞİM ANALİZLERİ

Dünya nüfusunun ve ekonominin büyümesi, hızlı şehirleşmeyle birlikte enerji talebinde önemli bir artışa neden olmaktadır. Bütün enerji kaynakları arasında en hızlı tüketim artışı yenilenebilir enerjide olmakta, ikinci sırayı ise nükleer enerji almaktadır. Türkiye Enerji ve Tabii Kaynaklar Bakanlığı son zamanlarda Yenilenebilir Enerji Kaynak Alanları (YEKA) programı kapsamında yeni projeler yayınlamakta ve 2030 yılına kadar üç nükleer santral projesi planlamaktadır. Ancak, fosil yakıtların iklim değişikliğinin en büyük nedeni olmalarına rağmen yakın gelecekte dünyadaki enerji talebine hâkim olmaya devam edeceği tahmin edilmektedir. Bunun sonucu olarak; enerji modellemesi iklim değişikliğinin azaltılmasında kilit rol oynamaktadır ve son yıllarda enerji planlamada yaygın olarak kullanılmaktadır. Bu tez; top-down ve bottom-up modellerin her ikisinin de avantajlarını kullanarak Türkiye enerji sistemi için enerji, ekonomi ve çevre arasındaki bağlantıyı tanımlayan bir model önermektedir. Bu çalışmada; TUBİTAK Bilimsel ve Teknolojik Araştırma Projesi (Proje No:114M348) kapsamında geliştirilen Boğaziçi Üniversitesi Enerji Modellemesi Sistemi (BUEMS) son yayınlanan Türkiye enerji sektörü verilerine göre kalibre edilerek bottom-up yapı için kullanılmaktadır. Macro model ise top-down yapı için kullanılmaktadır. BUEMS ve Makro modelleri, birlikte Boğaziçi Üniversitesi Enerji Modellemesi Sistemi ve Makroekonomik Modul (BUEMS-MACRO) olarak adlandırılmaktadır. Türkiye enerji sisteminin güncel durumu baz senaryo olarak alınıp hem BUEMS hem de BUEMS-MACRO model için farklı senaryo analizleri yapılarak sonuçlar baz senaryo sonuçları ile karşılaştırılmaktadır.

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A	Aggregate of capital and labor
aconst	Constant for capital-labor index
af	Annual availability factor
A_{KL}	Aggregate of capital and labor
bconst	Constant for energy index
bound_x_fix/lower/upper	Fix, lower, upper bounds on technology activity/capacity/investment/supply
C	Consumption
c	Energy conversion technology
C_0	Consumption for initial year
capunit	Unit conversion factor of a technology
cbs_e	Baseload electric conversion technology indice
ce	Electricity generation technology
cf	Capacity utilization factor of a technology
ch	LTH generation technology
cm	Cumulative supply
cme	Cumulative emission
crf	Capital recovery factor
cum	Cumulative capacity of a resource technology
cumem	Cumulative emission factor
d	Demand technology
decay	Maximum annual decay rate of a technology capacity
dm	Sectoral demand
e	Energy source
EC	Energy cost
EC_0	Initial energy cost
eff	Efficiency rate

envact	Emission factor for energy conversion technologies
envcost	Unit emission cost
envsep	Emission factor for supply technologies
fraclife	last period fraction rate
growth	Maximum growth of capacity between consecutive periods
I	Investment
I_0	Investment for initial year
INV_T	Total investment in terminal period
ibond / ibondfx / ibondlo	Annual upper/fix/lower bounds on the investment of the technology
ipm	Investment period multiplier
K	Capital
K_0	Initial capital stock
kgdp	Capital-to-GDP value
kpvs	Capital value share
K_T	Total period in terminal period
L	Labor
L_0	Labor for initial year
l	Technology life
lgrowthrate	Labor growth rate
m	Set of technologies
nyrsper	Number of years per period
P_E	Price for the production factor energy
Peref	Reference price for energy
P_{KL}	Price for the production factor of capital-labor
$potgdp_0$	Potential GDP for initial year
pridf	Period discount factor
pridisc	Periodic discount factor other than investment
qhr_d/n/s/w	Day/night/summer/winter time share of electricity generation from a technology

s	Supply technology
spda	Speed of adjustments
t	Period
v	Emission type
Y	Annual production
Y_0	Initial production
ρ	Parameter that controls the elasticity of substitution
σ	Elasticity of substitution

LIST OF ACRONYMS/ABBREVIATIONS

AGE	Applied General Equilibrium Models
AIM	Asian-Pacific Integrated Model
ANEMI	An Integrated System Dynamics Model for Analyzing the Behavior of the Social-Energy-Economic-Climatic System
ASAM	Abatement Strategies Assessment Model
BP	British Petroleum
BUEMS	Boğaziçi University Energy Modeling System
BUEMS-MACRO	Boğaziçi University Energy Modeling System together with a Macroeconomic Model
CO_2	Carbon Dioxide
CCS	Carbon Capture and Storage Technologies
CES	Constant Elasticity of Production
CETA	Clean Energy Technology Association Model
CGE	Computable General Equilibrium Model
CSP	Concentrated Solar Plants
DICE	Dynamic Integrated Model of Climate and the Economy
E3ME	Energy-Environment-Economy Model
EFOM-ENV	Energy Flow Optimization Model
EIA	U.S. Energy Information Administration
EMRA	Republic of Turkey Energy Market Regulatory Authority
ENDAM	Energy Economy Environmental Damage Model
ERIS	Energy Research and Investment Strategies Model
Esub	Elasticity Of Substitution
ESCAPE	Energy Systems Center for Analysis and Policy Evaluation Model
ETA-MACRO	Energy Technology Assessment Model together with a Macroeconomic Model
ETSAP	Energy Technology Systems Analysis Program

EU	European Union
EUAS	Turkey Electricity Generation Company
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
GAMS	General Algebraic Modeling System
GAZPROM	Public Joint Stock Company Gazprom
GCAM	Global Change Assessment Model
GDP	Gross Domestic Production
GEM	General Equilibrium Model
GEM-E3	Global Energy Model
GHG	Greenhouse Gas
GREEN	Tool for Assessing the Life Cycle Climate Performance Model
GTAP	Global Trade Analysis Project
GTAP-E	Global Trade Analysis Project Energy Model
HERMES	Harmonized European Research for A Multinational Economic and I/O Input-Output Models
IA	Integrated Assessment Models
ICAM	Integrated Climate Assessment Model
ICES	The Intertemporal Computable Equilibrium System
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IIAM	Indian Institute of Management Model
IMAGE	Energy-Industry System Model
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LEAP	Long-range Energy Alternatives Planning System
LNG	Liquefied Natural Gas
LP	Linear Programming
LTH	Low Temperature Heat
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change

MARKAL	Market allocation Model
MARKAL- Demand Function	Market allocation Model Combined with a Micro Model – Stepwise ED(LP)
MARKAL-LP	Market allocation Model with Linear Programming
MARKAL-MACRO	Market allocation Model Combined with a Macro Model
MARKAL-MICRO	Market allocation Model Combined with a Micro Model
MDM	Multisectoral Dynamic Model
MENR	Ministry of Energy and Natural Resources
MEPA	Massachusetts Environmental Policy Act Model
MERGE	Integrated Assessment Model for Global Climate Change
MESSAGE	Model for Energy Supply Systems and Their General Environment
MESSAGE-MACRO	Message Model Combined with a Macro Model
MIDAS	Multinational Integrated Demand and Supply Model
MINICAM	Mini-Climate Assessment Model
MIS	Macroeconomic Information System Model
mtoe	million tonnes of equivalent petrol
NEMS	National Energy Modeling System of USA
NLP	Non-Linear Programming
OECD	Organization for Economic Co-operation and Development
PAGE	Policy Analysis of the Greenhouse Effect
PJ	Peta Joule
POLES	Prospective Outlook on Long-Term Energy Systems Model
PRIMES	The Primes Energy System Model
PV	Photovoltaics
QUEST	A Macro Econometric Model for EU Countries
R&D	Research&Development
RICE	Regional Integrated Model of Climate and the Economy
RIAT	Regional Integrated Assessment Tool
SEM	Turkey's Solar Energy Map
SGM	Second Generation Model

SLICE	Stylized Integrated Assessment Model of Climate and the Economy
TANAP	Trans Anatolian Natural Gas Pipeline Project
TARGETS	Tool to Asses Regional and Global Environmental and Health Targets for Sustainability
TEIAS	Turkey Electricity Transmission Company
TIMES	The Integrated MARKAL-EFOM System
YEKA	The Renewable Energy Resource Area
TSI	Turkish Statistical Institute
WITCH	World Induced Technical Change Hybrid Model

1. INTRODUCTION

The International Energy Agency (IEA, 2017) indicates that global energy demands rise slowly compared to the past due to energy efficiency regulations, from an average of 8% each year to an average of 2% each year since 2012. However still it is forecasted that global energy demand will increase by 30% and population is forecasted to exceed 9 billion until 2040. Developing countries in Asia account for more than half of global energy growth. India accounts for 30% of demand growth and India’s global energy use share is expected to reach 11% by 2040. Besides India, Southeast Asia’s energy demand growth is two times higher than the China’s demand growth.

China also plays an important role in global energy demand. It is said that China is entering a new phase in terms of its energy trends. According to the new scenarios, the installed capacity in China will account for one-third of the world’s new installed capacity for wind and solar PV energy. Moreover, China makes considerable investments on electric vehicles. USA, on ther other hand, is already an exporter of gas and is forecasted to dominate world’s liquefied natural gas exports (LNG) in a couple of years (IEA, 2017).

Improving energy efficiencies and use of renewable energy technologies are the new policies which have been introduced to meet rapidly growing energy demand. Renewable energy starts to become “least-cost source” for many countries. According to IEA (2017), renewable energy will account for 40% of total power generation by 2040. China and United States contribute around for 50% of the renewable energy growth in 2017 and 36% of this electricity generation growth from renewables was from wind power (IEA, 2017).

Turkey’s energy demand is rapidly increasing and Turkey has many energy sources. Significant investments have been made throughout the past couple of years in Turkey. MENR indicates that Turkey’s total installed capacity has reached to 81,554.9 MW by the end of the December 2017 and the Turkish government recently has released new projects for wind and solar power under the YEKA scheme. In addition, to decrease its imported energy sources dependency, the Turkish government has announced intentions for three nuclear power plants by 2030 and starts construction of its first nuclear power plant in Akkuyu. There will be four units in Akkuyu plants that each unit will have 1200 MW installed capacity. According to the Turkey Electricity Transmission Company (TEIAS) Capacity Projection Report (2017-2021), total installed capacity will reach to 108,045 MW by 2021 in Turkey.

Greenhouse gas emission levels have been increasing fast over the last few decades which results in higher temperature levels on Earth and increases in Earth temperature leads to climate change. Climate change issue has been considered over a decade. The Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report indicates that the Earth temperature will rise between 2 and 6 degrees in the next century. Due to the concerns about the energy security and climate change, energy policy modeling has gained in importance in recent years. There are various types of energy models with different concepts and approaches. Bottom-up models which have technological details and top-down models which have economical details are the two approaches that are mainly used in energy policy modeling. Bottom-up and top-down models both have some advantages and disadvantages.

In most energy policy studies, energy sector is viewed in isolation from the remainder of the economy, and analysis is performed without consideration of the broader impacts (Hogan and Manne, 1979). From this perpective, this thesis aims to represent a methodology which links energy-economy-environment with the integration of bottom-up and top-down model frameworks. In this regard, the BUEMS model which has been developed under a project for the Scientific Technology and Research Council of Turkey (TUBİTAK, 2018),), is used for the bottom-up structure and the Macro model that has been proposed in this thesis is used for the top-down structure. The BUEMS and the Macro models are together referred to as BUEMS-MACRO.

The BUEMS model minimizes the total system cost, while the Macro model implements a nested constant elasticity of production (CES) production function. The objective of Macro model is maximization of the discounted sum of the logarithms of consumption. BUEMS and

Macro model link to each other via CES function of the Macro model and energy costs of the BUEMS model.

This thesis is structured as follows. Chapter 2 presents the literature survey on different energy models which are based on two different methodologies and the models’ application areas are explained. Chapter 3 represents a detailed description of the BUEMS modeling framework with the classification of model technologies and variables, and the formulations of equations and constraints. Chapter 4 describes the BUEMS-MACRO model, with the objective function, variables and equations. Chapter 5 explains the current energy profile of Turkey with a detailed information about energy sources. Chapter 6 is for model calibration. The BUEMS-MACRO model has been calibrated for the years 2012 and 2017 according to the data from TEIAS and MENR. Chapter 7 evaluates the results of the Base and emission scenarios of both BUEMS and BUEMS-MACRO models with indicating energy supply levels, installed capacities, electricity generation levels and sectoral consumption levels with the related emissions. In the final part, main conclusions and possible future studies are indicated.

2. ENERGY POLICY MODELING LITERATURE

In the 1970s, energy modeling was used to comprehend the impacts of first oil embargo. Then, environmental issues and energy supply security have increasingly gained importance and become a prominent subject for decision makers.

Energy modeling creates credible possibilities for the future that help modelers to understand the consequences of different alternatives. Recently, many alternative scenarios have been developed by the Intergovernmental Panel for Climate Change (IPCC).

Energy, economy and the environment all should be taken into account in order to optimize energy system. The energy-economic model is not only a numerical tool for predicting the future, but also a management tool for decision making (Keeney and Raiffa, 1993). It also makes information available to engineers in environmentally sound technologies (Johansson, 1992; Rubin, 2001) to design specifications for efficiency, emissions and costs. In order to introduce energy suppliers to practical and commercial application in world economy, it is important to perceive the economic aspects (Fiksel, 1996; Margolis and Kammen, 2001).

Energy, economy and the environment are main components of energy policy models. Karali (2012) explains the objective of energy modeling systems as cost minimization or utility maximization while meeting energy demands according to characteristics and limitations of the models in terms of supply, technology, economy, and environment.

An energy-environment policy model should be technologically explicit, behaviorally realistic and should have macroeconomic feedbacks (Hourcade *et al.*, 2006).

There are two wide-spread modeling approaches in energy modeling system: bottom-up models of the energy system and top-down models of the broader economy. The term “top” is referred to aggregate models and the term “bottom” is referred to disaggregated models.

Böhringer and Rutherford (2008) define bottom-up models as computation of the least-cost combination of energy system activities to meet a given demand for final energy or energy services subject to technical restrictions and energy policy constraints and Nakata (2004) defines top-down models as adressing the feedback between the energy sector and other economic sectors, and between the macroeconomic impacts of climate policies on the national and global scale. The key parameter of the top-down models is elastcities of substitution "esub". Esub parameter indicates substitutability between any two pairs of aggregate inputs as their relative prices change (Bataille *et al.*, 2006)

Nakata describes the different features of top-down models and bottom-up models as shown in (Table 2.1).

Table 2.1. Comparison of top-down models and bottom-up models.

Top-down models	**Bottom-up models**
Use an economic approach	Use an engineering approach
Cannot explicitly represent technologies	Allow for detailed description of technologies
Most efficient technologies are given by the production frontier	Efficient technologies can lie beyond the economic production frontier suggested by market behavior
Use aggregated data for predicting purposes	Use disaggregated data for exploring purposes
Based on observed market behavior	Independent of observed market behavior
Disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	Disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
Determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
Assumes no discontinuities in historical trends	Assumes interactions between energy sector and other sectors are negligible

Data Source: Nakata, 2004.

Nakata’s main concept of energy-economic models is represented in Figure 2.1.

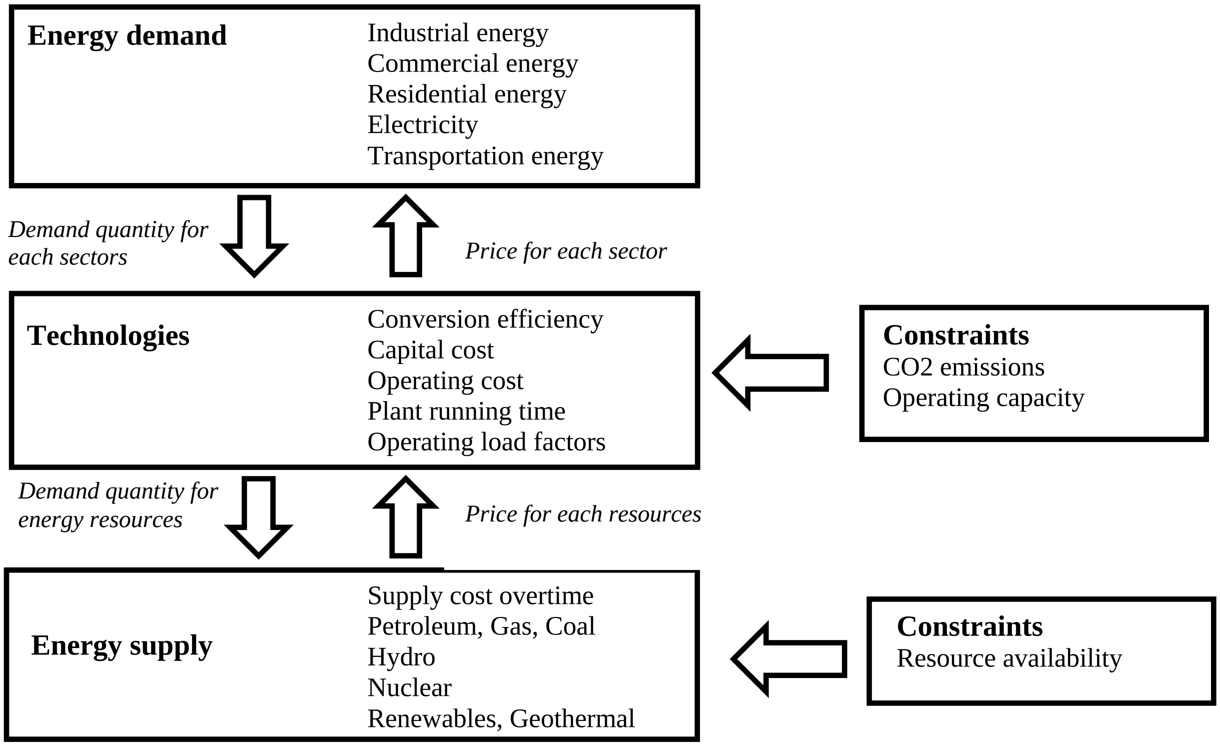

Figure 2.1. Main concept of energy-economic models.

Jaccard and others (Jaccard *et al.*, 2003) indicate that policy makers have faced difficulties to make desicions between bottom-up or top-down models to use. The top-down/ bottom-up debate first came to prominence during the efficiency-gap debate of the 1980s and '90s (Grubb *et al.*, 1993).

IPCC explains top down and bottom up models as follows: top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider technological options or project specific climate change mitigation policies.

Bottom-up analysis are mainly used by engineers and environmental advocates in order to analyze the effects of technological changes on energy use and environmental results of these changes. On the other hand, top-down analysis are used by economists in order to determine the relationships between economic inputs and the energy (Bataille *et al.*, 2006).

Bottom-up models (disaggregated models) and top-down models (aggregated models) both have advantages and disadvantages. From primary energy sources to end-use enegy demands, all processes including distribution and transportation of energy sources are represented in a detailed manner in bottom-up models. However, these models do not have any macroeconomic perspective. Top down models, on the other hand, have a macroeconomic perspective and are able to evaluate market interactions. However, these models do not represent technological details of the energy system (Böhringer and Rutherford, 2008).

2.1. Top-Down Models

The classification of top-down energy policy models are indicated in Table 2.2.

Table 2.2. Top-down models.

IO Models	**IA Models**	**CGE/AGE Models**	**Econometric Models**
MEPA – 1981	MESSAGE – 1981	HERMES – 1989	POLES – 1990
ENDAM – 1995	IMAGE – 1990	GREEN – 1992	QUEST – 2004
MIS - 1997	RAINS – 1990	SGM – 1993	E3ME - 2006
	CASM – 1991	GEM-E3 – 1995	
	IMAGE 2.0 - 1992	GTAP-E – 2002	
	CETA – 1992	AIM – 2006	
	PAGE - 1993	ICES - 2009	
	DICE – 1994		
	SLICE – 1994		
	ESCAPE – 1994		
	AIM – 1995		
	MERGE - 1995		
	TARGETS – 1997		
	ERIS - 1997		
	ICAM - 1998		
	IIAM - 1998		
	ASAM – 1999		
	RICE – 1999		
	FUND - 2000		
	WorldWater – 2002		
	WITCH – 2006		
	MAGICC – 2008		
	ANEMI – 2010		
	GCAM – 2010		
	RIAT, MINICAM-2012		

2.1.1. Input-Output Models

Input/output (I/O) models are composed of linear equations that inputs in one industry sector produce outputs for another industry sector. Every industry uses and produces many products, and that some products are produced by more than one industry (Rosenbluth, 1968).). I/O models are based on national input/output tables and can be used to compute many of the direct and indirect effects of mitigation policies and demonstrate the direct and indirect relations of energy or environmental goods or sectors (Bosello *et.al*., 1998).

I/O models are mostly developed to examine the final demand side effects at a national level (Bosello *et.al*., 1998) and they are mostly criticized for missing the feedback mechanism between energy demand and supply (Rosenbluth, 1968). To eliminate these deficiencies, input-output models are frequently combined with detailed econometric models and run iteratively (Rey, 1998). L'Esperance (1981:120) sees the integrated macroeconometric models and I/O models as a more consistent treatment of final demand.

Macroeconomic Information System (MIS) model (Kemfert and Kuckshinrichs, 1997), Energy Economy Environmental Damage Model (ENDAM) (Hawdon and Pearson, 1995) and Massachusetts Economic Policy Analysis (MEPA) model (Stevens *et al*., 1981) are I/O modeling frameworks. In the MIS framework, GDP growth rate is introduced to the model exogenously and the model describes the development of different sectors in detail. The MEPA framework is initially developed as a macroeconomic model with a production function which enables substitution among inputs (Stevens *et al*., 1981). ENDAM is developed for the case of UK and is used to analyze both the changes in exogenous variables and changes in structural matrices. This model stimulates the effects of many policies.

2.1.2. Integrated Assessment Models

Integrated Assessment Model (IAM) combines optimization decisions with environmental submodels (Bosello et.al., 1998). The aim of this modeling approach is to determine the effetcs of climate change control policies (Tol, 2002; Weyant *et al*., 1996).

IAMs calculate costs and benefits of environmental policy, and mostly applied in global economic and environmental simulations (Bosello et.al., 1998).

Cantore (2009) indicates the disadvantages of IAMs as, these models neglect transmission channels between policies and relevant variables and offer opposite conclusions for crucial assumptions.

DICE is a highly aggregated model with a one sector, one-region representation (Nordhaus, 1994). However, the high level of aggregation is often criticized for bringing uncertainties to data and parameters (Funtowicz and Ravetz, 1994).

MERGE (Manne *et al*., 1995) forecasts the effects of greenhouse gas reductions in both regional and global scale. MERGE deals with controversial issues such as costs of abatement or harm from climate change and explores alternative solutions of climate change (Manne, 2004).

Energy technologies and energy resources in CETA are the inputs of an energy sub-model and they provide energy for the production sub-model. Energy, labor and capital are the inputs of the production sub-model and they provide output which is then distributed to investment, consumption,energy costs and damage costs of warming (Peck and Teisberg, 1992).

GCAM examines large scale and long term changes in regional and global energy systems (Smith *et al*., 2010). GCAM explores emerging energy supply technologies potential role and policy measures' greenhouse gas (GHG) consequences. In addition, GCAM deals with energy technology adoption such as hydrogen systems, CO_2 capture and storage, renewable energy technology, energy use in industry, residential and transportation sectors (Clarke *et al*., 2007).

MINICAM is a well-roundend model that aims to reveal the dynamics of human climate interaction concerning emissions that result in global warming (Scott *et al*., 1999).

Earlier versions of IMAGE are defined in Rotmans (1990) and Rotmans *et.al.(1990).* IMAGE 2.0 is an integrated assesment model that includes a very detailed analysis of land use (Alcamo, 1994). One of the main aims of IMAGE 2.0 is to provide insight into the relative importance of different linkages in the society-biosphere-climate system (Alcamo *et.al.*, 1994).

2.1.3. Computable/Applied General Equilibrium Models

General equilibrium models (GEM) describe the total economy through the behaviour of optimising producers and households (Bosello et.al., 1998). GEMs use non–linear substitution-based production functions of the CES type to describe production behavior and the same type of functions to describe the consumption behavior of economic agents (Bosello *et.al*., 1998). The energy sector, like non-energy sectors, is mostly represented in an aggregate way by means of production functions, which capture substitution possibilities through elasticity of substitution (Karali, 2012).

GEMs are classified under two main approaches, namely Computable General Equilibrium (CGE) and Applied Gneral Equilibrium (AGE) models. CGE models are able to represent real-world macroeconomic responsiveness to policies to identify the orders of magnitude, of the resulting economic effects (Allan *et al*., 2007). CGE models are more likely used compared to AGE models. Examples of CGE models are GREEN (A Global Model for Quantifying The Costs of Policies to Curb CO_2 Emissions) of Burniaux *et al*. (1992), the EU (European Union) model GEM-E3 (Computable General Equilibrium model for Studying Economy-Energy-Environment Interactions) of Capros *et al*. (1995), the SGM (Second Generation Model) model of Fisher-Vanden *et al*. (1993), HERMES (Harmonized Econometric Research for Modeling Economic Systems) model of Mot *et al*. (1989), and GTAP-E (Global Trade Analysis Project - Energy) Model of Burniaux and Truong (2002).

GREEN mainly focuses on energy production and consumption (Nakata, 2004).

GREEN highlights the relationships between depletion of fossil fuels, energy production and use, and CO_2 emissions. Energy sector with the linkeage of economy is the primary focus of GREEN models (Burniaux and Truong, 2002).

GEM-E3 is a multi-sector and multinational general equilibrium model for energy–economics–environment (Nakata, 2004). GEM-E3 represents energy supply, consumption and pollution in a detailed way and formulates supply and demand trends based on production, consumption, investment and employment with the share of their financial assets (Van den Bergh, 1999).

SGM is specifically designed to analyze the climate problem caused by energy consumption (Fisher-Vanden *et al*., 1993).

HERMES has been developed to analyze economic development in the various European member states (Mot *et al*., 1989).

GTAP is a multi-regional applied general equilibrium model which represents the global economy. The aim of developing this model is to reduce the cost of entry for those which seek to conduct international economic issue analyses issues in an economy wide framework (Hertel and Tsigas, 1997). The extended version of the GTAP model is GTAP-E which enables carbon emissions internationally (Hertel and Tsigas, 1997).

2.1.4. Econometric Models

Econometric models have been developed as pure economic models to deal with the climate change issue by using a production function or a firm cost function to estimate energy demand (Bosello et.al., 1998). Examples of the economic modeling category are the POLES (developed by Institute of Energy Policy and Economics in Grennoble,1990), E3ME (developed by Cambridge Econometrics team, 2007, QUEST (developed by Rooger and Veld,2004).

POLES (Prospective Outlook on Long-Term Energy Systems Model), provides long-term scenarios for energy supply and demand. There are interconnected sub models in the model according to their regional, national and international level.

E3ME (Energy-Environment-Economy Model for Europe) was originally developed through the European Commission's research framework programmes and today used worldwide to address major economic and economy-environment policy challenges.

QUEST (A Macro-Econometric Model for EUC Countries) is designed to analyze the economies of European Union members. The older version of QUEST was based on the Keynesian tradition of econometric models and new version is based on the behavioural equations on fundamentals of dynamic optimisation of private households and firms (Rooger and Veld,2004).

2.2. Bottom-Up Models

Some of the most popular bottom-up energy models are indicated in Table 2.3.

Table 2.3. Bottom-up models.

Bottom-up Models
MARKAL
TIMES
MESSAGE
EFOM-ENV
LEAP
MIDAS
PRIMES

MARKAL (Market allocation model) is a widely applied bottom-up, dynamic linear programming (LP) model developed by the Energy Technology Systems Analysis Programme (ETSAP), of the IEA. It can be applied to scenarios or cases which embody a variety of assumptions or restrictions (Nakata, 2004).

MARKAL model includes Market allocation Model with Linear Programming (MARKAL-LP), Market allocation Model Combined with a Macro Model (MARKAL-MACRO), Market allocation Model Combined with a Micro Model (MARKAL-MICRO-NLP) and Market allocation Model Combined with a Micro Model –Stepwise ED-LP (MARKAL-ED-LP) models. The model is written in GAMS (a generalized algebraic modeling system). MARKAL does not represent economy by itself. Therefore, sub-model MACRO is added into the model in order to compensate model's economic aspects.

TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses long term energy scenarios to conduct in-depth energy and environmental analyses (Loulou *et al*., 2004).

TIMES is a developed version of MARKAL model and provides a technology-rich infrasracture. TIMES can be applied for both single or multi-region energy systems.

MESSAGE (Model for Energy Supply Systems and Their General Environment) has been developed at the International Institute for Applied Systems Analysis (IIASA) which is built as a dynamic linear programming optimization model and especially applied for complex, multi-regional models (Gritsevskyi and Nakicenovic, 2000). The objective of the model is to minimize total costs of energy supply over a given time horizon. There are more than 100 different technologies in the model. Main characteristics of the model are the consideration of load regions for electricity demand and the environmental impact of energy supply strategies, the disaggregation of resources into cost categories. (Schrattenholzer, 1981).

MESSAGE and MARKAL are both optimization models that make decisions among different technologies based on abatement costs and $C0_2$ emission targets. Both models use stochastic optimization technique to investigate the substantial uncertainty related with the time of arrival and performance of new technologies (Loschel, 2002).

LEAP (the Long-range Energy Alternatives Planning System) is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy (Heaps, 2016). LEAP uses a computer-based approach for creating integrated and reliable energy planning. The model is a fixed coefficient model runs on EXCEL spreadsheet (Nakata, 2004). It can be used for both multi-country regions and local purposes.

EFOM-ENV (Energy Flow Optimization Model) is a national dynamic optimization model. The sectors of energy production and consumption in EFOM-ENV are represented in each member state (Nakata, 2004). The model uses linear programing. Import fuel prices and energy demands are introduced to the model exogenously. National energy systems are subjected to energy and environment constraints such as emission standards and the availability of fuel supplies (Nakata, 2004).

MIDAS (Mini-Climate Assessment Model) is a large scale system of country-specific energy models for medium-term energy planning developed for European countries (Capros and Karadeloglu, 1992). MIDAS is a simultaneous system that composes of more than 1500 equations which are solved dynamically over a period of 10 years (Capros and Karadeloglu, 1992).

PRIMES (The Primes Energy System Model) is a partial equilibrium model for energy–environment analysis within the context of market driven behavior (Nakata, 2004). The model is solved under GAMS and it is formulated as a non-linear mixed complementarily problem.

While bottom-up and top-down models are still used a deal, many researchers are developing "hybrid" models that seek compensate for the limitations of one approach (Hourcade *et al.*, 2006).

2.3. Hybrid Models

Hybrid models cover technological explicitness of bottom-up models with the economic comprehensiveness of top-down models (Hourcade *et al*., 2006). ETA-Macro (Manne (1977)) and MERGE (Manne,Mendelsohn and Richels (2006)) are the main examples of hybrid models which link a bottom-up energy system model with a highly aggregate one-sector macro-economic model of production and consumption within a single optimization framework (Böhringer and Rutherford, 2007).

Examples of hybrid models are the NEMS (National Energy Modeling System of USA) model of DOE (2009), the MARKAL-MACRO model of Manne and Wene (1992), the HERMES-MIDAS model of Capros and Karadeloglu (1992), the MESSAGE-MACRO model of A. Gritsevskyi and Schrattenholzer (2003), the ETA-MACRO model of Manne (1977) and MDM 3M model of Barker and Peterson (1987).

Hybrid policy models are indicated in Table 2.4.

Table 2.4. Hybrid models.

Hybrid Models
MARKAL-MACRO
NEMS
ENVEES
ETA-MACRO
HERMES-MIDAS
SCREEN
MESSAGE-MACRO
CIMS
TIMES-MACRO

NEMS model represents the interactions of supply and demand in U.S. energy markets. The model has end-use demand modules in order to represent fuel usage in the residential, transportation, commercial and industrial sectors. These demands are subjected to fuel prices, macro economic affects, and technology features. On the other hand, energy supply and conversion modules determine domestic production and import levels, energy supply costs to meet end-use demands. NEMS uses gross domestic products (GDP) as a key variable for forecasting of energy consumptions. In this way, changes in energy price affect the main macro-economic variables which are gross domestic product, disposable personal income, housing starts, employment, industrial output, and interest rates (EIA, 2009).

MARKAL-MACRO (Manne and Wene, 1992) is the result of merging two existing model, the MARKAL and the MACRO, approaches into a model (Loulou *et al*., 2004b). The MARKAL is a mathematical model of the energy system that aims to supply energy services at minimum global cost and to operate decisions and make investment by region (Loulou *et al*., 2004a). Maximization of a utility function subject to a national budget constraint is the objective of the MACRO part (Allen, 1968). Merging these two models result in a new model that captures the characteristics of an intertemporal general equilibrium model, while retaining the rich technological detail of MARKAL (Loulou *et al*., 2004b).

HERMES model is a compact energy-economy model that is considered as equivalent to traditional neo-Keynesian macroeconometric models enhanced by the inclusion of energy within the set of production factors and MIDAS is a medium-term annual energy model, combining econometric with process analysis formulations (Capros *et.al.,* 1989). HERMES model can forecast energy related issues. However, the model fails to represent the engineering oriented aspect of energy issues. These requirements are met by MIDAS model as HERMES model has been linked to MIDAS model. Energy equations in HERMES modules and macroeconomic equations in MIDAS are eliminated in the linkage model which is called as HERMES-MIDAS hybrid model.

The linkeage between MESSAGE which is an energy supply model with MACRO which is a non-linear macroeconomic model generates MESSAGE–MACRO model. The main difference between the MARKAL-MACRO and the MESSAGE–MACRO approaches is that MARKAL–MACRO is a single model with complete integration, whereas MESSAGE–MACRO is solved by running two different models separately and applies iteration between these two models’ inputs until consistency between the energy and the macroeconomic part is achieved (Messner and Schrattenholzer, 2000).

ETA-MACRO modeling framework has a two-way linkage between the energy sector and the general economy (Manne, 1977). ETA-MACRO is a precursor of MARKAL-MACRO (Manne and Richels 1992), where the ETA module was however a less detailed energy supply module than MARKAL is (Loulou *et al*., 2004b).

TIMES-MACRO model is a result of linking the bottom-up energy systems model TIMES with the top-down model MACRO (Remme and Blesl, 2006). The approach for linking TIMES model with Macro model is similar to the MARKAL model with the Macro model. The purpose of the TIMES-MACRO is the integrated modeling of macro-economic impacts within the TIMES framework (Kypreos and Lehtilla,2014).

3. THE BUEMS MODELING FRAMEWORK

3.1. Description of the BUEMS Model

BUEMS is a linear optimization model with a bottom-up structure which evaluates different energy policies and long-term effects of investment alternatives. BUEMS is designed to reflect Turkish energy system and is built to satisfy the need for a national model representing local technology structure.

The objective of the BUEMS is to minimize total system cost, while meeting the useful energy demands and determining the primary energy supply levels, subject to a set of constraints over the pre-defined planning horizon. GAMS programming language has been used to solve the model.

A significant advantage of BUEMS model is that BUEMS does not need a vast level of data. The relations, parameters, commodity groups and technologies in the model are simplified compared to similar modeling structures such as MARKAL and TIMES. The reduction in data requirements does not lead to loss in accuracy as shown by Isık (2016).

3.2. Structure of the BUEMS Model

There exists two basic components in the BUEMS model which are technologies and commodities. The set of energy carriers compose of commodities that are generated or processed by technologies. There are a total number of 209 energy carriers in the model which consist of coal, natural gas, petroleum, nuclear, hydropower, wind, solar, geothermal and hydrogen energy sources.

The following sections explain technologies and variables in the BUEMS model.

3.2.1. Technologies and Parameters

Every process that converts one commodity into another is referred to as a technology. There are three different types of technologies in the model which are connected to each other via energy sources.

3.2.1.1. Supply Technologies.

These technologies introduce energy sources into the system. Energy sources can be provided domestically and externally. “Domestic Technologies” are classified into two subcategories: “extracted (mining) technologies” and “renewable technologies”. On the other hand, imported resources are provided by “import technologies”. “export technologies” are also included in supply technologies.

BUEMS model includes fossil fuels and renewable energy sources. Fossil fuels are coal, natural gas, oil, heavy fuel oil, light fuel oil, jet fuel and kerosene, whereas renewables are wind, solar, hydroelectric and geothermal energy. BUEMS model also includes hydrogen as an energy source and nuclear power energy that needs uranium as an energy source.

There are a total number of 108 of energy resource technologies in the BUEMS model. This total includes 14 technologies that belong to export resource technologies, 32 technologies that belong to import resource technologies, 44 technologies that belong to extracted resource technologies and remaining 18 of them belong to renewable resource technologies.

Supply technologies introduce energy carries into the model with a unit cost and without any input necessities. Supply costs are specified for fossil fuels. Fossil fuels supply costs play a significant role in the objective function which aims to minimize the total system cost. Renewable energy sources do not have any supply costs.

The classification of energy resources is given in Table 3.1.

Table 3.1. Supply technologies.

Supply Technologies
Import Technologies
Mining Technologies
Renewable Technologies
Export Technologies

Supply levels are limited by annual and cumulative bounds. Annual supply bounds put limitations on import and export activities. Also these bounds are used for renewable energy resources, since renewable energy resource availability relies on the weather and when sufficient conditions are not met, it is impossible to produce energy from renewables. Cumulative supply bounds, on the other hand, put limitations on the total supply of supply technologies over the entire planning horizon. Each technology has its unit supply cost and decay and growth bounds. These bounds indicate maximum decay/growth rate of supply level between the consecutive periods.

The main parameters of supply technologies are indicated below:

- *bound_s_upper(s,t)* : upper bound on the capacity of a supply technology
- *bound_s_lower(s,t)* : lower bound on the capacity of a supply technology
- *bound_s_fix(s,t)* : fix bound on the capacity of a supply technology
- *cum(m,cm)* : supply cumulative capacity
- *decayr(m,t)* : decay rate of a supply technology
- *growthr(m,t)* : growth rate of a supply technology
- *scost(m,t)* : supply cost
- *envsep(m,t)* : emission factor for supply technologies at period t

The contribution of these parameters' to the model will be explained in the equations section in detail.

3.2.1.2. Energy Conversion Technologies. An energy carrier is transformed to another energy carrier by energy conversion technologies. Energy conversion technologies are separated into three subcategories.

Table 3.2. Energy conversion tecnologies.

Energy Conversion Technologies
Electricity Generation Technologies
LTH Generation Technologies
Process Technologies

"Electricity Generation Technologies" produce electricity. "LTH Generation Technologies" produce LTH and "Process Technologies" produce remaining energy sources such as ethanol, methanol, coke and hydrogen.

The main parameters of energy conversion technologies are indicated below.

- *af (m,t)* : annual availability factor of the technology m at period t
- *baseload(e,t)* : the highest percentage of the baseload power plants in total electricity generation:
- *bound_p_fix(m,t), bound_p_upper(m,t)* : annual fix and upperbounds on the capacity of a technology at period t
- *bound_k_lower(m,t), bound_k_fix(m,t), bound_k_upper(m,t)* : annual lower, fix and upper bounds on the activity of a process technology at period t
- *bound_c_lower(m,t), bound_c_fix(m,t), bound_c_upper(m,t)* : annual lower, fix and upper bounds on the activity of a conversion technology at period t
- *bounds(b,t)* : annual bounds on scenario constraints at period t
- *ibond(m,t), ibondfx(m,t), ibondlo(m,t) :* annual lower, fix and upper bounds on the investment of the technology m at period t
- *capunit(m,t) :* unit conversion factor between capacity and activity of the technology m at period t

- *decay(m,t)* : maximum capacity decay rate of the technology m between consecutive periods
- *growth(m,t)* : maximum capacity growth rate of the technology m between consecutive periods
- *invcost(m,t)* : investment cost per unit of new capacity addition of the technology m at period t
- *edistinv(m,t)* : unit investment cost for electricity distribution system of electricity generation technology at period t
- *etraninv(m,t) :* unit investment cost for electricity transmission system of electricity generation technology at period t
- *dtraninv(m,t)* : unit investment cost for LTH transmission system of LTH generation technology at period t
- *dtranom(m,t)* : unit O&M cost for LTH transmisson system of LTH generation technology at period t
- *etranom(m,t)* : unit O&M cost for electricity transmisson system of electricity generation technology at period t
- *edistom(m,t)* : unit O&M cost for electricity distribution system of electricity generation technology at period t
- *ereserv(e,t)* : peak reserve factor for electricity generation
- *hreserv(e,t)* : peak reserve factor for LTH generation
- *fixom(m,t)* : fixed operation and maintenance cost per unit capacity of the technology m at period t
- *varom(m,t)* : variable operation and maintenance cost per unit activity of the technology m at period t
- *inpent :* level of input requirement per unit of technology activity
- *outent :* level of output generation per unit of technology activity
- *limit(m,t) :* activity limitation on a multiple output technology
- *refinhlm(e,t) :* “refinery parameter 1” for activity limitation on a multiple output technology

- *refinstd(e,t)* : “refinery parameter 2” for activity limitation on a multiple output technology
- *cokeprod(e,t) :* level of coke production of the technology e
- *life(m,l) :* useful lifetime of the technology m
- *peakcon(m,t)* : the fraction of the technology m’s capacity that should be credited towards the peaking requirement at period t
- *qhr_d(m,t)* : fraction of the year "day share"
- *qhr_n(m,t)* : fraction of the year "night share"
- *qhr_w(m,t) :* fraction of the year "winter share"
- *qhr_s(m,t) :* fraction of the year "summer share"
- *resid(m,t) :* residual capacity that was invested prior to the start of the planning horizon
- *teent(e,t)* : transmission efficiency of electricity
- *envact(m,t)* : emission factor for process technologies at period t
- *cumem(v,cme) :* cumulative emission level of emission type v
- *envcost(v,t) :* emission cost per unit emission

The contribution of these parameters’ to the model will be explained in the equations section in detail.

3.2.1.3. Demand Technologies. These technologies are end-use technologies that convert energy carriers into the final energy demands.

Demand technologies have similar parameters with energy conversion technologies except two parameters. Demand technologies have capacity and investment variables. However, they do not have any variables for their activity level. The activity level of a demand technology is a particular proportion of the capacity variable and it is represented by a specific parameter which is referred to as a “capacity utilization factor”. This factor gives the share of capacity that is active in the related period (This parameter is different than annual availability factor which gives the maximum share of the available capacity in the related period for energy conversion technologies). Then, unit conversion factor “capunit” is used for making the capacity level unit and the activity level unit the same.

Demand technologies' efficiency rate is indicated with a specific parameter which is represented as "*eff(m,t)*" in the model. On the other hand, there is no assigned efficiency rate parameter for energy conversion technologies. These technologies' efficiency rate is determined by their input/output ratio.

The parameters which are different than conversion technologies are indicated below.

- *cf(m,t)* : capacity utilization factor
- *eff(m,t)* : efficiency rate of demand technologies
- *demand(dm,t)* : level of sectoral demand dm at period t

Demands are provided exogenously into the model for the base year 2012. Sectoral energy demands of future periods are externally estimated according to GDP projections. Demand data is taken from Isik (2016).

Demand technologies are classified in sectors. There are five main demand sector technologies in the model, and there exists sub-sector demands for each sector. There are 99 sub-sector demands in total in the model. The descriptions of all demand technologies are displayed in the Appendix CD folder.

Table 3.3. Demand technologies.

Demand Technologies
Agriculture Sector Demand Technologies
Residential Sector Demand Technologies
Service Sector Demand Technologies
Industry Sector Demand Technologies
Transport Sector Demand Technologies

Agriculture sector demands are based on energy carriers such as bio-waste, coal, diesel, electricity and natural gas. The residential sector demands are grouped in two categories, one of them is for "existing houses" and the other is for "new houses". The service sector energy demands are grouped in 6 different sub-sectors, namely accommodation, commercial, education, governmental building, health care and office retail. The industry sector energy demands are divided into 10 sub-sectors, namely aluminum, cement, chemical, food & beverage, glass, iron & steel, nonferrous, pulp & paper, textile and other sector. The transportation sector demands are grouped in terms of transport type such as air, road, rail and sea, then vehicle types are also classified such as car, bus, minibus, etc.

3.2.2. Variables

There are two types of variables in the model: optimization variables and accounting variables. Optimization variables are used in optimization procedure. However, accounting variables are not used in optimization procedure. These variables are used for accounting and reporting purposes.

Supply, capacity, activity, investment, emission and discounted cost variables are optimization variables.

Supply technologies have only one desicion variable and this is for the level of supply (resource) production. It is represented as “*r_tsep*” in the model. Energy conversion technologies have three desicion variables. Each period capacity, investment and activity levels of each conversion technologies are determined with these variables. They are represented as “*r_cap*”, “*r_act*” and “*r_inv*” in the model. Similar to energy conversion technologies, demand technologies have also capacity and investment desicion variables. But they do not have any variables for activity level. On the other hand, emission variable provides information about emission level and it is represented by “r_em” in the model.

- *r_tsep (m,t)* : supply level of technology m at period t. Units are PJ per year for all supply technologies.

- *r_cap (m,t)* : installed capacity of technology m in period t. Units are PJ per year for all technologies.
- *r_inv (m,t)* : new capacity addition for technology m in period t. Units are GW for electricity conversion technologies, million tonnes per year for industy demand technologies, billion vehcile-kilometers per year for transportation demand technologies, and PJ per year for other technologies.
- *r_act (m,t)* : activity level of technology m in period t. Units are PJ per year for all energy technologies.
- *r_em (v,t)* : level of emissions for emission type v in period t. Units are million tonnes of CO_2.

Cost variables are seperated into two different groups as discounted and undiscounted costs. Undiscounted costs are used for accounting and reporting purposes. Discounted costs are used in the objective function.

3.3. Equations/Constraints of the BUEMS Model

Equations in BUEMS model consist of two types which are constraint and non-constraint equations. The model has to meet constraints' requirements during the optimization process. On the other hand, when model results need to be reported, non-constraint equations are used.

There are 14 groups of constraints in the model: (i) Objective function and cost constraints, (ii) Energy balance constraints, (iii) Demand satisfaction constraints, (iv) Accounting constraints, (v) Capacity transfer constraints, (vi) Capacity-activity relationship constraints, (vii) Cumulative supply limit, (viii) Activity limitation on a multiple output technology, (ix) Electricity and LTH peaking constraint, (x) Baseload constraint for electricity production, (xi) Periodic emission constraints, (xii) Emission bound, (xiii) Cumulative emission limit, (xiv) Periodic limitations, (xv) Intertemporal decay/growth constraints

3.3.1. Objective Function and Cost Constraints

3.3.1.1. Total System Cost- The BUEMS Objective Function. The objective of the BUEMS model is to minimize the total cost of the system. The total system cost is obtained by the summation of the discounted annual costs of each period.

$$totcost = \sum_{t} disanntcost(t) \tag{3.1}$$

where

- *disanntcost(t)* : discounted annual total system cost at period t
- *totcost* : total system cost

Discounted annual total system cost of each period is calculated from undiscounted annually adjusted total system cost. Undiscounted annually adjusted total system cost of period t is summation of annual supply, investment, fix, variable and environmental cost of period t in all undiscounted form.

$$\begin{gathered} undanntcost(t) = \\ undannsupply(t) + undanninv(t) + undannother(t) + undannenv(t) \end{gathered} \tag{3.2}$$

where

- *undanntcost(t)* : undiscounted annually adjusted total system cost

Undiscounted annually adjusted total system cost is calculated as,

$$\begin{aligned} undanntcost(t) = &\sum_{m}(scost(m,t) * r\_tsep(m,t)) \\ &+ \sum_{m}(edistom(m,t) * r\_act(m,t)) \\ &+ \sum_{m}(etranom(m,t) * r\_act(m,t)) \\ &+ \sum_{m}(dtranom(m,t) * r\_act(m,t)) \\ &+ \sum_{m}\sum_{u}^{t}(costinv(m,u) * r\_inv(m,u)) \\ &+ \sum_{m}(fixom(m,t) * r\_cap(m,t)) \\ &+ \sum_{m\in k\cup c} varom(m,t) * r\_act(m,t)) \\ &+ \sum_{m\in d} capunit(m,t) * cf(m,t) * varom(m,t)) * r\_cap(m,t)/eff(m,t)) \\ &+ \sum_{v}(envcost(v,t) * r\_em(v,t)) \end{aligned} \tag{3.3}$$

where

- *undannsupply* : undiscounted annually adjusted total supply cost
- *undanninv* : undiscounted annually adjusted total investment cost
- *undannother* : undiscounted annually adjusted total other cost
- *undannenv* : undiscounted annually adjusted total environmental cost

"undannsupply" cost is represented by first four summations, *"undanninv"* cost is repsented by fifth summation, *"undannother"* cost is represented by sixth and seventh summations and *"undannenv"* cost is represented by the last summation accordingly. Parameters in the calculation are described in the following sections in detail.

There is also undiscounted total system cost which is different than undiscounted annually adjusted total system cost by means of its investment cost.

Undiscounted total system cost is represented as,

$$
\begin{aligned}
undtcost(t) = {} & \sum_{m}(scost(m,t) * r\_tsep(m,t)) \\
& + \sum_{m}(edistom(m,t) * r\_act(m,t)) \\
& + \sum_{m}(etranom(m,t) * r\_act(m,t)) \\
& + \sum_{m}(dtranom(m,t) * r\_act(m,t)) \\
& + \sum_{m}\sum_{u}^{t}\big(invcost(m,t) + edistinv(m,t) + etraninv(m,t) + dtraninv(m,t)\big) \\
& \quad * r\_inv(m,t)/5) \\
& + \sum_{m}(fixom(m,t) * r\_cap(m,t)) \\
& + \sum_{m \in k \cup c} varom(m,t) * r\_act(m,t)) \\
& + \sum_{m \in d} capunit(m,t) * cf(m,t) * varom(m,t)) * r\_cap(m,t)/eff(m,t)) \\
& + \sum_{v}(envcost(v,t) * r\_em(v,t)) \\
& - \sum_{m}(salvinv(m,t) * r\_inv(m,t))
\end{aligned}
\tag{3.4}
$$

where

- *undtcost(t)* : undiscounted total system cost

In this equation, investment cost is not in annualized form. However, it needs to be annualized. Because it is paid once at the period, when investment is realized. For this reason, it is different than the other costs in the total system cost. Annualization is achieved according to the lifetime of the technology. In this regard, capital recovery factor is used.

The fifth summation in the "*undtcost*" calculation is multiplied by "*crf*" to obtain discounted annual investment cost.

$$costinv(m,t) = crf(m) * invcost(m,t) + edistinv(m,t) + etraninv(m,t) + draninv(m,t) \tag{3.5}$$

where

- crf : capital recovery factor
- $costinv$: discounted annual investment cost

After calculating *"undanntcost",* period discount factor is used to calculate "disanntcost".

Discounted annual total system cost is represented as;

$$\begin{aligned} disanntcost(t) = & \sum_{m} pridf(t) * scost(m,t) * r\_tsep(m,t)) \\ & + \sum_{m} (pridf(t) * fixom(m,t) * r\_cap(m,t)) \\ & + \sum_{m \in k \cup c} pridf(t) * varom(m,t) * r\_act(m,t)) \\ & + \sum_{m \in d} pridf(t) * capunit(m,t) * cf(m,t) * varom(m,t)) \\ & \qquad * r\_cap(m,t)/eff(m,t)) \\ & + \sum_{m} (pridf(t) * edistom(m,t) * r\_act(m,t)) \\ & + \sum_{m} (pridf(t) * etranom(m,t) * r\_act(m,t)) \\ & + \sum_{m} (pridf(t) * dtranom(m,t) * r\_act(m,t)) \\ & + \sum_{m} (priinv(m,t) * r\_inv(m,t)) \\ & + \sum_{v} (pridf(t) * (envcost(v,t) * r\_em(v,t)) \end{aligned} \tag{3.6}$$

where

- $pridf$: period discount factor

As mentioned above, the total discounted annual system costs of each period are summed to obtain the total cost of the system that the BUEMS aims to minimize.

The following sections elaborate supply, investment, fix, variable and environmental costs.

3.3.1.2. Total Annual Supply Cost. All costs related with providing energy carriers to the model at period t constitute annual supply cost.

Supply costs are separated into two types which are treated differently in the total supply cost calculation. Domestic resource supply costs (mining and renewable supply costs) positively contribute to the total supply cost. Import supply costs are considered as additional costs and they also positively contribute to total system cost. However, since export technologies are considered as revenues, these types of costs are multiplied with a minus sign, when total system cost is calculated.

For energy conversion technologies, delivery cost of the input energy carrier is also taken as an annual supply expenses. In addition to that, transmission and distribution costs of LTH and electricity are also included into annual supply cost.

(i) *Total Undiscounted Annual Supply Cost:* Total undiscounted annual supply cost in the model includes the total cost of supplying energy resources, transmission and distribution costs for electricity and transmission cost for LTH generation.

$$\begin{aligned} undannsupply(t) = &\sum_{m \in s} (\, scost(m,t) * \ r\_tsep(m,t)) \\ &+ \sum_{ce \in s} edistom(m,t) * outent(m,t) * r\_act(m,t) \\ &+ \sum_{ce \in s} etranom(m,t) * outent(m,t) * r\_act(m,t) \\ &+ \sum_{ch \in s} dtranom(m,t) * outent(m,t) * r\_act(m,t) \end{aligned} \tag{3.7}$$

The first summation mark represents that unit supply cost of each supply technology is multipled by the total supply level of this resource technology at period t.

- *r_tsep(m,t)* : the level of supply technology variable m at period t
- *scost(m,t)* : unit supply cost of technology m at period t

The second and the third summation marks represent the total costs of distributing and transmitting electricity.

- *edistom(m,t)* : Unit operational cost for distribution of electricity at period t
- *etranom(m,t)* : Unit operational cost for transmission of electricity at period t

The fourth summation mark represents the total cost of transmitting LTH.

- *dtranom(m,t)* : Unit operational cost for transmission of LTH

(ii) *Total Discounted Annual Supply Cost:* Total undiscounted annual supply cost is multiplied by discount factor to form total discounted annual supply cost.

$$disannsupply(t) = pridf(t) * undannsupply(t) \tag{3.8}$$

where

- *disannsupply* discounted annually adjusted total supply cost

$$pridf(t) = \sum_{y=1}^{nyrsper} (1 + discount)^{-(y-1)} * (1 + discount)^{-(startyrs+nysper*(t-1))} \tag{3.9}$$

First multiplier is used for calculating the discounted cost of each year in the period and second multiplier is used for discounting the total discounted period cost to the beginning of the planning horizon.(Exponential expression in the second multiplier indicates the number of years to which all discounted costs are to be calculated.)

3.3.1.3. Annualized Investment Cost. Investment costs are paid for each unit new capacity addition of technology m at period t. But different than the other costs, it needs to be annualized according to technology lifetime as mentioned before. In this regard, capital recovery factor is used to spread the actual investment cost of period t over the lifetime of the technology.

$$crf(t) = discount(m)/(1 - \left(1 + discount(m)\right))^{-life(m)} \tag{3.10}$$

- *crf* : capital recovery factor
- *discount(m)* : discount rate of technology m
- *life(m)* : life time of technology m

(i) *Total Undiscounted Annualized Investment Cost:* The new investment realized at period t and investments which come from previous periods and still exist at that period constitute annual investment cost. As mentioned above, since the annualization is based on the lifetime of the technology, when the related technology's lifetime is over, there is no investment cost to be paid.

First, the annualized investment cost is calculated, and then multiplication of this annualized investment cost and investment variable are summed over technology m

- *costinv(m,u)* : annualized investment cost of technology m at period u

$$\begin{gathered} costinv(m,u) = \\ crf(m) * (invcost(m,t) + edistinv(m,t) + etraninv(m,t) \\ +dtraninv(m,t)) \end{gathered} \tag{3.11}$$

where

- *invcost(m,t)* : unit investment cost of technology m at period t
- *edistinv(m,t)* : unit investment cost for electricity distribution system of technology m at period t
- *etraninv(m,t)* : unit investment cost for electricity transmission system of technology m at period t
- *dtraninv(m,t)* : unit investment cost for LTH transmission system of technology m at period t

$$undanninv(t) = \sum_{m}\sum_{u}^{t}(costinv(m,u) * r\_inv(m,u)) \tag{3.12}$$

where

- *u :* max (0, t-lifetime of the technology (m) / nyrsper)
- *"t-u" represents the interval for available investments* of technology m at period t

Investment is available as a fraction of the last period, when the technology lifetime is not a multiplier of the number of years in a period. In this case, investment cost is also applied for a fraction of the last period. The lifetime of the technology and the number of years in a period are used to determine the fraction rate.

$$fraclife(m) = \left(\frac{life(m)}{nyrsper}\right) - t \tag{3.13}$$

where

- *fraclife(m)* : the last period fraction rate

(ii) *Total Discounted Annualized Investment Cost:* Annualized and discounted investment costs of the system at period t are summed to obtain total discounted annual investment cost.

Similar to the total undiscounted annualized investment cost, unit investment costs for electricity distribution and transmission, and unit investment cost for LTH transmission are summed here. However, in this case, salvage cost is also taken into consideration in the calculation. Since salvage cost is the value of technology m when its life time is over, it is a revenue to the system. For this reason, salvage cost negatively contribute to the system cost and it is multiplied with a negative sign in the calculation.

For the purpose of calculating the total discounted annualized investment cost, first, periodic discount factor is determined and then this factor is used to calculate the discounted actual investment cost. Finally, the discounted actual investment cost is used to obtain the total discounted annualized investment cost.

- *pridisc* : periodic discount factor other than investment

$$pridisc(m,t) = crf(m) * (\frac{1}{1+discount})^{(-startyrs+nyrsper*(t-1))} \tag{3.14}$$

First multiplier (capital recovery factor) is used for annualization and and second multiplier is used for discounting the annualized cost to the beginning of the planning horizon. In this regard, discount factors and annualization are aggregated under the *“pridisc”* parameter.

After *“pridisc”* factor is found, “priinv” is calculated accordingly.

- *priinv(m,t)* : Annualized and discounted unit investment cost of technology m at period t

$$priinv(m,t) = pridisc(m,t) * (invcost(m,t) \tag{3.15}$$
$$+edistinv(m,t) + etraninv(m,t) + dtraninv(m,t) - salvinv(m,t))$$

where

- *salvinv(m,t)* : unit salvage cost of technology m at period t

After “*priinv*” parameter is found, “disanninv” is calculated accordingly.

$$disanninv(t) = \sum_{m} (priinv(m,t) * r\_inv(m,t)) \tag{3.16}$$

where

- *disanninv(t)* : Total Discounted Annualized Investment Cost

3.3.1.4. Fix and Variable Operational & Maintenance Cost. This cost is summation of all fixed and variable costs. For fixed operation and maintenance costs, technology capacities are used. On the other hand, technology activities are used to calculate variable operation and maintenance costs. Since demand technologies do not have any activity variables, these technologies’ activity level is determined by capacity utilization factor. Demand technologies also use unit conversion factor if capacity unit and activity unit are different from one another.

(i) *Total Undiscounted Annual Fix and Variable Cost:* As mentioned above, fixed operation and maintenance cost is applied on capacities for each technology. Variable operation and maintenance cost is applied on technology activities which are calculated differently according to the technology type (energy conversion technology or demand technology).

$$\begin{aligned} undother(t) = & \sum_{m \in k \cup c \cup d} fixom(m,t) * r\_cap(m,t) \\ & + \sum_{m \in k \cup c} varom(m,t) * r\_act(m,t) \\ & + \sum_{m \in d} \big(capunit(m,t) * cf(m,t) * varom(m,t)\big) \\ & * r\_cap(m,t) / eff(m,t) \end{aligned} \tag{3.17}$$

where

- *undother(t)* : undiscounted total other expenditures (fix and variable costs)
- *fixom(m,t)* : fixed operation and maintenance cost per unit capacity of technology m at period t
- *varom(m,t)* : variable operation and maintenance cost per unit activity of technology m at period t
- *capunit(m,t)* : unit conversion factor of technology m at period t
- *cf(m,t)* : capacity utilization factor of technology m at period t
- *eff(m,t)* : technical efficiency

The first multiplier gives the total fixed operation and maintenance cost over all technologies. The second multiplier gives variable operation and maintenance cost for energy conversion technologies and third multiplier gives variable operation and maintenance cost for demand technologies. As it can be seen from the equation, in the third multiplier, capacity is multiplied by capacity utilization factor. Then *"capunit"* is applied, if it is necessary.

(ii) *Total Discounted Annual Fix and Variable Cost:* Total annual undiscounted fix and variable cost is multiplied by period discount factor to obtain total annual discounted fix and variable cost.

$$disother(t) = pridf(t) * undother(t) \tag{3.18}$$

where

- *disother(t)* : discounted total other expenditures costs (fix and variable costs)

3.3.1.5. Total Annual Environmental Cost. All costs related with the negative effects of energy generation, consumption and transmission activities to the system are considered as environmental costs.

$$undannenv(t) = \sum_{v} envcost(v,t) * r\_em(v,t) \tag{3.19}$$

where

- v : emission type
- *envcost(v,t)* : unit emission cost per v at period t
- *r_em(v,t)* : level of emissions
- *disannenv(t)* : undiscounted total annual environmental cost

$$disannenv(t) = pridf(t) * undannenv(t) \tag{3.20}$$

3.3.2. Energy Balance Constraints

These constraints ensure that the total supply of any energy carrier is always greater than or equal to its total usage. In these constraints, left hand side represents the technologies which are supplying (extraction or import technologies) and producing (energy conversion technologies) the energy source, whereas right hand side represents the technologies which are consuming (resource, energy conversion and demand technologies) or exporting the energy source.

In this regard, *"outent (m,t)"* parameter is used on the left hand side. It represents output generation level per unit activity of a technology m at period t. On the other hand, *"inpent (m,t)"* parameter is used on the right hand side. It represents input requirement level per unit activity of a technology m at period t.

$$\begin{aligned} \sum_{m\in s} r_{tsep(m,t)} + \sum_{m\epsilon k\cup c} r\_act(m,t) * outent(m,t) & \\ \geq \sum_{m\in s} inpent(m,t) * r\_tsep(m,t) & \\ + \sum_{m\epsilon k\cup c} inpent(m,t) * r\_act(m,t) & \\ + \sum_{m\in d} inpent(m,t) * capunit(m,t) * cf(m,t) & \\ * r\_cap(m,t)/eff(m,t) & \end{aligned} \tag{3.21}$$

where

- *eff(m,t)* : efficiency rate of technology m at period t
- *inpent(m,t)* : level of input requirement per unit activity of technology m at period t
- *outent(m,t)* : level of output generation per unit activity of technology m at period t

3.3.3. Demand Satisfaction Constraints

These constraints guarantee that the available capacity always meets the demand requirements. In this regard, the total activity of end-use technologies servicing that demand must be greater than or equal to the specified demand.

$$\sum_{m \in d} (outent(dm)(m,t) * capunit(m,t) * cf(m,t) * r\_cap(m,t) \\ = demand(dm,t) \qquad (3.22)$$

where

- *dm* : sectoral demand
- *demand(dm,t)* : level of demand service dm at period t
- *outent(dm)(m,t)* : level of demand service dm satisfied per unit activity of technology m∈d that services the particular demand dm at period t

3.3.4. Accounting Constraints

Accounting constraints are used for reporting and accounting purposes.

3.3.4.1. Primary Energy. This relationship represents the total supply limit of any source.

(i) For supply technologies that produce energy source e;

$$energy\_supply(t) = \sum_{\substack{m \in s \cap (set\ of \\ technologies \\ producing\ e)}} r\_tsep(m,t) \tag{3.23}$$

(ii) For energy conversion technologies that produce energy source e;

$$energy\_supply(t) = \sum_{\substack{m \in c \cap (set\ of \\ technologies \\ producing\ e)}} outent(m,t) * r\_act(m,t) \tag{3.24}$$

where

- *energy_supply(t)* : total supply level of energy source e at period t.

3.3.4.2. Installed Capacity. This relationship represents the total installed capacity of electricity conversion plants that generate electricity from a specified energy source at period t.

$$energy\_e\_cap(t) = \sum_{\substack{m \in c \cap (set\ of \\ technologies \\ producing\ e)}} r\_cap(m,t) \tag{3.25}$$

where

- *energy_e_cap(t)* : total installed capacity of electricity generation plants at period t

3.3.4.3. Electricity Sector Energy Consumption. This relationship represents the level of an energy source consumed to produce electricity.

$$energy\_e\_cons(t) = \sum_{\substack{m \in c \cap (set\ of \\ technologies \\ producing\ e)}} inpent(m,t) * r\_act(m,t) \tag{3.26}$$

where

- *energy_e_cons(t)* : level of an energy source used for electricity generation at period t

3.3.4.4. Electricity Sector Electricity Generation. This relationship represents the overall level of electricity generated by technologies using an energy source.

$$energy\_e\_gen(t) = \sum_{\substack{m \in c \cap (set\ of \\ technologies \\ producing\ e)}} inpent(m,t) * r\_act(m,t) \tag{3.27}$$

where

energy_e_gen(t) : level of electricity generated by technologies using an energy source at period t

3.3.4.4. Total Electricity Generation. This relationship represents the total electricity generation at period t.

$$elc\_prod(t) \equiv \sum_{m \in ce} r\_act(m,t) \tag{3.28}$$

where

- *elc_prod(t)* : total electricity generation at period t

3.3.4.5. Energy Consumption by Sectors. This relationship represents the level of energy source e used in sectors.

$$energy\_x\_cons(t) = \sum_{\substack{m \in c \cap (set\ of \\ technologies \\ producing\ e)}} inpent(m,t) * r\_act(m,t) \tag{3.29}$$

where *energy_x_cons(t)* : the level of energy source e consumed in sector x at period t.

3.3.5. Capacity Transfer Constraints

These constraints guarantee that the available capacity in period t is equal to the sum of investments made by the model at past and current periods, and whose physical life has not ended yet, plus capacity in place prior to the modeling horizon and still in place (Loulou *et al.*, 2004a)

The lifetime of the technology indicates if an investment is active or not in a period. For this reason, when an investment no longer exists, it should be removed from the total capacity.

$$t' = t - life(m,l)/nyrsper \tag{3.30}$$

where

- l : technology life
- *nyrsper* : number of years per period

The difference between t and t' *(t-t')* indicates available investments of technology m at period t. Total available capacity of each technology m is determined by capacity transfer constraints.

$$r\_cap(m,t) = resid(m,t) + \sum_{x=t'}^{t} r\_inv(m,x) \tag{3.31}$$

where

- *r_cap (m,t) :* level of capacity of technology m at period t
- *resid(m,t)* : level of residual capacity of technology m at period t

Residual capacities do not have any investment cost since they are put into the model at the beginning of the planning horizon.

3.3.6. Capacity-Activity Relationship Constraints

These constraints ensure that the activity of any energy conversion technology is always less than or equal to its available capacity.

$$r\_act(m,t) \leq capunit(m,t) * af(m,t) * r\_cap(m,t) \quad m \in k \cup c \tag{3.32}$$

where

- *af(m,t)* : annual availability factor of technology m at period t
- *capunit(m,t)* : unit conversion factor of technology m at period t

Unit conversion factor is used if capacity unit and activity unit are not same (activity unit is usually PJ, and capacity unit is usually GW).

Capacity-activity relationship constraint is only valid for energy conversion technologies. No activity variable is defined for demand technologies. Activity of end-use technologies is always assumed to be directly proportional to their installed capacities (Loulou *et al*., 2004a).

3.3.7. Cumulative Supply Limit

These constraints are valid for supply technologies. There are some limitations on supply technologies such as contact limitations on imported resources or reserve capacity limitations on domestic resources. These constraints guarantee that the cumulative supply level of any resource technology is always greater than or equal to its total supply level.

$$\sum_{t} (nyrsper * r\_tsep(s,t)) \leq cum(s,cm) \tag{3.33}$$

where

- cm : cumulative supply

- *cum(s,cm)* : cumulative supply level on resource technology s

3.3.8. Activity Limitation on a Multiple Output Technology

The technologies which produce more than one output (such as refineries) use activity limitation constraint. This constraint represents that, the total production generated from these kinds of technologies equals to a fraction of the total technology activity.

$$limit(m,t) * r\_act(m,t) = \sum_{e} (r\_act(m,t) * outent(m,e,t)) \tag{3.34}$$

where

- *limit(m,t)* : limiting fraction for activity of multiple output technology m at period t.
- *outent(m,e,t)* : level of energy source e, produced per unit activity of technology m at period t.

This outent is represented by *"refinhlm"* parameter in the model.

where

- *refinhlm(e,t)* : refinery parameter 1
- *refinstd(e,t)* : refinery parameter 2

3.3.9. Electricity and LTH Peaking Constraint

Total electricity generation capacity always has to meet the highest electricity and LTH demand at any period. In this regard, this inequality ensures that there is always sufficient capacity to meet the peak electricity and LTH demand.

Electricity peaking constraint and LTH peaking constraint are different from each other.

(i) *Electricity peaking constraint:*

$$\begin{aligned}
&\sum_{m\in s} teent(e,t) * peakcon(m,t) * r\_tsep(m,t)) \\
&+ \sum_{m\epsilon ce} teent(e,t) * peakcon(m,t) * outelc(m,t) \\
&* capunit(m,t) * af(m,t) * r\_cap(m,t)) \\
&\geq \sum_{m\in s} inpelc(m,t) * r\_tsep(m,t) \\
&+ \sum_{m\in k} inpelc(m,t) * r\_act(m,t) + \sum_{m\in c} inpelc(m,t) * r\_act(m,t) \\
&+ \sum_{m\in d} inpelc(m,t) * capunit(m,t) * cf(m,t) \\
&* r\_cap(m,t)/eff(m,t) * (1 + ereserv(e,t))
\end{aligned} \tag{3.35}$$

where

- *ce* : electricity generation technology
- *teent(e,t)* : transmission efficiency of electricity at period t
- *peakcon(m,t)* : peak contribution parameter that is used to determine the fraction of the technology m’s capacity at period t that should be credited towards the peaking requirement at period t
- *ereserv(e,t)* : peak reserve factor for electricity generation at period t
- *inpelc(m,t)* : level of electricity demand per unit activity of technology m at period t
- *outelc(m,t)* : level of electricity generation per unit activity of technology ce at period t

(ii) *LTH peaking constraint*:

$$
\begin{aligned}
\sum_{m\in ch} peakcon(m,t) * outlth(m,t) * capunit(m,t) * af(m,t) * r\_cap(\,m,t)) \quad (3.36)\\
\geq \sum_{m\in s} inplth(m,t) * r\_tsep(m,t))\\
+ \sum_{m\epsilon k} inplth(m,t) * r\_act(m,t)\\
+ \sum_{m\epsilon c} inplth(m,t) * r\_act(m,t)\\
+ \sum_{m\epsilon d} inplth(m,t) * capunit(m,t) * cf(m,t)\\
* r\_cap(m,t)/eff(m,t) * (1 + hreserv(e,t))
\end{aligned}
$$

where

- *ch* : LTH generation technology
- *hreserv(e,t)* : peak reserve factor for LTH generation at period t
- *inplth(m,t)* : level of LTH demand per unit activity of technology m at period t
- *outlth(m,t)* : level of LTH generation per unit activity of technology ch at period t

Left hand side represents the total electricity and LTH generation capacity which can meet the peaking requirement. The fraction of this capacity reserved for peak time is determined by the peaking contribution parameter.

Right hand side represents the total electricity and LTH demands of all technologies that consume electricity and LTH.

3.3.10. Baseload Constraint for Electricity Production

This inequality ensures that non-baseload plants meet most of the total night time demand and only a certain percentage of the total night time demand is met by baseload plants. The reason is that, large plants run at full capacity all the time and since total demand declines at nights, there can be reasonable difference between the total generation capacity of these baseload plants and the night time demand. Thus, when there is a sudden decline of night time demand, non-baseload plants are deactivated instead of baseload plant, since shutting down and restarting processes are not easy for baseload plants.

$$\sum_{m \in ce} outelc(m,t) * qhr\_n(m,t) * r\_act(m,t) * baseload(e,t)) \geq \sum_{m \in ce \cap cbs\_e} qhr\_n(m,t) * outelc(m,t) * r\_act(m,t)) \tag{3.37}$$

where

- *baseload(e,t)* : the highest percentage of the baseload power plants in total electricity generation at period t
- *qhr_n(m,t)* : night time share of electricity generation from technology m at period t
- *cbs_e(m)* : baseload electric conversion technology indice.

3.3.11. Periodic Emission Constraints

These constraints are used for tracking the emission levels. They are different than the equations which are used as scenario emission bounds. The level of emissions emitted per unit supply of supply technology s is tracked as,

$$\sum_{s} (envsep(s,t) * r\_tsep(s,t)) = r\_em(v,t) \tag{3.38}$$

where

- *v* : emission type
- *envsep(s,t)* : emission factor for supply technologies
- *r_em(v,t)* : level of emissions emitted per unit supply of technology s at period t

The level of emissions emitted per unit activity of energy conversion technology c is tracked as,

$$\sum_{m \in c} envact(m,t) * r\_act(m,t) = r\_em(v,t) \tag{3.39}$$

where

- *envact(m,t)* : emission factor for energy conversion technologies

The level of emissions emitted per unit activity of demand technology d is tracked as,

$$\sum_{m \in d} envact(m,t) * capunit(m,t) * cf(m,t) * r\_cap(m,t) \\ = r\_em(v,t) \tag{3.40}$$

Since there is no activity variable for demand technologies, the activity level of these technologies is determined by using capacity utilization factor *“cf”*. Unit conversion factor “capunit” is used for making capacity unit and activity unit the same.

The level of total emission is tracked as,

$$totemis(t) = \sum_{v} r\_em(v,t) \tag{3.41}$$

where

- *totemis(t)* : level of total emissions emitted at period t.

3.3.12. Emission Bound

This inequality ensures that total emission is always below a certain level.

$$totemis \leq bounds(b,t) \tag{3.42}$$

where

- *bounds(b,t)* : scenario constraints

3.3.13. Cumulative Emission Limit

This inequality guarantees that the emission level of each period is restricted by a certain cumulative emission level.

$$\sum_{t} nyrsper * r\_em(v,t)) \leq cumem(v,cme) \tag{3.43}$$

where

- *cme* : cumulative emission
- cumem (v,cme) : cumulative emission factor per emission type v

3.3.14. Periodic Limitations

Supply, capacity, activity and investment levels of any technologies can be restricted by these constraints. As mentioned before, supply technologies only have supply variable and demand technologies do not have any activity variable.

$$r\_x(m,t) \leq bound\_x\_upper(m,t) \tag{3.44}$$

$$r\_x(m,t) = bound\_x\_fix(m,t) \tag{3.45}$$

$$r\_x(m,t) \geq bound\_x\_lower(m,t) \tag{3.46}$$

where

- *bound_x_upper(m,t)* : upper bound on the suppcly/capacity/activity/investment of technology m at period t
- *bound_x_fix(m,t)* : fixed bound on the supply/capacity/activity/investment of technology m at period t

- *bound_x_lower(m,t)* : lower bound on the supply/capacity/activity/investment of technology m at period t.

3.3.15. Intertemporal Decay/Growth Constraints

(i) *Intertemporal Decay/Growth Constraints for Supply Level:* For a particular supply technology, supply level is restricted with decay and growth parameters between consecutive periods.

$$r\_tsep(s, t+1) \geq r\_tsep(s, t) * (decayr(s, t+1)^{nyrsper} \tag{3.47}$$

$$r\_tsep(s, t+1) \leq r\_tsep(s, t) * (growthr(s, t+1)^{nyrsper} \tag{3.48}$$

- *decayr(s,t)* : maximum annual decay rate of a supply technology’s supply level between period *t* and period *t+1*
- *growthr(s,t)* : maximum annual growth rate of a supply technology’s supply level between period *t* and period *t+1*

(ii) *Intertemporal Decay/Growth Constraints for Capacity Level:* For any technology, capacity level is restricted with decay and growth parameters between consecutive periods.

$$r\_cap(m, t+1) \geq r\_cap(m, t) * (decay(m, t+1)^{nyrsper} \; m \in k \cup c \cup d \tag{3.49}$$

$$r\_cap(m, t+1) \leq r\_cap(m, t) * (growth(m, t+1)^{nyrsper} \; m \epsilon k \cup c \cup d \tag{3.50}$$

where

- *decay(m,t)* : maximum annual decay rate of a technology capacity between period *t* and period *t+1*
- *growth(m,t)* : maximum annual growth rate of a technology capacity between period *t* and period *t+1*

(iii) *Intertemporal Decay/Growth Constraints for Activity Level:* For any technology, activity level is restricted with decay and growth parameters between consecutive periods.

$$r\_act(m,t+1) \geq r\_act(m,t) * (decay(m,t+1)^{nyrsper} \; m \in k \cup c \qquad (3.51)$$

$$r\_act(m,t+1) \leq r\_act(m,t) * (growth(m,t+1)^{nyrsper} \; m \in k \cup c \qquad (3.52)$$

where

- *decay(m,t)* : maximum annual decay rate of a technology activity between period *t* and period *t+1*
- *growth(m,t)* : maximum annual growth rate of a technology activity between period *t* and period *t+1*

4. THE BUEMS MACRO MODELING FRAMEWORK

4.1. Description of the BUEMS MACRO Model

In this thesis, the macroeconomic submodel MACRO is integrated with BUEMS which are together referred to as BUEMS-MACRO. The economy is modeled using aggregate model approach and the energy sector is modeled in a disaggregated way. BUEMS-MACRO model links a macroeconomic model with a detailed bottom-up model. The main goal of the linkage is to determine the effects of energy costs on the end-use energy demands.

The trajectory of the energy demand for the original BUEMS model is estimated exogenously in the absence of price changes. However, in the real economy, energy prices affect energy demands. In the BUEMS-MACRO model, energy demands are determined endogenously according to the production growth rates which are determined under the impacts of energy prices. In other words, the demands are variables of the model that are aggregated to become the energy input into the MACRO production function, alongside Labor and Capital (Loulou *et al.*,2004b).

The Macro Base model uses the energy costs which are obtained from the BUEMS Base scenario. According to these energy costs, Macro model calculates gross output, GDP (gross domestic product), investment and consumption levels for the each period and determines endogenous energy demands in accordance with the production growth rate (the gross output). Accordingly, BUEMS model is run with these endogeneous energy demands. This process continues until the growth rate of energy demands in the BUEMS model are consistent with the the production growth rates in the Macro model for each period.

BUEMS-MACRO model is seperated from other models by its solving method. While MARKAL-MACRO or TIMES-MACRO models are fully integrated single models, BUEMS-MACRO is solved by running both models separately. The advantage of running two models separately instead of a fully integrated model is to have non-linear equations in the numerically smaller of the two models. Thus, it can be solved in a short period of time. Moreover, the model can be run with different production functions easily without solving energy supply model every time.

Figure 4.1. depicts the BUEMS-MACRO model.

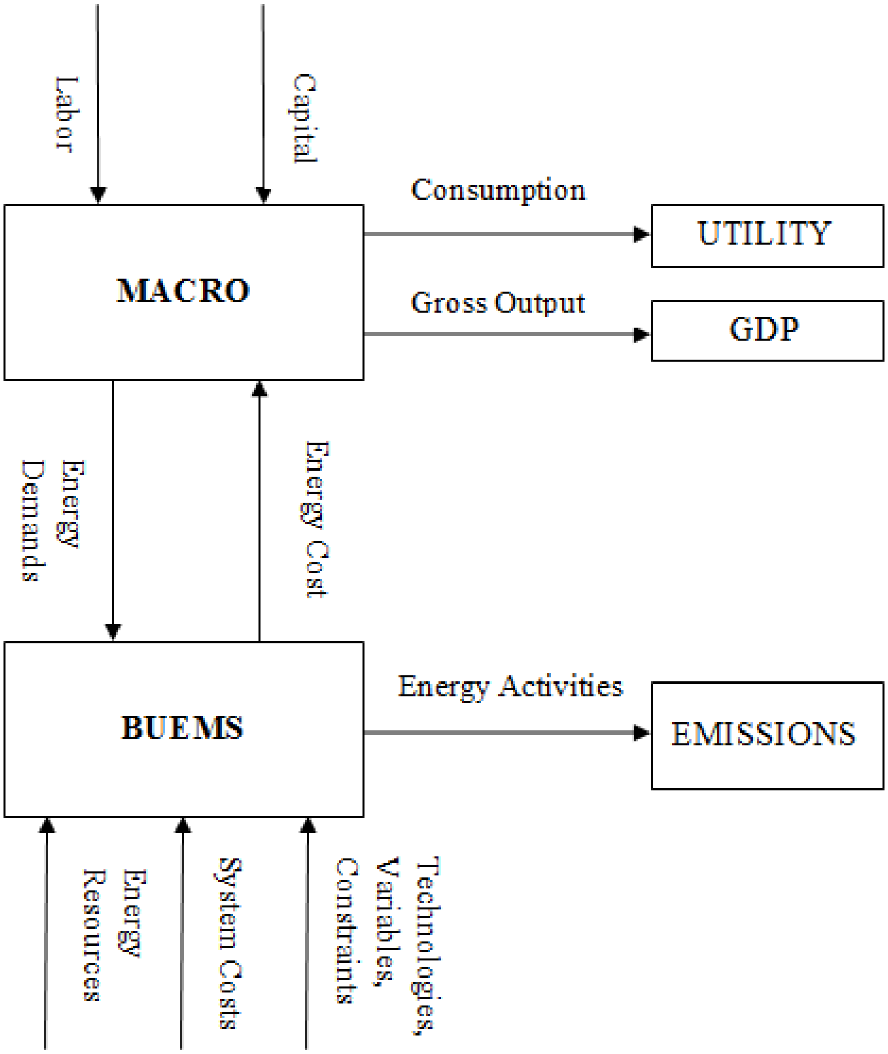

Figure 4.1. The BUEMS-MACRO flows.

4.2. Equations of the BUEMS-MACRO Model

4.2.1. Utility

The objective function of the MACRO module is the maximization of the discounted utility. The utility function is the discounted sum of the logarithms of consumption at each period (Loulou *et al*., 2004b).

$$utility = max \sum pridf(t) * \log(C(t)) \tag{4.1}$$

where

- *utility :* utility of overall planning horizon
- *C(t)* : annual consumption in period t

A logarithmic utility function has been chosen, instead of a linear one, to avoid “bang-bang” solutions related to linear functions (Remme and Blesl, 2006)

Since a logarithmic utility function has a concave nature, as consumption increases, the marginal utility of consumption decreases.

4.2.2. Production Function

The macroeconomic optimization results with investment and consumption decisions. The total output of the economy is determined by the capital stock, labor and energy cost variables which together constitute a nested CES production function.

A constant elasticity of substitution function describes the "Gross Output' Y. of the economy, as function of the primary inputs (Kypreos, 1996).

$$Y(t) = (aconst * K(t)^{(rho*kpvs)} * L(t)^{rho*(1-kpvs)}) + (bconst * demand(t)^{rho}))^{(1/rho)} \tag{4.2}$$

where

- *Y(t)* : annual production in period t
- *K(t) :* total capital in period t
- *L(t)* : annual labor in period t
- *demand(t)* : annual end-use energy demand in period t
- *kpvs* : capital value share
- *aconst* : constant for capital-labor index
- *bconst* : constant for energy index

The production input factors "*labor(t)*" and "*capital(t)*" form an aggregate A_{KL} , in which both can be substituted by each other represented by a Cobb-Douglas function. Then, the aggregate of the energy services and the aggregate of capital and labor can substitute each other (Remme and Blesl, 2006).

When the relative prices change, the CES production function enables substitution between the pair capital-labor and the energy.

The capital value share "*kpvs*" indicates the share of capital in overall production function. It is defined by the user.

The parameters "*aconst*" and "*bconst*" are taken from Karali (2006). Karali calculates share parameters by taking partial derivatives of the production function respect to capital and the energy and indicates a production function for Turkey in the CES form with the share parameters which are 0.02 for capital-labor share (aconst) and 0.15 for energy share (bconst).

"rho" is used instead of *"esub"* in the function. This form of production function is adapted from neoclassical growth models (Allen 1968).

$$\rho = (\sigma - 1)/\sigma \tag{4.3}$$

where

- ρ: parameter that controls the elasticity of substitution (rho)
- σ : elasticity between capital-labor and energy cost

The elasticity of substitution between the aggregate of capital and labor on the one side and energy on the other side is the ratio between the relative change in the quotient of two production factors and the relative change in their prices. For the production factors energy E and the aggregate of capital and labor A_{KL} the elasticity of substitution has the general form Remme and Blesl, 2006).

$$\sigma = \frac{\partial\left(\frac{AKL}{E}\right)/\frac{AKL}{E}}{\partial\left(\frac{PKL}{E}\right)/\frac{PKL}{PE}} = \frac{\partial ln(AKL/E)}{\partial ln(PKL/PE)} \tag{4.4}$$

where

- A_{KL} : aggregate of capital and labor,
- E : energy,
- P_{KL} : price for the production factor aggregate of capital and labor,
- P_E : price for the production factor energy.

Besides nested production function formula, annual production is also represented by another formula which is the summation of annual consumption, annual investments and annual energy costs in that period.

Consumer can choose to spend the annual production on consumption or they can also decide to spend the annual production on investments to maximize their utility over the model horizon. In addition, energy cost has to be covered by the annual production at the same time for that period.

$$Y(t) = C(t) + I(t) + EC(t) \tag{4.5}$$

where

- *I(t)* : annual investment in period t
- *EC(t)* : annual energy cost in period t

If the energy price increases, due to resource depletion or environmental constraints then, energy is substituted by capital and labor (CES production function), while the output Y and the demand for energy services are decreasing (Kypreos, 1996).

Energy cost is calculated as the multiplication of supply price and the level of supply.

$$EC(t) = scost(m,t) * r\_tsep(m,t) \tag{4.6}$$

where

- *scost(m,t)* : supply cost for technology m in period t
- *r_tsep(m,t)* : level of supply in period t

4.2.3. GDP

The model calculates the GDP growth rate endogenously. On the other hand, potential GDP growth rate is introduced into the model by the user. GDP consists of consumption and investment variables.

$$GDP(t) = I(t) + C(t) \tag{4.7}$$

where

- *GDP(t)* : gross domestic product at period t

The GDP variable of the initial year is fixed to the initial GDP value which is determined exogenously by the modeler.

Since energy cost does not include taxcost, tax costs should be added into the summation of GDP and energy cost formula as a new parameter when gross output is calculated in the emission tax scenarios. For the emission tax scenarios, these taxes should be included into the production function calculation, since emission taxes are revenue for the government. The government receives the revenue from indirect and environmental taxes and spends them on purchasing goods and services at market prices (Kumbaroglu, 2003).

$$Y(t) = GDP(t) + EC(t) + taxcost(t) \qquad (4.8)$$

where

- *taxcost(t)* : tax cost in period t

4.2.4. Capital and Investment

The capital in current period equals to depreciated capital in the previous period plus investments made in the current and the previous period.

$$K(t+1) = K(t) * (spda)^{nyrsper} + ipm(t) * I(t) \qquad (4.9)$$

where

- *K(t+1) :* capital accumulation function
- *spda :* speed of adjustments
- *ipm(t) :* investment period multiplier

Investment period multiplier is used for the growth of investment within each period. The speed of adjustment depends on a parameter which defines the fraction of the initial capital stock that survives after one year of use (Vickson and Ziemba, 1975). Manne takes speed of adjustment as 0.96.

A terminal condition is defined in order to gurantee that the depreciation of the existing capital stock and labor growth rate are covered by the investment in the final period, and also ensures that after the final period, the capital stock continues its existence for the next generations.

$$K_T(growv_T + depr) \leq INV_T \tag{4.10}$$

where

- K_T : total capital in the terminal period
- INV_T : total investment in the terminal period

4.2.5. Initial Values

For the first period, the user describes the initial year GDP, the capital-to-GDP value, the depreciation rate and potential GDP growth rate to the model.

These parameters are indicated below.

- gdp_0 : GDP of the initial year
- $potgdp_0$: potential GDP of the initial year
- *kgdp* : capital-to-GDP value,
- *dep* : depreciation rate,
- L_0 : labor for the initial year
- *lgrowthrate* : labor growth rate
- y_0 : initial production function
- EC_0 : initial energy cost
- K_0: initial capital stock

After introducing these parameters to the model, the initial capital stock can be calculated by the parameters “*kgdp*” and “*potgdp0*”.

$$K_0 = kgdp * potgdp_0 \tag{4.11}$$

where

- K_0 : initial capital stock

Once the initial capital value is calculated, then the initial investment value can be obtained. The capital stock is assumed to increase with the labor growth rate plus the depreciation of the capital stock which leads to the initial investment.

$$I_0 = K_0 * (dep + lgrowthrate) \tag{4.12}$$

where

- I_0 : the initial investment

It is noted that “*laborgrowthrate”* is exogenously specified and labor for the initial year is taken as 1.

$$L_0 = 1, \qquad L_{t+1} = (1 + lgrowthrate)^{nyrsper*L_t} \tag{4.13}$$

The third step is to find the initial consumption value. The difference between the initial potential GDP and the initial investment gives the initial consumption value.

$$C_0 = potgdp_0 - inv_0 \tag{4.14}$$

where

- C_0 : initial consumption

The fourth step is to find the initial production function. The initial production function is used to find "*aconst*" and "*bconst*" in the production function "*Y(t)*".

$$Y_0 = I_0 + C_0 + EC_0 \tag{4.15}$$

where

- Y_0 : initial production function
- EC_0 : the initial energy cost

The real GDP data for the initial year is taken from Turkish Statistical Institute (TSI). In this regard, "*gross domestic product in chain linked volume, index and percentage change by expenditure approach (2009=100)*" data has been used. In this data, the real GDP values are indicated up to the year 2016. However, 2017 is defined as the initial year in the BUEMS-MACRO model. To calculate the real GDP for the year 2017, the report which has been published by the Turkish Statistical Institute in March 2018 is used. According to the "Gross Domestic Product, Quarter IV: October-December, 2017" report, Gross Domestic Product with chain linked volume index (2009=100), increased by 7.4% in 2017 compared with the previous year". Based on this information, the real GDP for the year 2017 has been calculated.

The elasticity of substitution parameter used in the Macro module is taken from Karali (2006). Karali indicates that a production function in the CES form can be interpreted economically with the elasticity of substitution parameter which is equal to 0.3. This means that the aggregate of capital and labor can be substituted with energy with a rate of 0.3.

5. THE CURRENT ENERGY PROFILE

5.1. Energy Sources

5.1.1. Coal

Coal plays a key role in meeting global energy demand. According to the International Energy Agency (IEA, 2017), a third of all energy consumed worldwide is provided from coal, which is accounted for 40% of global electricity generation. Besides electricity generation, coal is also an important fuel for industry sector, mainly in cement and iron & steel production.

The World Energy Council (2016) has reported that the largest coal producing countries are China, the USA, India, Indonesia, Australia and South Africa. Other countries mostly import coal from these countries and smaller amounts from other countries and they also use their domestic coal supply. Especially developing countries mainly rely on coal, since it is relatively cheaper than natural gas and oil.

The International Energy Agency Coal Information Report 2017 indicates that world coal production declined by 458 million tonnes (Mt) in 2016, it is mainly because of lower gas prices, energy efficiency improvements and concerns about greenhouse gas emissions. While China, the USA, Europe, Canada have experienced a decrease, India and Southeast Asia have seen an increase in coal demand. China has taken steps to mitigate its environmental damage and promote the shift from coal to clean technologies. On the other hand, the USA has seen an increase in the supply of gas and the USA has switched gradually from coal power plants to gas power plants.

Coal has the most carbon-content fossil fuel that is used in electricity generation. Despite causing the largest share of greenhouse gas emissions, coal will continue to be an important energy source in the near future. For this reason, clean coal technologies will play an essential role in order to reduce CO_2 emissions from coal plants in the coming decades. Modern technological advancements enable coal power plants to be more efficient and have low carbon emissions. Integrated gasification combined cycle (IGCC) and carbon capture and storage (CCS) are the clean coal plant technologies that result in lower emission levels. In IGCC plants, more clean fuel is burned due to usage of syngas and CCS technolopgies capture and deposit the CO_2 in the way that it will never release to the atmosphere.

Turkey has large reserves of lignite, according to MENR, approximately 3,2% of the total world reserves of lignite/sub- bituminous coal are in Turkey, however they are low calorie, with 23,5% between 2000-3000 kcal/kg, 5,1% between 3000-4000 kcal/kg, and 3,4% is above 4000 kcal/kg grading. The reserves of lignite are 15.6 billion tonnes and lignite production reached 50.4 million tonnes in 2015, whereas the reserves of hard coal are 1.3 billion tonnes and hard coal production was 1.4 million tonnes in 2015 in Turkey.

Turkey import hard coal from Colombia, Russia, South Africa, Australia and smaller amounts from other countries. MENR has reported that hard coal imports have increased by %97.5 between 2005 and 2015 due to growing demand. To reduce its dependence on imported coal, the Turkish government has aimed to increase the use of domestic coal in electricity generation since 2009. The Turkish government’s strategic plan for 2015-2019 underlines that electricity generation from domestic coals should reach a level of 60 billion kW/year until the end of the plan period.

According to the International Energy Agency Energy Polies of IEA Countries Report 2016, in Turkey, electricity sector consume 68% of coal supply, industry sector consume 16.8% of coal supply, agriculture sector consume 9.7% of coal supply and remaining 5.5% of coal supply is consumed by households.

According to the balance tables by MENR; the amount of coal consumed by electricity sector increased considerably between 2012 and 2016, whereas the amount of coal consumed by industry and residential &commercial sector fell by approximately %3 and %20 respectively between 2012 and 2016.

5.1.2. Natural Gas

Natural gas plays a significant role in the world's energy demand, and the share of world natural gas consumption will continue to increase for the foreseeable future. According to the latest World Energy Council Report, 22% of all energy consumed worldwide is met by natural gas.

According to the BP Statistical Review of World Energy Report (2015), total world proved reserves were 187.1 trillion cubic meters (tcm) and the top nations with the largest reserves are Middle East with 79.8 tcm (the world's largest proved reserves holder is Iran) and Russia with 32.6 tcm. On the other hand, North America has seen a significant increase in the amount of natural gas produced each year due to shale gas (which is referred as an unconventional gas). IEA and World Energy Outlook (2014) estimates that 30% of all natural gas consumption could be provided from unconventional gas by 2040. Furthermore, IEA and World Energy Outlook (2017) projects that the US will become the world's largest liquefied natural gas (LNG) exporter by the mid-2020s as the world's leading LNG exporter is Qatar currently.

The IEA Countries Report 2016 shows that Turkey import natural gas mostly from five countries which are Russia, Iran, Azerbaijan, Algeria, Nigeria with 55,1%, 16,2%, 12,3%, 8,1% and 2,9% of the total imported natural gas respectively and smaller amounts from other countries and receive LNG from global spot market. The Energy Market Regulatory Authority (EMRA) has reported that, the amount of imported LNG accounted for 16.46% of the total imports in 2016 which 27.84% of the total LNG imports was provided from spot market and the remaining was supplied from Algeria and Nigeria. On the other hand, there has been some natural gas export to Greece, the export amount was 0.6 billion cubic meters (bcm) in 2015.

MENR indicates that Turkey's producible reserves of natural gas were 18.8 billion m3 as the end of 2016 and natural gas supply of Turkey is almost completely provided by imports. MENR Energy Balance Table shows that 37,886 thousand tonnes of oil equivalent natural gas were imported from various countries in 2012 and this value has reached to 38,240 thousand tonnes of oil equivalent in 2016. Whereas, in 2016 the amount of domestic production declined by 3.69% compared to 2015 according to Turkish Natural Gas Market Report 2016, released by MENR Energy Market Regulatory Authority.

According to MENR Energy Balance Table, natural gas is mainly used in the electricity sector which accounted for the amount of 19,040 thousand tonnes of oil equivalent in 2012 and 14,841 in 2016. It is followed by industry sector. The amount of consumption in the industry sector increased by approximately %38 from 2012 to 2016, reaching to 8,674 thousand tonnes of oil equivalent in 2016.

Two important natural gas pipeline projects are under construction in Turkey which will become operational most recently. One of them is the Trans Anatolian Natural Gas Pipeline Project (TANAP) and the other is the TurkStream.

TANAP Natural Gas Transmission Company declared the aim of TANAP as “to bring natural gas produced from Azerbaijan’s Shah Deniz-2 gas field, and other areas of the Caspian Sea, primarily to Turkey, but also on to Europe”. TANAP is of key importance for both Turkey and Azerbaijan. It is expected that this project will meet the natural gas demand of Turkey which is increasing rapidly and Turkey will be an energy bridge between the Caspian Region and Europe. At the same time, it will contribute Europe’s energy diversification. It is projected that, the pipeline capacity will reach to 24 billion cubic meters, and finally to 31 billion cubic meters a year. The gas supply to Turkey is planned to start in 2018.

GAZPROM defines the TurkStream as “a new export gas pipeline stretching from Russia to Turkey across the Black Sea”. The project will enable natural gas reserves in Russia to connect Turkish gas transportation network. The project will consist of two pipelines which will supply natural gas for both Turkey and south and south-east Europe. It is projected that, pipelines will have a total throughput capacity of 31.5 billion cubic meters of gas per annum and Turkey is projected to consume about 15.75 billion cubic meters per year when it will be operational.

5.1.3. Oil

Oil remains the world's leading fuel which is accounting for 32.9% of total global energy consumption according to the World Energy Council latest report.

According to the International Energy Agency Market Report Series Oil2017 Report, it is forecasted that global oil demand growth will be average 1.2% per annum until 2022. The main increase in demand will come from the transport and petrochemical sectors. BP Energy Outlook 2018 indicates that transport sector will continue to dominate global oil demand, accounting for the majority of the overall growth. The World Energy Council indicates that substitution of oil in the transport sector is not expected to exceed %5 for the coming 5 years.

The International Energy Agency Market Report Series Oil 2017 has reported that oil demand growth will come from OECD countries between 2016 and 2022, while oil demand for non-OECD countries will decline because of using fuel-saving technologies and slower economic growth.

OPEC countries currently have 71.5% of overall reserves. According to the BP statistics global proved oil reserves increased by 0.9% in 2016 compared to 2015, reached to 1707 billion barrels that will be expected to sufficient for 50.6 years of global demand.

EMRA has reported that, import of diesel types rose by 4.03%, import of aviation fuels rose by 23%, whereas import of crude oil declined by 0.43% and imports of petroleum products overall increased by 1.09% in 2016 compared to 2015. In addition, refinery petroleum production has seen an increase by 3.11% totally in 2016.

5.1.4. Renewables

According to MENR, the total power plants installed capacity has risen to 80,546 MW by the end of July 2017. The percentage distribution of the Turkey's installed capacity by energy resources are 33,6% , 28,1%, 21,5%, 7,7%, 1,1%, 7,4% for hydraulic, natural gas, coal, wind, geothermal and other sources respectively. In addition, there are total number of 3,098 electricity energy production plants in Turkey that consist of 613 hydraulic, 40 coal, 186 wind, 33 geothermal, 288 natural gas, 1,773 solar, 165 other power plants.

The Turkish Government has made significant reforms in energy sector in the last decade. The Government let private sector be in the energy market and they also create energy stock exchange. As a result of this exchange, energy market has become a liberal market and it has helped the energy sector become more balance between supply and demand.

In order to decrease Turkey’s energy dependency, renewable energy plays an important role. According to the government’s Energy Efficiency Strategy Paper 2012-2023, the share of renewable energy in the country’s electricity production is planned to be 30% in 2023 and the amount of energy consumed per GDP in Turkey in the year 2023 is targeted to decrease at least %20 compared to year 2011.

According to the Turkey Energy Efficiency Strategy Paper 2017-2023, the amount of primary energy consumption is targeted to decrease by 14% in the year 2023. It is forecasted that a total amount of 10.9 billion USD is required for new generation investments in order to achieve 23.9 million tonnes of oil equivalent (mtoe) energy savings.

The International Renewable Energy Agency (IRENA) indicates that renewables contribute to climate change mitigation, but at the same time renewable energy creates a considerable number of job opportunities worldwide each year (to beyond 24 million employed by 2030) and leads to economic growth that is mainly as a result of higher investments and IRENA claims that “Achieving a 36 per cent share of renewable energy in the global energy mix by 2030 would increase global gross domestic product (GDP) by up to 1.1 per cent, roughly USD 1.3 trillion”.

The following sections will elaborate renewables in detail.

5.1.4.1. Wind. The Global Wind Energy Council Statistics Report 2017 reveals that the global cumulative total wind power capacity has reached to nearly 539,581 MW at the end of 2017, and the report shows that China is the global wind power leader with having 188,232 megawatts of wind energy capacity at the end of 2017. China’s closest competitors are the United States and Germany with having wind power capacities 89,077 MW and 56,132 MW respectively. According to the World Energy Council World Energy Resources Report (2016), global wind capacity could reach to 977 GW by 2030.

The wind energy sector in Turkey has seen rapid growth over recent years. MENR indicates that the installed capacity of the wind energy has reached to 5,751.3 MW by the end of 2016. The installed wind capacity is projected to increase to 9,993 MW in 2021 according to the capacity projections (for the years between 2017 and 2021) which have been released by Turkey Electricity Transmission Company (TEIAS) in 2017.

The MENR launched an investment project for wind energy in 2017. The project title is “*the Wind Energy Renewable Energy Resource Area (YEKA)*” that is planned to have 1000 megawatts of installed wind capacity overall. The winning consortium offered the lowest bid in the tender at 3.48 cents per kilowatt-hour (kWh) (feed in tariff) for the delivery of electricity to the national grid. The consortium will construct wind power plants in 5 different regions in Turkey. In addition, the project includes a minimum 10-year R&D requirement that will be carried out by the winning firms’ technical personnel and it is mandatory that Turkish engineers will constitute 80% of technical employees. Furthermore, the winning consortium will construct a wind turbine factory that will produce 450 wind turbines with a capacity of 2.3 GW each and power plants will have 65% local content.

5.1.4.2. Solar. According to IEA, global installed solar photovoltaic (PV) capacity has reached to 300 GW in 2016 which constitutes 1% of all electricity generation worldwide. It is expected that PV will play a major role in the future global electricity generation mix and over the coming 5 years it is projected that solar PV capacity will increase to 440 GW worldwide. On the other hand, IEA has reported that the installed capacity of concentrated solar power (CSP) plants was 4.8 GW in 2016, and it is expected to reach 10 GW in the coming 4 years.

Turkey has high solar energy potential. Turkey's Solar Energy Map (SEM) has indicated that the country’s total insolation time is 2.737 hours a year (a total of average 7.5 hours a day). According to MENR, the area where solar collectors are established in Turkey was close to 18640000 square meters (m^2) in 2012. In 2015, solar collectors produced 811,000 tons of oil equivalent (toe) heat energy. 65% of the heat energy was used in residential sector and the remaining was used in industrial sector.

MENR reported that, as the end of 2016, the installed capacity of licensed solar power plants was 12.9 MW and according to the Turkey Electricity Transmission Company (TEIAS), the installed capacity of solar energy plants has reached to 13.9 MW in November 2017. Whereas, unlicensed solar power plants were accounted for 819.6 MW in 2016 and the installed capacity of these power plants has reached to 2463.9 MW in November 2017.

5.1.4.3. Hydropower. The International Energy Agency has reported that around 17% of the world’s electricity is obtained from hydropower with having 1,700 GW installed capacity. According to the World Energy Council World Energy Resources report 2016, China accounted for 26% of the total hydropower installed capacity worldwide, followed by the USA, Brazil and Canada which accounted for %8.4, %7.6 and %6.5 respectively.

Hydropower is the largest renewable energy source for electricity generation and it is expected to continue to be the world’s major energy source among renewables in the near future. According to the World Energy Council World Energy Resources 2016 Report; hydropower accounted for %71 of all renewable electricity in total electricity generation in 2015.

MENR reveals that Turkey’s potential for hydroelectric is 433 billion kWh, however hydroelectric usable capacity is 216 kWh technically and when economic factors are taken into consideration, this potential decreases to 140 billion kWh/year. MENR indicates that, the total installed capacity of hydroelectricity power plants were 26,246.6 MW with a total number of 572 hydropower plants and 24.7% of the country’s electricity demand was generated from hydropower as of the end of 2016 June. By January 2017, number of 22 hydropower plants were licensed and the total installed capacity has reached to 26,678 MW.

5.1.4.4. Geothermal Energy. Today, geothermal energy has met less than 1% of global energy demand. IEA indicates that the total global geothermal power capacity has reached to 13 GW in 2016 and it is expected to increase to 17 GW by 2021. Main contributors are Indonesia, Turkey, the Philippines and Mexico.

Turkey has significant potential for geothermal energy due to country's geographical location and there has been continuous expansion of installed geothermal power in Turkey. According to the International Geothermal Association Report (September, 2017), Turkey is ranked fourth in geothermal power worldwide after the U.S., the Philippines and Indonesia.

MENR indicates that in terms of direct use of geothermal heat, Turkey is among the top 5 countries in the world. According to TEIAS, the total geothermal installed capacity has raised to 1019.7 GW in November 2017 which was 820.9 MW in 2016.

5.1.4.5. Bioenergy. IEA indicates that 9% of world total primary energy supply consists of bioenergy. According to IRENA, agricultural residues and waste constitute about 38 – 45% of total biomass supply while energy crops and forestry products and residues constitute the remaining biomass supply.

Bioenergy is predominantly used for heating and cooking in developing countries. However, it can lead to pollution and deforestation. Using biomass in a sustainable way should be ensured. Because biomass is considered as a renewable fuel only if it is produced in a sustainable way, which is called as modern biomass. IEA reveals that modern bioenergy accounts for 6% of global heat consumption which means 13 EJ bioenergy was used in 2015.

Turkey as a developing country has rich biomass potential. MENR indicates that 8,6 mtoe biomass potential exist in Turkey and the amount of biogas produced from biomass is 1,5-2 mtoe.

5.2. Turkey Strategic Plan 2015-2019

Turkey’s electricity demand is growing rapidly, for this reason it is important that transmission and distribution infrastructure should be developed continuously especially for renewable energy. Due to its geographical location, Turkey has many advantages for renewable energy usage. In order to use this potential efficiently, infrastructure should be improved. Furthermore, as it is indicated in the Turkish government strategic plan; legislation should be updated and financial support should be increased.

Turkey’s energy import dependency is mainly on natural gas and oil. Turkey provides 98.5% of its natural gas requirement from other countries. For this reason, government has initiatives for share gas research in the country to reduce this dependency. On the other hand, there have been researches on exploration of new natural gas and oil resources in the country.

Diversification is the key component for effective usage of energy resources. Within the scope of 2015-2019 Strategic Plan, Turkey aims diversification both in the import country and in primary energy resource types. In this regard, it is intended to add two new countries to the countries that natural gas is supplied. On the other hand, the share of natural gas in electricity generation is aimed to be decreased to 38% and domestic coal resource usage is to be increased until the end of plan period. Furthermore, government has a series of initiatives and considerable new investments for renewable energy resources. They aim to increase the share of renewable energy resources in electricity generation. On the other hand, government has taken serious actions to deploy three nuclear power plants into electricity production in the next decade and there have been researches to find domestic uranium and thorium to be used as energy sources in nuclear energy power plants.

6. THE BUEMS MODEL CALIBRATION

BUEMS model is calibrated for the years 2012 and 2017, which in accordance with the situation of Turkey. Electricity generation, installed capacity and end-use energy demand levels for the years 2012 and 2017 have been calibrated according to the data from TEIAS and MENR. In addition, lower bounds for installed capacities have been introduced for the year 2022 according to TEIAS Electricity Generation Capacity Production Report (2017-2021).

6.1. Supply Level

In this regard; energy supply levels are calibrated according to the publications of Republic of MENR. Coal supply levels are fixed according to the Coal Market Report and natural gas supply levels are fixed according to the Electricity Generation Company Sector Report (EUAS).

Domestic and import coal supply levels for 2012 is taken from Coal Market Report 2013 and coal supply levels for 2017 is estimated according to the Coal Market Report 2016 and preceding trend data.

6.1.1. Coal Supply Levels

Table 6.1. Domestic and import coal supply levels in 2012 and in 2017 in Turkey.

Energy Sources	**2012 (PJ)**	**2017 (PJ)**
Domestic Coal Supply Level		
Lignite	644.77	477.30
Hard Coal	46.05	37.68
Asphaltites	25.12	20.93
Import Coal Supply Level		
Hard Coal	803.87	916.91
Petroleum Coke	117.23	-
Coke	8.37	12.56

Data Source: Coal Market Reports 2013-2016

6.1.2. Natural Gas Supply Levels

According to EUAS, Turkey supplied 54% of its natural gas demand from Russia, followed by Iran with 19%, Algeria with 10%, Azerbaijan with 8%, Nigeria with 3% and spot LNG with 6% in 2012. In the following three years, the import natural gas level from Russia decreased by nearly 6.7% compared to 2012, the import natural gas level from Azerbaijan increased by nearly 7.2% compared to 2012 whereas the remaining countries' share slightly changed compared to 2012.

Table 6.2. Domestic and import natural gas supply levels in 2012 and in 2017 in Turkey.

Energy Sources	**2012 (PJ)**	**2017 (PJ)**
Import Natural Gas Supply Level	**1549.09**	**1651.81**
Russia	836.51	781.30
Iran	294.33	318.80
Azerbeijan	123.93	251.07
Algeria	154.91	158.57
Nigeria	46.47	51.21
LNG	92.95	90.85
Domestic Natural Gas Supply Level	**15.65**	**8.30**
Total Natural Gas Supply Level	**1564.74**	**1660.11**

Data Source: Turkey Electricity Generation Company Market Report 2013-2016

It is assumed in the BUEMS model that, the percentage distribution of natural gas supplies between these countries will remain the same throughout the planning horizon.

6.1.3. Installed Capacity

MENR indicates that Turkey electricity installed capacity has reached to 80546 MW by the end of the July 2017. Hydropower accounted for 33,6%, and natural gas and coal for 28,1% and 21,5% respectively whereas the share of wind power was 7,7% and the share of geothermal was 1,1% and other resources were 7,4% . In addition, TEIAS has declined that, by the end of the December 2017, the installed capacity has increased to 81,554.9 MW.

On the other hand, the distribution of installed capacity by primary energy resources in 2012 is indicated in Table 6.4. (based on TEIAS). The BUEMS model installed capacities for the year 2012 has been fixed to these values.

TEIAS has released best and worst case scenarios of capacity projections for the years between 2017 and 2021, called the Turkish Electricity Generation Capacity Projection. The existing installed capacities, the projects which are currently under construction, new projects awarded by generation licence and pre-licence and plants in the project phase are taken into account in forecasting the future installed capacities. The best and worst case scenarios have been prepared based on forecasts of the TEIAS regional directorates and TEIAS department of planning and strategic management. In addition, EMRA progress reports have taken into account in the projection study.

According to the best case scenario, the total installed capacity will reach to 108,045 MW by the year 2021 which was 78.497 MW in 2016, with the addition of 27.610,1 MW capacity under construction and 7.765,3 MW capacity which includes pre-licenced, under licensing phase and unlicensed power plants and also YEKA projects. On the other hand, according to the worst case scenario, the total installed capacity is expected to be 103,433 MW by the year 2021.

Worst case scenario installed capacity projections are introduced into the BUEMS as lower bounds on the year 2022 installed capacities.

The installed capacities by energy resources, their percentage contributions to the total installed capacity and total number of power plants for the year 2017 are given in Table 6.3.

Table 6.4 indicates the installed capacities by energy resources and their percentage contributions to the total installed capacity for the year 2012 in Turkey.

Table 6.3. Installed capacities in 2017 in Turkey.

Energy Sources	Total Installed Capacity (MW)	Percentage Contribution (%)	Total number of power plants
Fuel oil+ Naphtha+ Diesel Oil	303.6	0.4	12
Domestic Coal (Hard coal+ Lignite+ Asphaltite)	9,872.6	11.6	30
Imported Coal	8,793.9	10.3	11
Natural Gas+LNG	2,3063.7	27.1	243
Renewables+ Wastes+ Waste Heat+Pyrolytic Oil	575.1	0.7	98
Multi Fuel Fired (Solid+Liquid)	682.9	0.8	22
Multi Fuel Fired (Liquid+ Natural Gas)	3,433.6	4.0	47
Geothermal	1,063.7	1.2	40
Hydropower	2,7265.7	32	618
Wind	6,482.2	7.6	161
Solar	17.9	0.0	3
Thermal (Unlicenced)	201.1	0.2	67
Wind (Unlicenced)	34	0.0	46
Hydropower (Unlicenced)	7.4	0.0	10
Solar (Unlicenced)	3,402.8	4.0	3613

Data Source: Turkey Electricity Transmission Company

Table 6.4. Installed capacities in 2012 in Turkey.

Energy Sources	Total Installed Capacity (MW)	Percent Contribution (%)
Hard coal+Imported Coal+Asphaltite	4,382.6	7.7
Lignite	8,193.3	14.4
Fuel oil+Diesel oil+LPG+Naphtha	1,285.5	2.3
Natural Gas	1,4116.4	24.7
Natural gas+ Liquid *	6,282.2	11.0
Natural gas+ Liquid+Solid	245.4	0.4
Solid+Liquid	353.2	0.6
Renewables and Wastes	168.8	0.3
Hydropower	1,9609.4	34.4
Geothermal	162.20	0.3
Wind	2,260.6	4.0

Data Source: Turkey Electricity Transmission Company

6.1.4. End-use Energy Demands by Sectors

End-use energy demand levels of industry, residential, service and transportation sectors for the years 2012 and 2017 are updated according to the National Energy Balance Tables which are published by MENR. End-use energy demand levels for the year 2017 has been estimated based on the preceding data from 2012 to 2016.

Table 6.5. Industry sector energy consumption levels in Turkey.

Energy Sources	2012 (PJ)	2017 (PJ)
Hard Coal	155.37	176.7
Lignite	87.38	68.1
Asphaltite	5.36	2.6
Coke	245.64	142.2
Cokegas	13.36	18.8
Natural Gas	319.33	189.6
Petroleum	39.86	373.2
Electricity	323.85	395.6
Geothermal Heat	47.06	12.4
Solar	11.22	52.0

Data Source: Ministry of Energy and Natural Resources

Table 6.6. Residential&Commercial sector energy consumption levels in Turkey in 2012.

Energy Sources	2012 (PJ)
Hard Coal	207.46
Lignite	104.38
Asphaltite	4.02
Wood	98.18
Biowaste	38.98
Petroleum	33.66
Natural Gas	368.40
Electricity	338.13
Geothermal Heat	45.26
Solar	20.93

Data Source: Ministry of Energy and Natural Resources

Table 6.7. Residential sector energy consumption levels in Turkey in 2017.

Energy Sources	2017 (PJ)
Hard Coal	43.54
Lignite	46.02
Asphaltite	2.39
Natural Gas	410.01
Petroleum	10.78
Electricity	188.48
Solar	23.05
Biowaste	101.06
Geothermal Heat	15.05

Data Source: Ministry of Energy and Natural Resources

Table 6.8. Service sector energy consumption levels in Turkey in 2017.

Energy Sources	2017 (PJ)
Hard Coal	152.59
Lignite	14.55
Asphaltite	0.00
Coke	0.82
Petroleum	29.80
Natural Gas	110.39
Electricity	238.88
Geothermal Heat	41.38

Data Source: Ministry of Energy and Natural Resources

Table 6.9. Transportation sector energy consumption levels in Turkey.

Energy Sources	2012 (PJ)	2017(PJ)
Petroleum	799.47	1099.83
Natural Gas	12.52	13.69
Biodiesel	0.96	4.86
Electricity	2.15	3.17

Data Source: Ministry of Energy and Natural Resources

6.1.5. Electricity Generation

Turkey’s gross electricity generation by primary energy resources accounted for 239496.8 GWh (862.19 PJ) in 2012 and this value increased to 295510.6 GWh (1063.34 PJ) in 2017. Electricity generation from coal was 68013.1 GWh (244.85 PJ) in 2012. The share of imported coal, lignite and hard coal& asphaltite were 29210.5 GWh (105.16 PJ), 34688.9 GWh (124.88 PJ, 4113.7 GWh (14.81 PJ) in total electricity generation respectively. The share of coal in electricity generation increased by nearly 43%, and the value reached to 351.22 PJ in 2017.

On the other hand, electricity generation from natural gas accounted for 104499.2 GWh (376.2 PJ) in 2012 and it increased to 108168.8 GWh (389.41 PJ) in 2017. In addition, electricity generation from hydropower accounted for 57865 GWh (208.31 PJ) in 2012, whereas electricity generation from hydropower reached to 58450 GWh (210.42 PJ) in 2017. The wind power became the fastest growing energy generation. Electricity generation from wind power increased from 5860.8 GWh (21.1PJ) in 2012 to nearly 17722GWh (63.8 PJ) in 2017.

Turkey’s electricity generation by primary energy resources in 2012 and in 2017 are represented below (based on TEIAS, 2012).

Table 6.10. Turkey electricity generation by resources in 2017.

Energy Sources	**2017 (PJ)**
Hard Coal+Imported Coal	205.27
Lignite	145.95
Liquid Fuels	7.10
Natural Gas	389.41
Hydropower	210.42
Geothermal+Wind+Solar	95.63

Data Source: Turkey Electricity Transmission Company

Table 6.11. Turkey electricity generation by resources in 2012.

Energy Sources	2012 (PJ)
Hard Coal+Asphaltite	14.81
Imported Coal	105.16
Lignite	124.88
Fuel Oil	3.53
Diesel Oil	2.37
Natural Gas	376.20
Renewables+Wastes	
Hydropower	208.31
Geothermal	3.24
Wind	21.10
Solar	-

Data Source: Turkey Electricity Transmission Company

6.1.6. Electric Car Vehicles

The electricity demand of electric car vehicles in the BUEMS model has been calibrated throughout the planning horizon based on results from an ownership survey and various expert interviews carried out under a scientific research project (Boğaziçi University Research Project BAP 12281). Accordingly, the electricity demand values of electric vehicles are provided in Table 6.12.

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Table 6.12. Electric vehicles consumption levels predicted in the Base scenario.

Year	Electric Vehicles (PJ)
2012	0.00
2017	0.12
2022	0.88
2027	2.15
2032	5.35

Data Source: Boğaziçi University Research Project BAP 12281

BUEMS model has also been run under no electric car vehicle usage case. In that case, it is observed that transport sector emission levels increase, while electricity sector emission levels decrease compared to Base scenario. The reason is that, BUEMS tends to use more petroleum for transportation sector when no electric car is expected to be used throughout the planning horizon. In addition to that, since electricity demand decreases in no electric car vehicle usage case, electricity sector emission levels decrease accordingly. On the other hand, transport sector emission levels decrease from 2042 to the end of the planning horizon compared to previous periods for both scenarios, since hydrogen fueled vehicles are projected to be used which starts from the year 2042. It should be noted that, hydrogen fuel consumption levels in no electric car vehicle usage case are the same level with the Base scenario.

Table 6.13 Percentage change in CO2 emissions in the “No Electric Vehicle” scenario compared to the Base scenario.

Sector Name	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Transportation	0.03%	0.18%	0.37%	0.62%	2.54%	7.58%	8.82%	16.48%
Electricity	0.00%	-0.15%	-0.15%	-0.72%	-1.52%	-3.26%	-3.35%	-6.46%

7. RESULTS

7.1. Base Scenario

7.1.1. Energy Supply

In the Base scenario, fossil fuels such as coal, natural gas and petroleum account for around 94.2% of total energy supply in 2012. Coal supply level in 2037 is almost three times higher than in 2012. They are used for the generation of electricity and heat. In addition, transport sector uses fossil fuels for powering vehicles and industrial sector use fossil fuels as materials for some industrial processes.

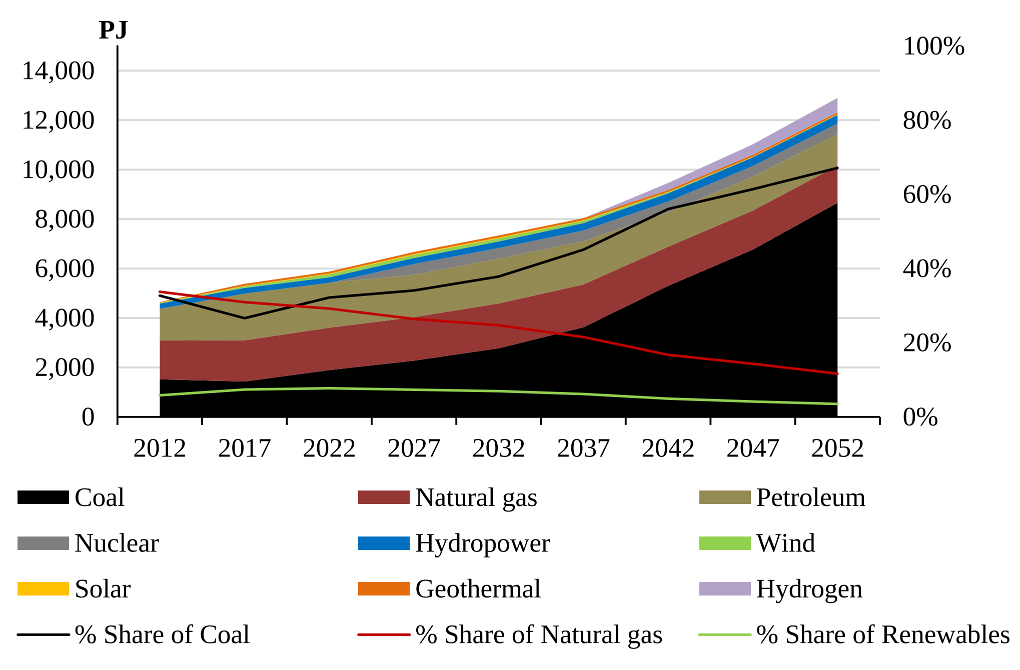

Figure 7.1. Energy supplies predicted in the Base scenario.

In the Base scenario, fossil fuels dominate primary energy consumption throughout the planning horizon, thus new investments are mainly realized for these types of energy sources.

On the other hand, the share of renewable energy in total energy supply accounts for 5.8% of total energy sources in 2012, whereas this figure declines to 3.5% in 2052 since new investments for renewable energy sources are realized in lower levels after the useful lifetimes of the renewable energy technologies that are introduced in the first three periods are over.

Besides fossil fuels and renewable energy sources, nuclear power technology is considered in the Base scenario. The Akkuyu Project has been taken into account and 4.8 GW installed capacity has been introduced for nuclear power technology which starts from the year 2027. The installed capacity for the Akkuyu has introduced to the model as no additional capacity will be provided until the end of the planning horizon. For this reason, the electricity generation from nuclear power remains the same throughout the planning horizon. The Sinop Project is not considered in the model.

As can been seen from Figure 7.1, the share of natural gas is higher than the share of coal in the first three periods, however, from the year 2022 the share of coal is dominant until the end of the planning horizon. The share of coal in total energy supply increases from 32.7% to 67.1%, while the share of natural gas decreases to 11.6% in 2052 from 33.8% in the base year and petroleum decreases to 9.9% in 2052 from 27.7% in the base year. The share of renewable energy sources increases to 7.3% in 2027 and after the year 2027, this figure starts to decline gradually until the end of planning horizon. On the other hand, hydrogen fueled vehicles are projected to be used which start from the year 2042. Their share in total energy supply is expected to be 3% in 2042 and increase continuously.

7.1.2. Electricity Generation

Natural gas accounted for 43.8% of total electricity generation in 2012 and it decreases continually throughout the planning horizon, whereas coal is the second dominant fuel used for electricity generation in 2012. The electricity generation provided from coal is 244 PJ in 2012 and around 351 PJ in 2017 and from the year 2027, coal becomes the dominant energy source in electricity generation until the end of the planning horizon. On the other hand, hydropower accounts for 208 PJ in 2012 and around 210 PJ in 2017. The share of hydropower in total electricity generation decreases until the end of the planning horizon. Wind power accounts for 2.4% of total electricity generation in 2012 and reaches to around 10% in 2022. After reaching its peak share, the share of wind power in total electricity generation decreases since new investments for renewables are not realized in the Base model.

On the other hand, there was no electricity generation from solar energy in 2012 and around 4.67 PJ electricity energy was generated from solar energy in 2017. The share of solar energy in total electricity generation reaches to 1.51% in 2022 and decreases continually until the end of the planning horizon. Figure 7.2 indicates Base scenario electricity generation levels.

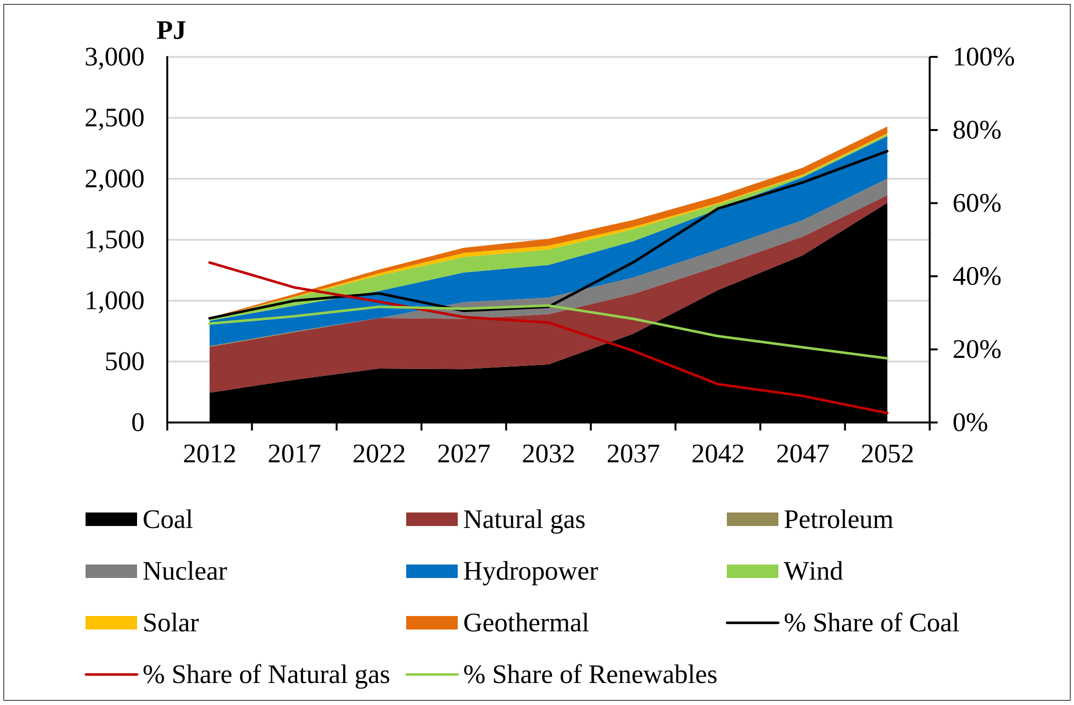

Figure 7.2. Electricity generation levels predicted in the Base scenario.

In 2027, nuclear energy accounted for 9.5% of total electricity generation. As mentioned above, it is considered that no additional capacity will be provided for nuclear energy. Although its share decreases in total electricity generation due to considerable increase in coal share, the electricity generation from nuclear energy remains at its maximum potential throughout the planning horizon.

7.1.3. Installed Capacities

The installed capacity of coal fired power plants is 12.6 GW in 2012 and 18.6 GW in 2017. The installed capacity increases to 22.2 GW in 2021 for coal fired power plants according to the worst case scenario of TEIAS Electricity Generation Capacity Production Report (2017-2021). Since coal continues to be dominant energy sources in the Base scenario, the installed capacity of coal power plants increase throughout the planning horizon and reach to 68.02 GW in 2052.

Table 7.1. Installed capacities predicted in the Base model.

Enery Resources	**2012 (GW)**	**2017 (GW)**	**2022 (GW)**	**2027 (GW)**	**2032 (GW)**	**2037 (GW)**	**2042 (GW)**	**2047 (GW)**	**2052 (GW)**
Coal	12.60	18.60	22.20	20.30	21.97	34.44	51.85	60.00	68.03
Natural Gas	20.60	23.10	29.30	29.18	29.06	22.94	13.77	10.74	4.42
Petroleum	1.28	0.45	0.45	0.45	0.21	0.21	0.21	0.21	0.21
Nuclear	-	-	-	4.80	4.80	4.80	4.80	4.80	4.80
Hydropower	19.60	27.30	31.53	29.92	28.31	27.36	27.55	27.81	27.59
Wind	2.30	6.50	10.30	10.30	10.30	8.00	3.80	1.14	1.14
Solar	-	1.14	8.26	8.26	8.26	7.12	2.14	2.14	2.14
Geothermal	0.16	1.10	1.37	1.91	2.54	2.54	2.54	2.54	2.54

Data Source: BUEMS Base model Results

The installed capacity of natural gas power plants is 20.6 GW in 2012, and decreases gradually after the year 2027, as electricity generation from natural gas decreases after the year 2027 as well. On the other hand, the installed capacity of nuclear energy remains the same (4.8 GW) throughout the planning horizon.

The installed capacity of wind power is 2.3 GW in 2012 and almost triples in 2017, reaching to 6.5 GW and rises to at least 9.99 GW in 2021 according to the worst case scenario of TEIAS Electricity Generation Capacity Production Report (2017-2021). The wind power installed capacity decreases after the year 2032. The installed capacity of solar power is zero in 2012 and 1.14 GW in 2017. It is expected that solar power installed capacity reaches to 8.26 GW in 2021. The solar power installed capacity decreases after the year 2032.

7.1.4. Sectoral Fuel Consumptions and Associated Emission Values

Energy consumption in electricity sector accounts for around 26.45% of total energy consumption in 2012, which is followed by the industry and residential sectors. The industry sector accounts for 24.24% and residential sector accounts for 24.09% of total energy consumption in 2012 whereas the transportation sector accounts for 17.02% of total energy consumption in 2012. Throughout the planning horizon, electricity continues to be largest energy consumed sector and industry continues to rank as the second largest energy consumed sector.

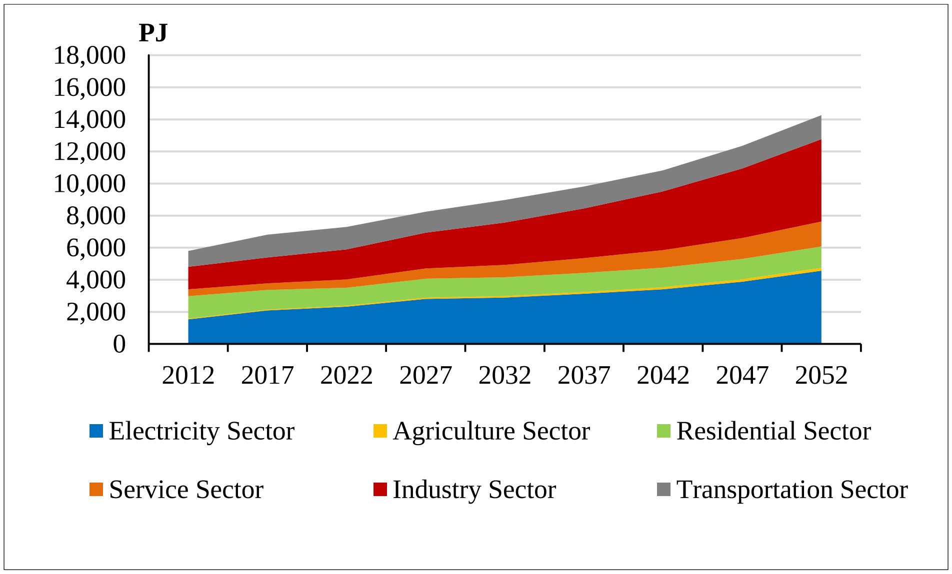

Figure 7.3. Sectoral energy consumption levels predicted in the Base scenario.

Total CO_2 emission level increases by 50% until 2032 compared to the initial year emission values and total CO_2 emission level increases by 70% in 2052 compared to 2032 levels due to an increased use of coal in the electricity production. Since the Base scenario tends to abandon renewable energy resources after their useful lifetimes are over and relies on coal until 2052, it is expected that coal consumption increases faster in the second half of the planning horizon.

The electricity generation sector produces the largest share of greenhouse gas emissions which accounts for approximately 28.91% of total CO_2 emission in 2012 and this sector maintains the largest emitter of emissions in 2052, accounting for 38.09%. Greenhouse gas emissions from the electricity sector primarily come from burning fossil fuels, especially coal. The industry sector is the second largest emitter, which accounts for 25.12% in 2012 and 37.05% in 2052. On the other hand, the transport sector experiences a decline in CO_2 emission, since the use of electric vehicles is expected to increase after 2037.

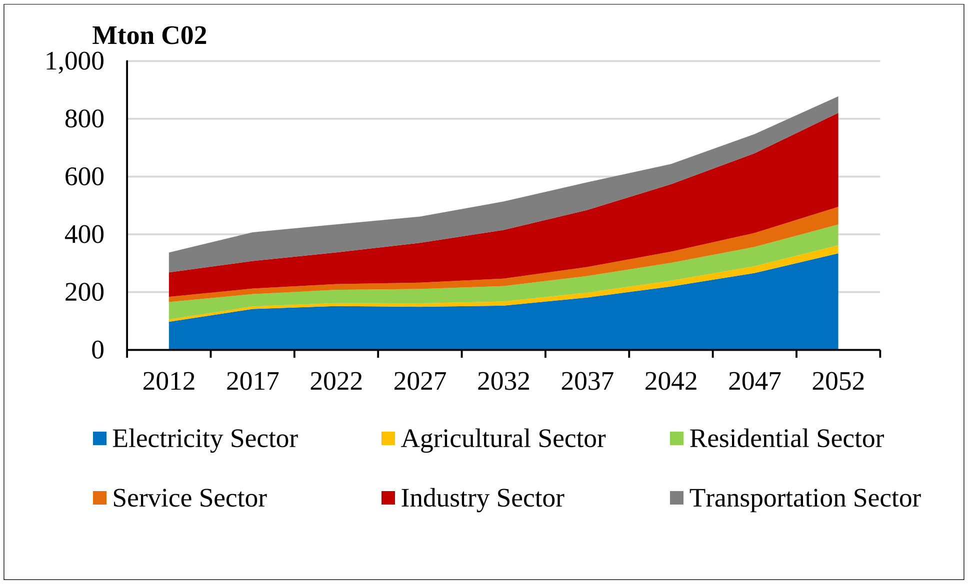

Figure 7.4. CO_2 emission levels predicted in the Base scenario.

The residential and service sectors accounted for 17.86% and 5.34% of total CO_2 emission in 2012 respectively and their share decreases gradually in total CO_2 emission due to replacement of coal with natural gas in these two sectors.

7.2. $C0_2$ Emission Restriction Scenarios

In these scenarios, emission restrictions are applied to the Base model which start from 2022. In this regard, emissions are restricted 10%, 20% and 25% below of those in the Base scenario.

As can be seen from Figure 7.5, energy supply levels decrease in all CO_2 emission restriction scenarios compared to the Base scenario. Total supply levels decline by %5, %9 and %10 in the 10%, 20% and 25% CO_2 emission restriction scenarios respectively. The main reason is that, coal supply level decreases in emission restriction scenarios, since coal is the largest contributor of the emissions. Total coal supply levels decrease by 14%, 28%, 33% in the 10%, 20% and 25% CO_2 emission restriction scenarios respectively.

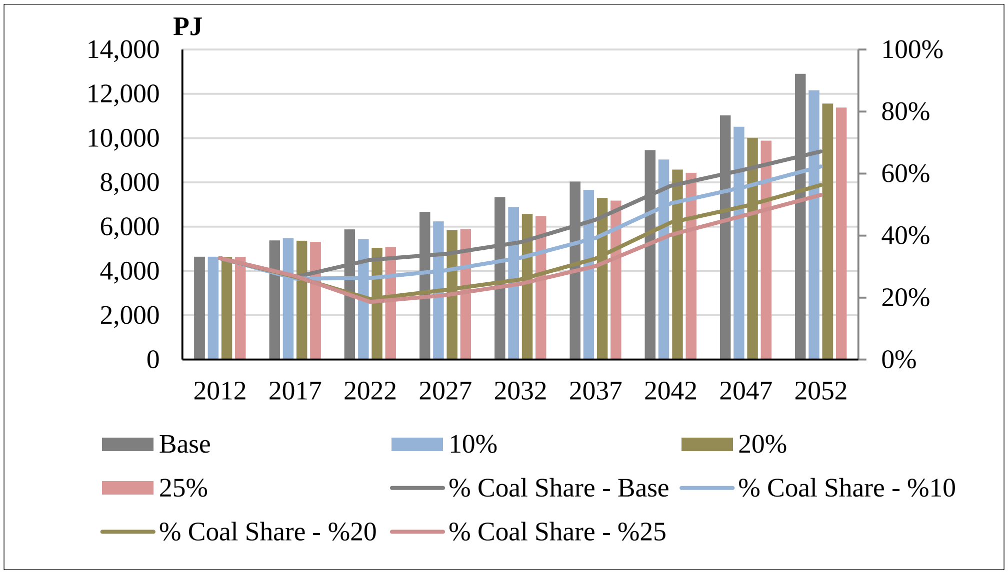

Figure 7.5. Energy supplies predicted in the 10%, 20%, 25% C02 emission restriction scenarios.

The share of coal accounts for 32% of total energy supply in 2022 in the Base scenario. However, as soon as restrictions become active, the coal share in total energy supply decreases to 26%, 20% and 19% in 2022 as it can been seen from Figure 7.5. After 2022, although the coal supply level continues to increase, the share of coal in the total energy sources become lower compared to the Base scenario.

BUEMS tends to use renewable resources which are considered to produce low or zero emissions. In the 10% CO_2 emission restriction scenario, total electricity generation from renewables increases by 9% in 2022 compared to Base scenario as emission restrictions are applied and continue to increase throughout the planning horizon. %20 and %25 $C0_2$ emission restriction scenarios follow the same trend with the %10 $C0_2$ scenario. Total electricity generation from renewables increases by 23% and 39% in 20% and 25% $C0_2$ emission restriction scenarios respectively in 2022 and continue to increase throughout the plannin horizon.

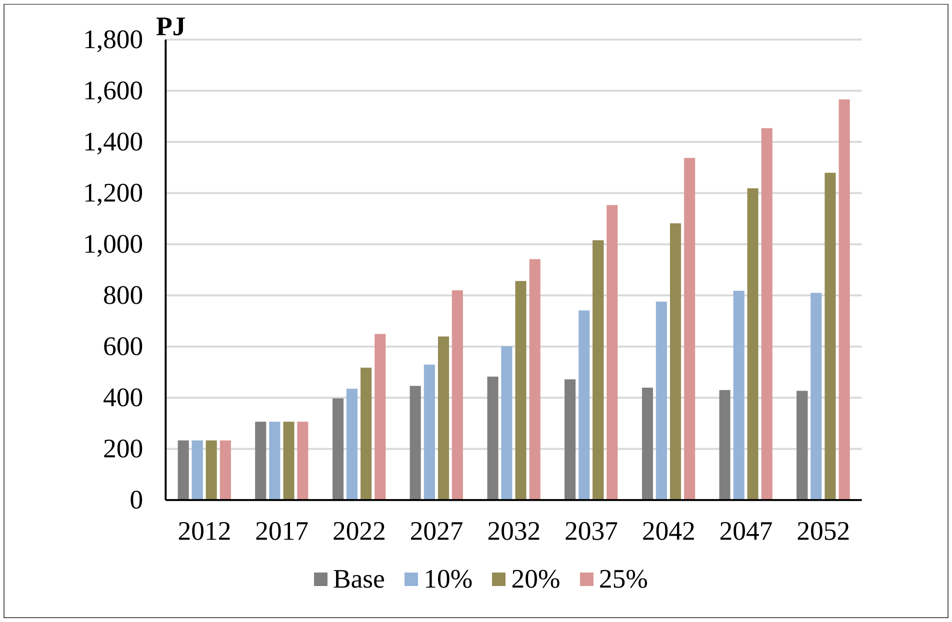

Figure 7.6. Electricity generation levels by renewables in the 10%, 20%, 25% CO_2 emission restriction scenarios.

Total installed capacities of coal fired power plants decline by 3%, 26%, 42% in the 10%, 20% and 25% CO_2 emission restriction scenarios respectively. On the other hand, as emission scenarios applied, total installed capacities of wind power plants start to increase in all emission restriction scenarios. The increase rates are 22%, 55% and 68% in the 10%, 20% and 25% CO_2 emission restriction scenarios respectively in 2027 compared to 2022 and installed capacities of wind power plants continue to increase for the two scenarios throughout the planning horizon. The installed capacities of solar power plants follow the same trend with wind power plants.

Total investment costs are higher in the emission restriction scenarios. Especially in 2022, there are considerable differences between Base and emission restriction scenarios in investment costs. The reason is that the emission restriction scenarios become valid in that year and the model invests on renewable energy technologies immediately. In addition, year 2032 experiences higher investment costs than the Base scenario because some technologies' useful lifetimes are over and reinvestment is needed.

7.3. Emission Tax Scenarios

In these scenarios, carbon taxes are introduced into the Base model which start from 2022. In this regard, 0.01$, 0.02$ and 0.03$ are applied on per kilotonne of CO_2 emissions in 3 different scenarios.

As mentioned in emission restriction scenarios, due to decrease in coal supply level, energy supply levels decrease in all emission tax scenarios compared to the Base scenario. Total supply levels decrease by 2%, 8%, 10% in the 10$, 20$ and 30$ emission tax scenarios respectively mainly due to decrease in coal supply levels.

Energy supply levels and the share of coal in all emission tax scenarios are displayed in Figure 7.7.

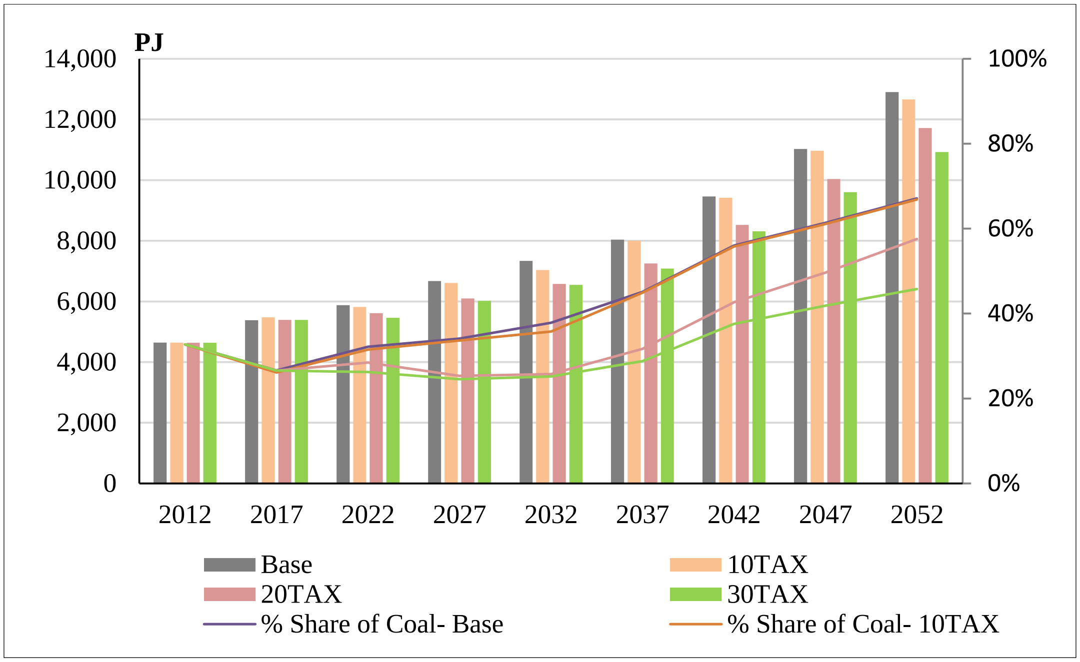

Figure 7.7. Energy supplies predicted in the 10$, 20$, 30$ emission tax scenarios.

Since there is a lower bound on wind capacity due to the calibration for the year 2022, the electricity generation from wind power in 2022 doubles compared to the level in 2017 in the Base Macro scenario. However, the electricity generation from renewable energy decreases starting from 2032, since the model continues to use fossil fuels as main energy sources in the Base scenario. On the other hand, while electricity generation from renewable energy remains the same with Base scenario in 10$ tax scenario in 2022, electricity generation from renewable energy increases by 42% and 47% in 20$ and 30$ tax scenairos compared to previous period. This means that, as soon as the emission taxes are applied, the model prefers to invest more on wind power technologies. The electricity generation from solar energy follows a similar trend with wind energy technologies.

In the 10$ emission tax scenario, the model invests on renewable energy technologies in lower levels compared to the other emission tax scenarios. The reason is that, since the 10$ tax is cheaper than the other taxes, the model prefers to pay taxes. In addition, in all emission tax scenarios, since the emissions are higher and taxes gets more expensive accordingly in the later periods, the use of renewable energy technologies increases in the later periods.

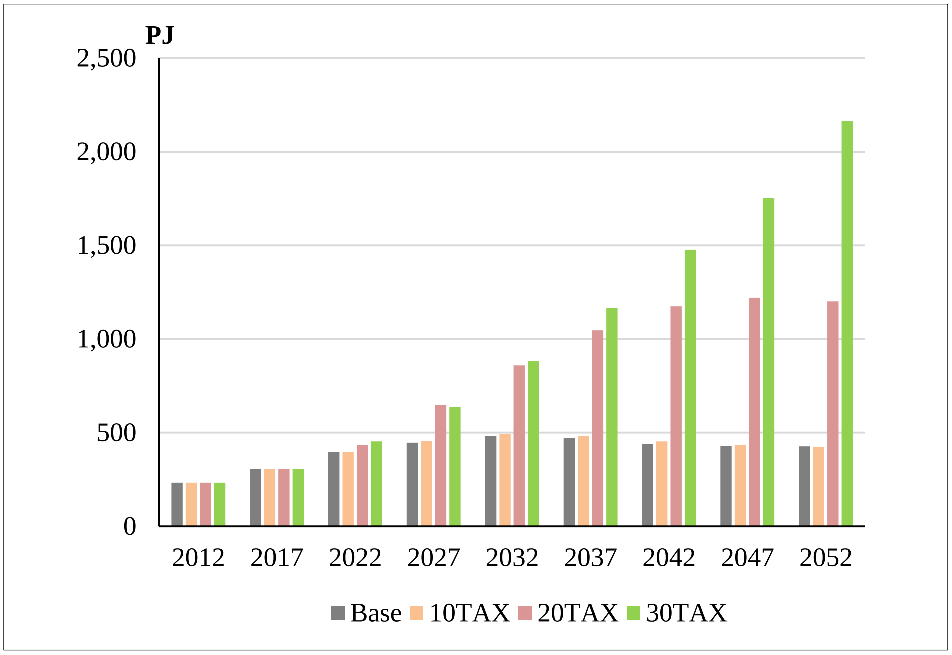

Figure 7.8. Electricity generation levels by renewables in the 10$, 20$, 30$ emission tax scenarios.

Total installed capacities of coal fired power plants decline by 37% and 66% in the 20$ and 30$ emission tax scenarios respectively compared to Base scenarios while total installed capacity of of coal fired power plants remains the same in 10$ tax scenarios with Base scenario. On the other hand, similar to $C0_2$ emission restriction scenarios, total installed capacities of wind and solar power plants increase in emission tax scenarios. In 2022, wind power plants increase by 21% in both 20$ and 30$ emission tax scenarios and continue to increase throughout the planning hozrion whereas 10$ emission tax scenario remains the same level with the Base scenario in 2022 and then increase in the following periods.

Total investment costs are higher in emission tax scenarios. Like emission restriction scenarios, for the years 2022 and 2032, the highest differences are observed.

Compared to the emission restriction scenarios, total energy supply levels in the emission tax scenarios are higher except for the 30$ tax scenario. The 30$ tax scenario provides less energy supplies than all CO_2 emission scenarios in total. Accordingly, total coal supply levels are higher in the emission tax scenarios except for the 30$ tax scenario. The 30$ tax scenario provides relatively lower coal energy source compared to the Base scenario and mainly prefers to generate electricity from renewables. The gap for electricity generation level from renewables between Base and 30$ tax scenario is more obvious in the later periods, since investment cost for wind and solar power technologies get cheaper over the years. In addition to that, as the emissions are higher in the later periods, the tax amounts are also much higher and as a result of this the model prefers to use renewable technologies rather than paying emission taxes for the fossil fuels.

7.4. Base Macro Scenario

In BUEMS-MACRO model, demands are endogenously determined based on the energy prices of the bottom-up model except for the years 2012 and 2017. End-use energy Macro model demand levels are the same with the end-use energy original model demand levels for the years 2012 and 2017 which are exogenously determined. Endogenous demand calculation starts from the year 2022.

In BUEMS model, end-use energy demand growth rate is determined according to MENR energy balance tables 2012 and 2016. According to these tables, there is a 18% increase in end-use energy demand in 5 years. Based on this growth rate, end-use energy demand levels have been calculated for future years throughout the planning horizon. In this method, end-use energy demand levels are determined exogenously in the absence of price changes. On the other hand, in BUEMS-MACRO model, end-use energy demand growth rate is determined endogenously under the impacts of energy prices and BUEMS-MACRO generates lower end-use energy demand growth rate compared to BUEMS. For thir reason, BUEMS-MACRO end-use energy demand levels are less than BUEMS end-use energy demand levels. Total end-use energy demands decrease by 4% in 2022 and 7% in 2027 in

BUEMS-MACRO model compared to BUEMS model and the difference between these two models in end-use energt demand level rises to 25% in 2052.

7.4.1. Energy Supply

The BUEMS-MACRO Base model generates lower energy supply levels since demand levels are lower in the BUEMS-MACRO model. In this model, total energy supply increases from 5459.04 PJ in 2022 to 9235.29 PJ in 2052. Fossil fuels account for 92% of total energy supply in 2022 and fossil fuels continue to provide most of the energy consumption throughout the planning horizon. In the begining, the share of natural gas is 30% and the share of coal is 31%. Since the electricity generation levels are calibrated according to the data from TEIAS for the years 2012 and 2017, this result is expected. However, in the following periods the share of coal increases due to having the cheapest supply cost while the share of natural gas decreases.

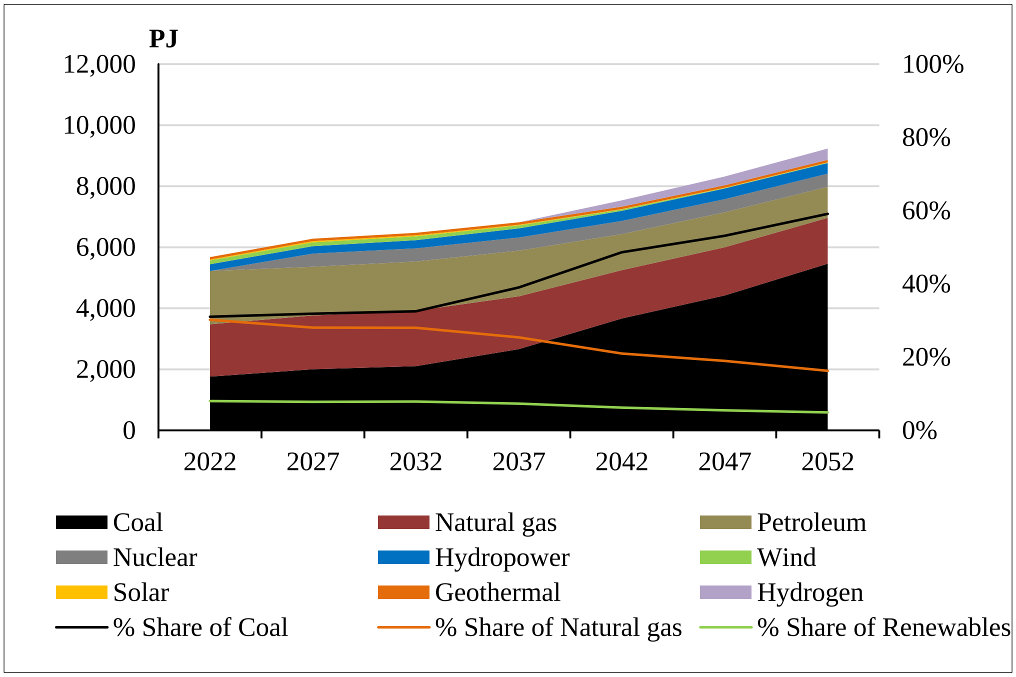

Figure 7.9. Energy supplies predicted in the Base Macro scenario.

On the other hand, the share of renewable energy in total energy supply accounts for 8% in 2022 and this figure decreases continually, since new investments are not realized, when the useful lifetimes of existing renewable energy technologies are over in the Base Macro model.

Nuclear power technology is introduced to the model which starts from 2027. The energy supply level, the installed capacity and the level of electricity generation from nuclear power are considered as the same with the BUEMS model. Hydrogen fueled vehicles are projected to be used which start from the year 2042. Their share in total energy supply is expected to be 3% in 2042 and remain nearly unchanged until 2052.

7.4.2. Electricity Generation

Natural gas and coal account for 34% and %33 of total electricity generation in 2022 respectively. After 2022, while electricity generation from natural gas decreases until the end of the planning horizon, electricity generation from coal increases and coal becomes the dominant energy fuel in electricity generation which accounts for 63% of total electricity generation in 2052.

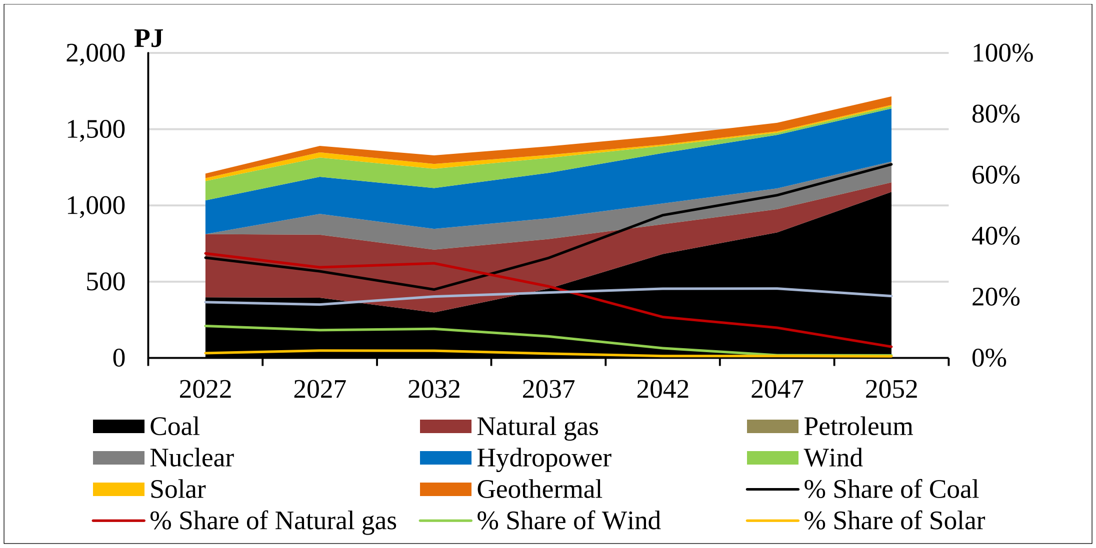

Figure 7.10. Electricity generation levels predicted in the Base Macro scenario.

As it can be seen in Figure 7.10, there is a decrease in the share of coal for the years 2027 and 2032 since nuclear energy becomes active in 2027. Nuclear energy provides 9.80% of total electricity generation in 2027, and its share decreases gradually in total electricity production although the level of electricity production from nuclear power remains at its maximum potential throughout the planning horizon. The reason is that, only Akkuyu Project has been taken into account in the model and the electricity generation from nuclear power remains the same level throughout the planning horizon accordingly. Thus, due to increase in energy demand, the share of coal rises again after 2032.

Hydropower accounts for 18% of total electricity generation in 2022 and the share of hydropower in electricity generation slightly changes throughout the planning horizon. On the other hand, wind and solar power account for 10% and 2% of total electricity generation in 2022 respectively and their share decrease considerably until the end of the planning horizon.

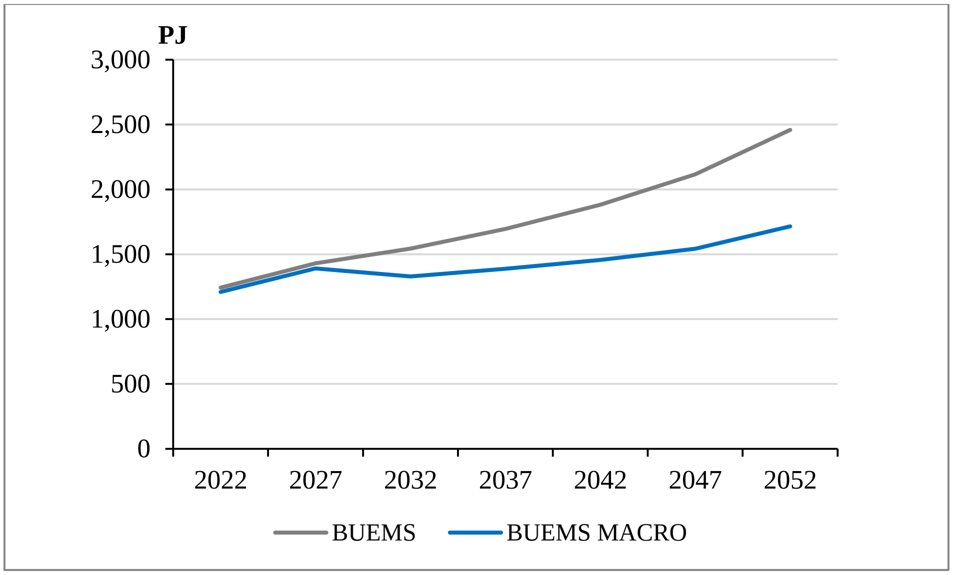

Figure 7.11. Electricity generations levels predicted in the Base and Base Macro scenarios.

Total electricity production is 1209.27 PJ in 2022 and reaches to around 1715.40 PJ in 2052. Since end-use energy demand levels in BUEMS-MACRO model are less than BUEMS model, electricity generation levels are also lower compared to BUEMS model. The difference in electricity generation level is 3% in 2022 and reaches to 30% in 2052.

7.4.3. Installed Capacities

The installed capacities in the BUEMS-MACRO model for the year 2022 are the same with the BUEMS model since the installed capacities are calibrated according to the worst case scenario of TEIAS Electricity Generation Capacity Production Report (2017-2021). After 2022, the installed capacities are lower than the BUEMS model, since the Macro module provides lower demands compared to BUEMS model until the end of the planning horizon.

The installed capacity of coal fired power is 22.20 GW in 2027 and reaches to 42.87 GW in 2052, since coal continue to be dominant energy fuel until the end of the planning horizon and the installed capacity of natural gas decreases continually after 2027. On the other hand, the installed capacities of renewable energy technologies are almost the same with the BUEMS Base model due to the calibration levels.

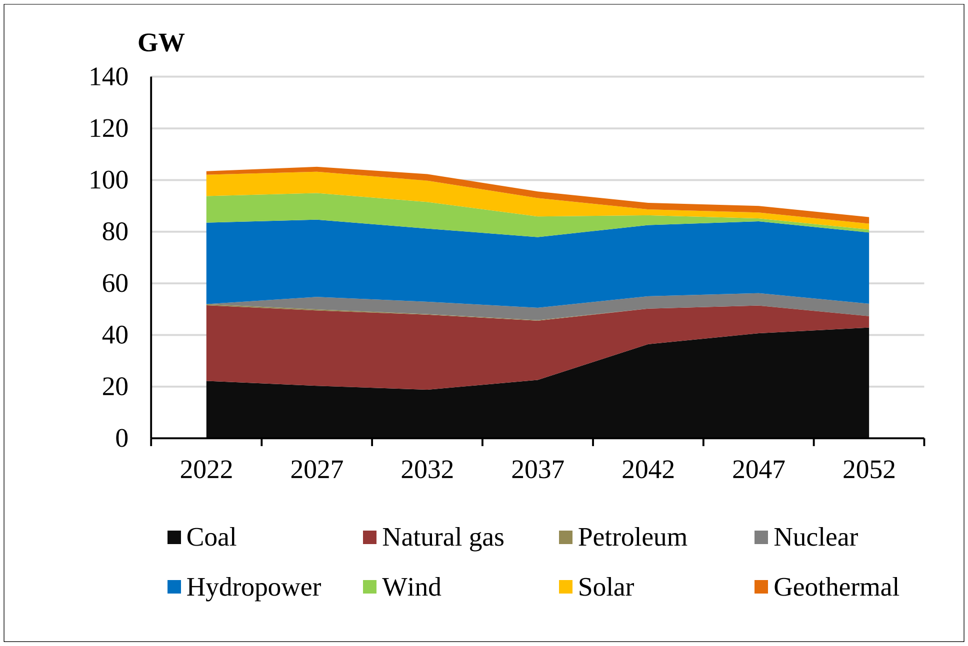

Figure 7.12. Installed capacities predicted in the Base Macro Scenario.

As it can be seen in Figure 7.12, renewable energy installed capacities increase for the first period 2022 due to model calibration and then decrease, since Base Macro model does not tend to invest on renewable energy technologies when the useful lifetimes of existing renewable energy technologies are over.

7.4.4. Sectoral Fuel Consumptions and Associated Emission Values

Sectors in the Base Macro scenario feature similar energy consumption profiles to the Base scenario. The electricity sector accounts for 31.35% of total energy consumption in 2022 and the share of energy consumption in electricity sector changes slightly throughout the planning horizon. Industry is the second largest energy consumed sector, which accounts for 25.60% of total energy consumption in 2022 and reaches to 35.58% in 2052. On the other hand, the transport sector accounts for 19.16% of total energy consumption in 2022 and the energy consumption by transport sector decreases gradually and since the use of electric vehicles is expected to increase after 2037.

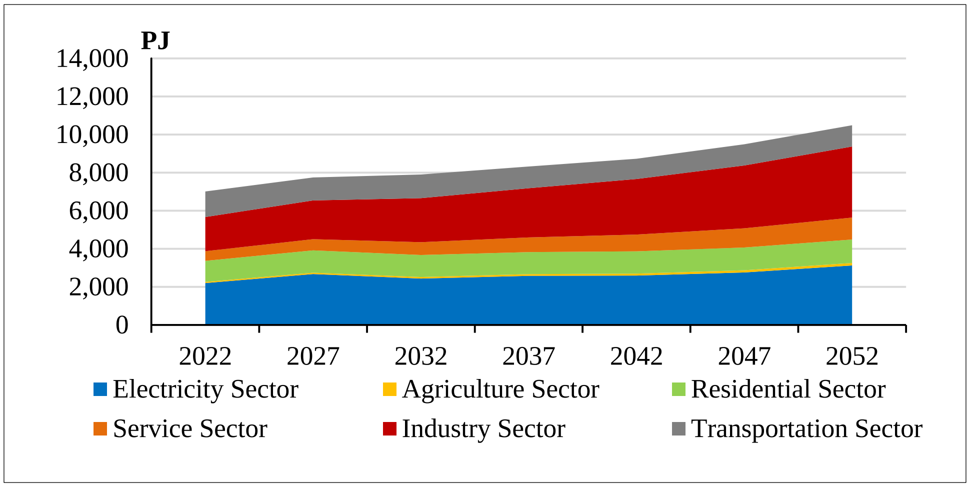

Figure 7.13. Sectoral energy consumption levels predicted in the Base Macro scenario.

Total CO_2 emission levels increase continually, since coal continue to be the dominant fuel throughout the planning horizon. Especially from 2042, total emission level increases faster due to the decrease in the level of renewable energy consumption.

Since end-use demands are lower in BUEMS-MACRO compared to BUEMS model, BUEMS-MACRO generates lower CO_2 emission levels than the original model.

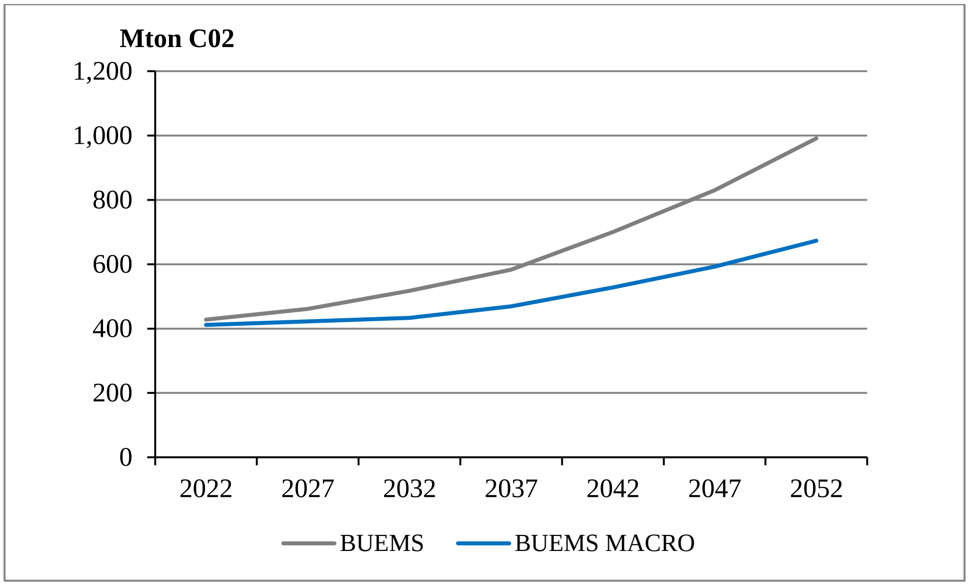

Figure 7.14. Total CO_2 emission levels predicted in the Base and in the Base Macro scenarios.

The electricity generation sector produces the largest share of greenhouse gas emissions, accounting for %34 of total CO_2 emission levels in 2022 which is followed by industry sector. The industry sector accounts for 24% of total emission levels in 2022 and the figure for this sector reaches to 31% until the end of the planning horizon. On the other hand, the transportation sector contributes 22% of total CO_2 emission levels in 2022, and due to an increase in the use of electric vehicles after 2037, the transport sector experiences a gradual decline in emissions.

7.5. $C0_2$ Emission Restriction Macro Scenarios

In these scenarios, emission restrictions are applied to the Base Macro model which start from 2022. In this regard, emissions are restricted 10%, 20% and 25% below of those in the Base Macro scenario.

The emission restriction scenarios that are run under the BUEMS-MACRO model provide different approach than the BUEMS model. In this model, demands are generated endogenously according to the energy prices. For this reason, as soon as emission restrictions are applied, the model tends to shrink its economy and prefers to reduce its end-use demands instead of investing on renewable energy sources immediately. However, in the BUEMS model, since demands are exogenously provided into the model, they remain unchanged in the emission restriction scenarios and when emission scenarios become active, the model invests on renewable energy sources to meet the same end-use demands with the Base scenario.

Table 7.2. Percentage reduction of total demand levels in emission restriction Macro scenarios compared to Base Macro scenario.

Scenario Name	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
10% CO_2	0.00%	0.42%	0.73%	1.07%	1.42%	1.78%	2.12%	2.45%
20% CO_2	0.00%	0.55%	0.87%	1.21%	1.57%	1.93%	2.27%	2.60%
25% CO_2	0.00%	0.76%	1.09%	1.43%	1.79%	2.16%	2.50%	2.84%

Figure 7.15 shows energy supply levels predicted in the Macro emission restriction scenarios.

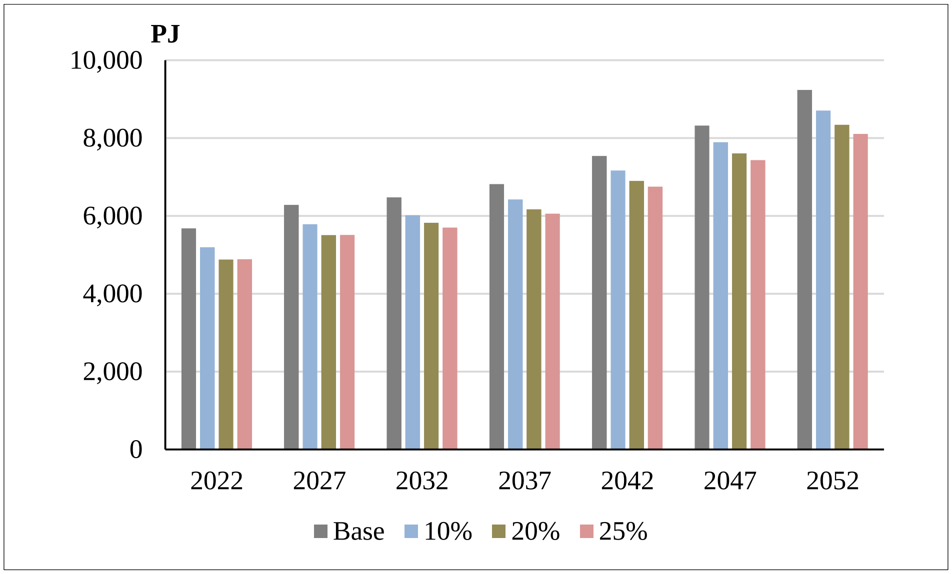

Figure 7.15. Energy supplies predicted in the 10%, 20%, 25% CO_2 Macro emission restriction scenarios.

As it can be seen in Figure 7.15, total energy supply levels decrease in emission restriction scenarios. Total supply levels decrease by 6%, 9%, 11% in the 10%, 20% and 25% CO_2 emission restriction Macro scenarios respectively.The reason is that, as soon as emissions are restricted, model tends to use less coal since coal has the most carbon-content fossil fuel.

Figure 7.16 shows total coal supply levels. Total coal supply levels decrease in all the emission restriction Macro scenarios compared to the Base Macro scenario. Total coal supply levels decrease by 18%, 32%, 39% in the 10%, 20% and 25% CO_2 emission restriction Macro scenarios respectively. In the 10% CO_2 emission restriction scenario, coal share in total supply level decreases by 7% in 2022, while coal share decreases by 13% and 16% in total supply for the 20% and 25% CO_2 emission restriction scenarios respectively in 2022.

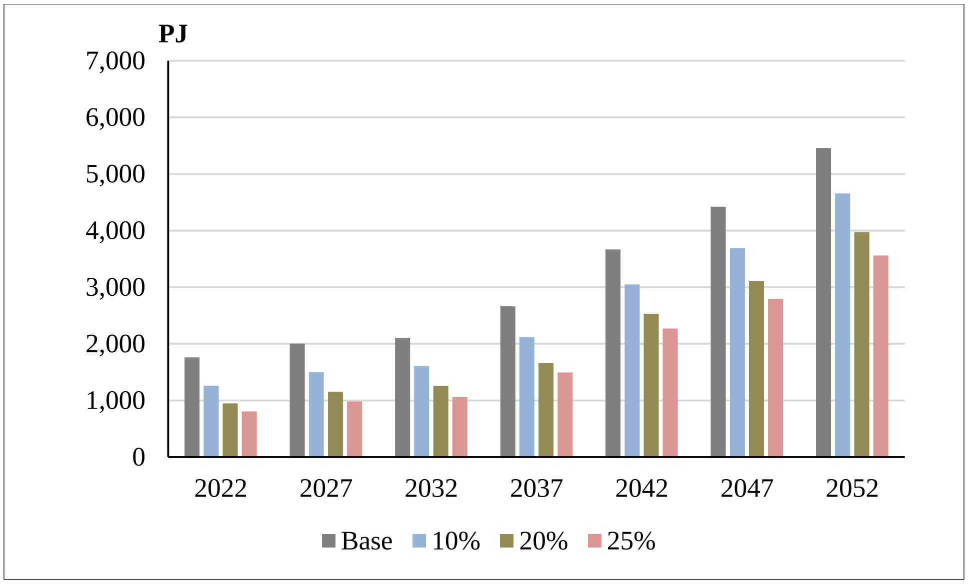

Figure 7.16. Total coal supply levels predicted in the Base Macro and emission restriction scenarios.

Electricity generation from coal experiences a decline while electricity generation from renewable energy increases in emission restriction Macro scenarios. In all emission restriction Macro scenarios, the electricity generation from renewable energies increase as soon as emission restriction scenarios become active and continue to increase in all emission restriction Macro scenarios throughout the planning horizon, rising by 23%, 41% and 49% in total compared to the Base Macro scenario.

10% CO_2 emission restriction scenario prefers to use more natural gas than coal in residential heating since emission level due to natural gas is much lower than coal. In addition to that, electricity consumption in residential sector decreases slightly due to increase in the usage of natural gas. Total electricity production decreases by nearly 4% in 10% CO_2 emission restriction scenario. On the other hand, 20% and 25% CO_2 emission restriction scenarios prefer to use more electricity than natural gas and coal in residential sector. The reason is that, as CO_2 emission restriction percentages are higher, the model shifts away from fossil fuels and invest in renewable energy technologies. Thus, electricity generation from renewable energy technologies increase and the usage of electricity increases accordingly. It should be noted that, however natural gas has less carbon-content than coal, it is still a fossil fuel and the model also tends to use less natural gas as emission restrictions get higher.

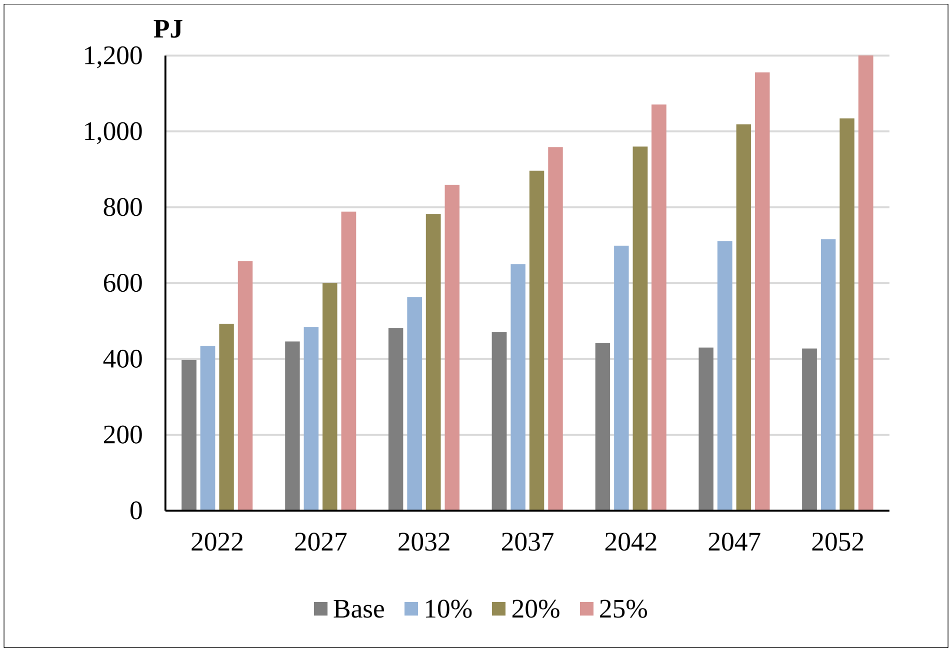

Figure 7.17. Electricity generation levels by renewables in the 10%, 20%, 25% CO_2 Macro emission restriction scenarios.

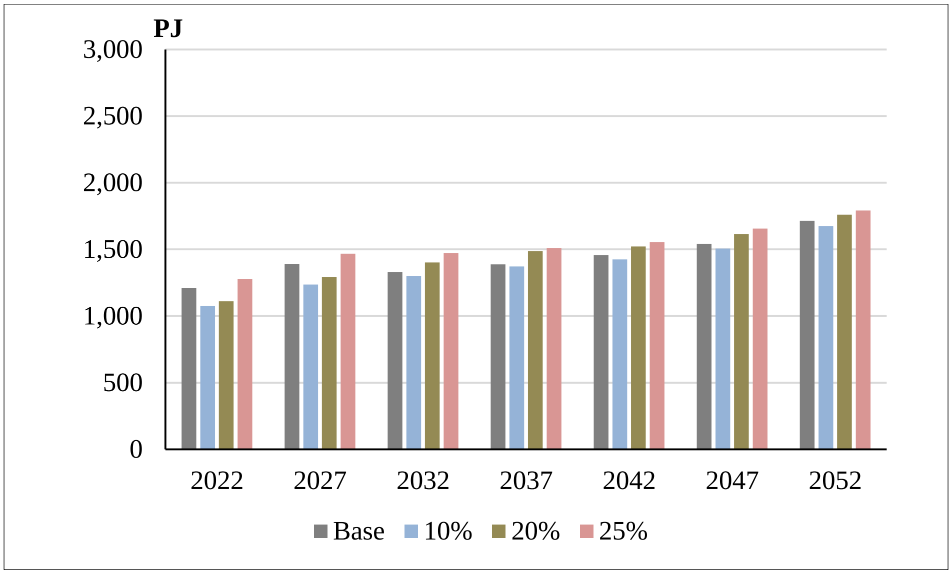

Figure 7.18. Total electricity generation levels predicted in the Base, 10%, 20% and 25% emission restriction scenarios.

Total installed capacity of coal fired power plants decline by 6%, 27%, 32% in the 10%, 20% and 25% CO_2 emission restriction scenarios respectively. On the other hand, total installed capacity wind power increase by 20%, 21%, 21% as soon as emission restriction scenarios are applied and continue to increase until the end of the planning horizon. Total installed capacity of solar power follows the same trend with wind power throughout the planning horizon.

7.6. Emission Tax Macro Scenarios

In these scenarios, carbon taxes are introduced into the Base Macro model which start from 2022. In this regard, 0.01$, 0.02$ and 0.03$ are applied on per kilotonne of CO_2 emissions in 3 different scenarios.

The emission tax Macro scenarios follow the same approach with the emission restriction Macro scenarios and total end-use enegy demands decrease when emission restrictions are applied.

Table 7.3. Percentage reduction of total demand levels in emission tax Macro scenarios compared to Base Macro scenario.

Scenario Name	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
10 TAX	0.00%	0.45%	0.76%	1.10%	1.45%	1.81%	2.15%	2.48%
20 TAX	0.00%	0.59%	0.90%	1.24%	1.60%	1.95%	2.30%	2.63%
30 TAX	0.00%	0.79%	1.11%	1.45%	1.82%	2.18%	2.53%	2.86%

Total supply levels decrease by 3%, 8%, 10% in the 10$, 20$ and 30$ emission tax Macro scenarios respectively compared to the Base Macro scenario as a result of lower coal supply levels.

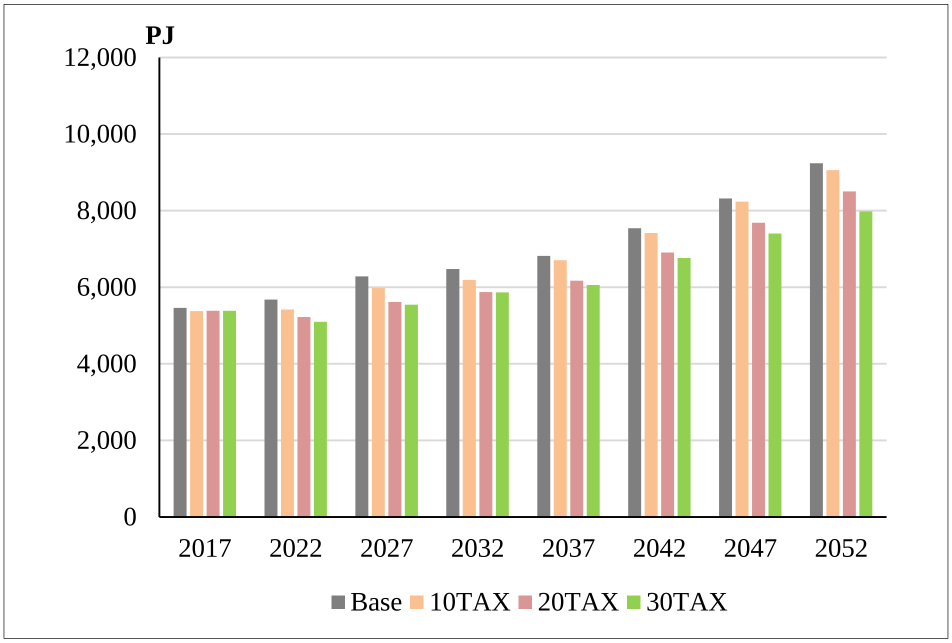

Figure 7.19. Energy supplies predicted in the 10$, 20$ 30$ Macro emission tax scenarios.

Coal supply levels decrease by 5%, 27%, 37% in the 10$, 20$ and 30$ emission tax Macro scenarios respectively compared to the Base Macro scenario.

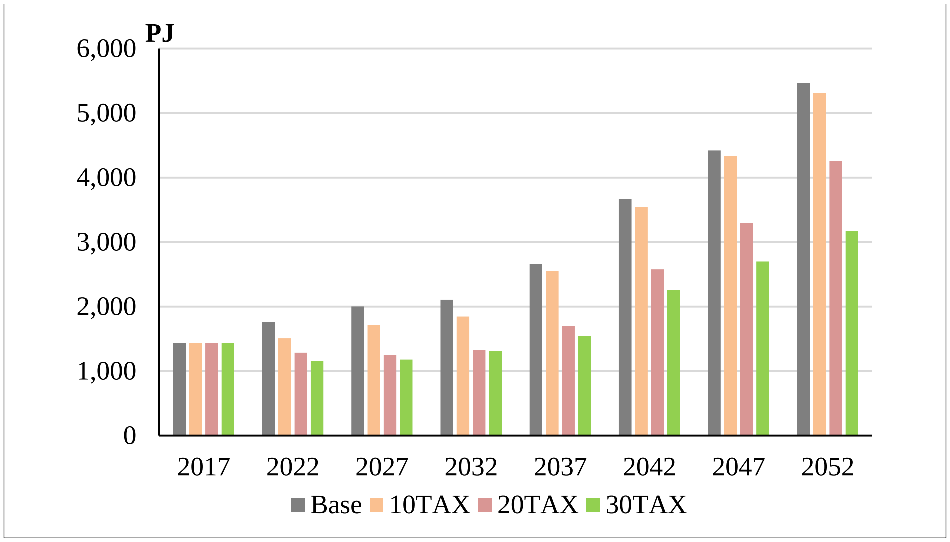

Figure 7.20. Total coal supply levels predicted in the Base Macro and emission tax scenarios.

Total coal supply levels predicted in the Base Macro and emission tax scenarios.

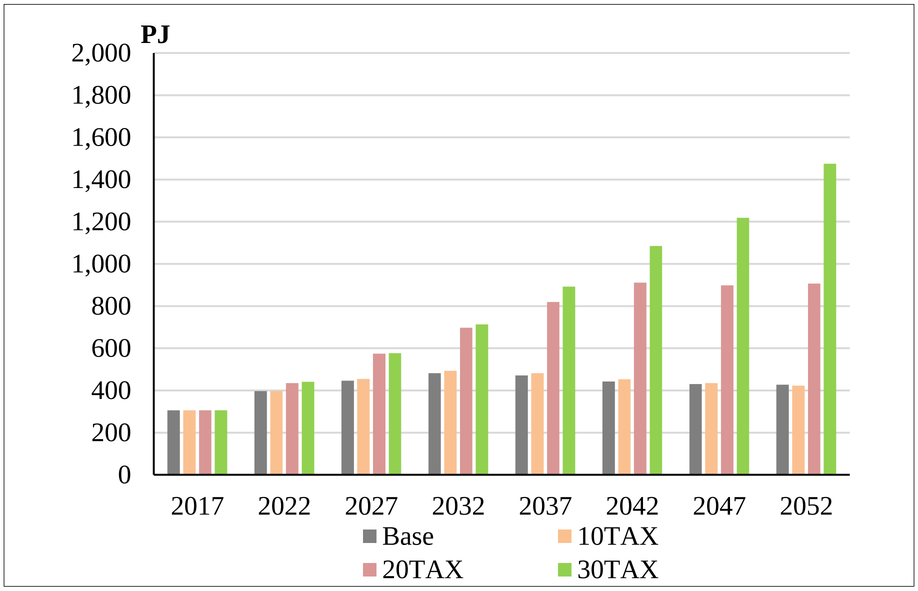

Figure 7.21. Electricity generation levels by renewables in the 10$, 20$, 30$ Macro emission tax scenarios.

Total electricity generation from renewable energy slightly increases in 10$ emisson tax Macro scenario since the model prefers to pay emission taxes instead of investing in renewable energy technologies. On the other hand, total electricity generation from renewables increase by 8.7% and 10.6% in the 20$ and 30$ emission tax Macro scenarios respectively compared to Base Macro scenario in 2022 as soon as emission taxes are applied and the level of renewable energy usage in electricity generation increases in both 20$ and 30$ emission tax Macro scenarios throughout the planning horizon.

Total electricity production decreases by 3%, 4%, 4% in the 10$, 20$ and 30$ emission tax scenarios respectively. Although electricity generation level from renewable energy increases in all emission tax scenarios, coal usage in electricity production decreases in higher levels than the increase of renewable energy usage. As a result of this, total electricity generation level decreases throughout the planning horizon compared to Base Macro scenario.

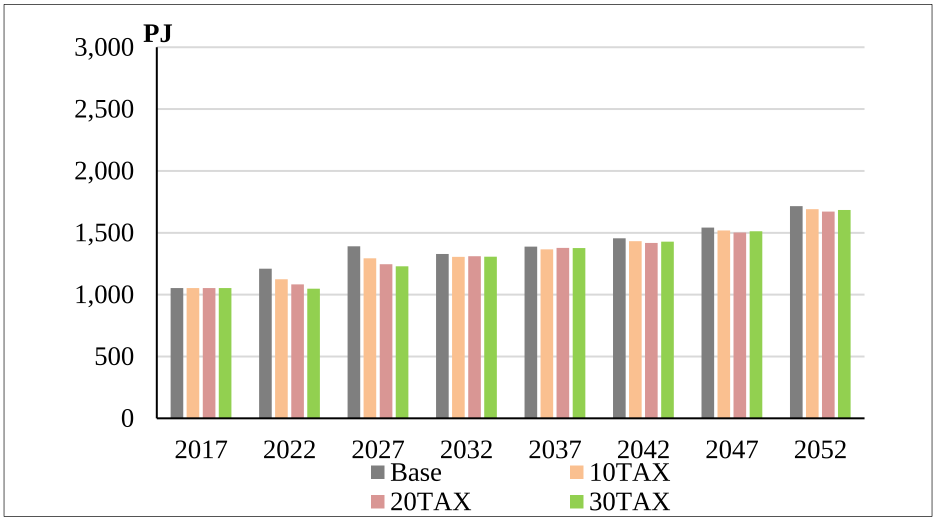

Figure 7.22. Total electricity generation levels predicted in the Base, 10$, 20$, 30$ Macro emission tax scenarios.

Total installed capacities of coal fired power plants slightly change in 10$ tax scenarios, while total installed capacities of coal fired power plants decline by 20%, 42% in the 20$ and 30$ emission tax scenarios respectively. Total installed capacity of wind power for the 10$ emission tax scenario slightly changes for the first two periods and then start to increase throughout the planning horizon whereas total installed capacities of wind power for the 20$

and 30$ emission tax scenarios increase by 21% as soon as emission taxes become active in 2022 and continue to increase throughout the planning horizon. Total installed capacity of solar power follows the same trend with wind power throughout the planning horizon.

In emission tax scenarios, different than $C0_2$ emission restriction scenarios, it is observed that model prefers to decrease electricity sector consumption levels instead of decreasing other sectors consumption levels such as residential and service sector. In all emission tax scenarios, coal consumption in residential sector slightly changes compared to Base Macro scenario, whereas coal consumption decreases and model prefers to use more natural gas and electricity in residential sector when $C0_2$ emission restrictions are applied. For this reason, total electricity generation increases in emission restriction scenarios while total electricity generation decreases in emission tax scenarios despite the increase in electricity generation from renewable energy when emission taxes are applied.

7.7. Gdp Losses

The real GDP data for the initial year is taken from Turkish Statistical Institute (TSI), as 1,110.5 billion dollar for the year 2017 and in the Base Macro model, the GDP value has reached to 2,666.1 billion dollar by 2052.

Table 7.4. Gdp values predicted in the Base Macro Model.

Year	**GDP (billion $)**
2017	1,110.5
2022	1,266.2
2027	1,433.3
2032	1,619.6
2037	1,833.1
2042	2,081.3
2047	2,355.2
2052	2,666.1

As mentioned before, in emission scenarios model tends to shrink its economy when restrictions are applied. For this reason, GDP values which are estimated by the Macro model decrease compared to the Base Macro scenario.

Table 7.5. Gdp values predicted in the emission restriction and tax Macro scenarios (in billion $).

Year	**%10 $C0_2$**	**%20 $C0_2$**	**%25 $C0_2$**	**10TAX**	**20 TAX**	**30 TAX**
2017	1,110.5	1,110.5	1,110.5	1,110.5	1,110.5	1,110.5
2022	1,260.9	1,260.1	1,256.5	1,256.3	1,250.9	1,244.4
2027	1,422.7	1,421.5	1,418.2	1,417.9	1,413.0	1,406.1
2032	1,602.6	1,600.8	1,596.6	1,597.6	1,592.4	1,584.6
2037	1,807.7	1,805.6	1,801.3	1,801.9	1,796.9	1,789.0
2042	2,044.6	2,042.0	2,037.0	2,038.2	2,032.3	2,023.9
2047	2,305.8	2,302.7	2,297.1	2,298.8	2,291.6	2,282.9
2052	2,602.4	2,598.9	2,592.7	2,594.6	2,586.2	2,577.9

Table 7.6 shows percentage GDP losses in emission emission restriction and tax scenarios compared to the Base scenario.

Table 7.6. % GDP losses predicted in emission scenarios compared to Base Macro scenario.

Year	**%10 $C0_2$**	**%20 $C0_2$**	**%25 $C0_2$**	**10TAX**	**20 TAX**	**30 TAX**
2017	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2022	0.42%	0.48%	0.77%	0.78%	1.21%	1.72%
2027	0.74%	0.82%	1.05%	1.07%	1.42%	1.90%
2032	1.05%	1.16%	1.42%	1.36%	1.68%	2.16%
2037	1.39%	1.50%	1.73%	1.70%	1.97%	2.41%
2042	1.76%	1.89%	2.13%	2.07%	2.35%	2.76%
2047	2.10%	2.23%	2.47%	2.39%	2.70%	3.07%
2052	2.39%	2.52%	2.75%	2.68%	3.00%	3.31%

For the year 2022, significant reductions are not observed in both emission restriction and emission tax scenarios. However, the gap between the Base Macro and the emission scenarios increase in later periods. Table 7.6 shows percentage GDP losses in emission scenarios compared to the Base Macro scenario.

7.8. Sensitivity Analysis

As it is indicated earlier, BUEMS-MACRO results have been evaluated with the CES production function based on the esub value 0.3 which is taken from Karali (2006).

Esub value is one of the most important parameters in economic analysis. For this reason, BUEMS-MACRO model has been run under the esub value 0.25 to analyze how sensitive the model is to alternative esub values. The results reveal that the model generates differentiated results when different elasticity of substitution parameters are used. A reduction in the flexibility of substitution between capital-labor and energy leads to more shrinkage in the economy with lower end-use energy demand levels. As a result of this, lower GDP levels are observed in the Base model with esub value 0.25 compared to the esub value 0.3.

In addition, BUEMS-MACRO model has been run under the emission restriction and emission tax scenarios with the esub value 0.25. The results reveal that more GDP losses are observed in scenarios with esub value 0.25 compared to the esub value 0.3. This result is expected since the flexibility of the substitution between capital-labor and energy decreases with the esub value 0.25. The results of those scenarios are displayed in Appendix CD folder.

BUEMS-MACRO model have also been run under the esub value 0.645 which is taken from Kucuk (2017) with the (KL)E nesting structure to the production function. Kucuk indicates that a production function for Turkey in the CES form can be interpreted economically with the elasticity of substitution parameter which is equal to 0.645. This means that the aggregate of capital and labor can be substituted with energy with a rate of 0.645. Kucuk interprets this esub value as that the high share of capital-labor in the production function is due to relatively high energy prices in Turkey, since Turkey is dependent on imported energy to meet its domestic energy demand. In this structure, energy has been taken in terms of energy cost in the production function which Kucuk (2017) explains as energy in the form of energy cost leads to significant results for Turkey data. The results reveal that GDP losses between Base scenario and emission restriction and tax scenarios are lower compared to original BUEMS-MACRO results. The results of those scenarios are displayed in Appendix CD folder.

7.9 Model Validation

The BUEMS-MACRO Base model GDP results have been compared with the TIMES-MACRO Base model GDP results for the model validation. In this regard, BUEMS-MACRO model has been run with esub value 0.25 in order to make a realistic comparison with the TIMES-MACRO model, since TIMES-MACRO has been run with the esub value 0.25. However, it should be noted that, although esub values and potential GDP growth rates of both models are the same, there are some differences between these two models in terms of model structure and data. Firstly, end-use energy demand levels of BUEMS-MACRO Base model are less than end-use energy demand levels of TIMES-MACRO model. Secondly, "*the gross domestic product in chain linked volume by TSI*" has been used for the initial GDP in BUEMS-MACRO accordingly. However, in TIMES-MACRO model, "*the gross domestic product at current prices by TSI"* has been used for the initial GDP. Lastly, time periods are divided into three years in TIMES-MACRO, while BUEMS-MACRO has five years in each period. For this reason, interpolation has been used to obtain GDP results of both models for the same periods.

Figure 7.23 shows GDP levels predicted in the Base scenarios and Figure 7.24 Figure 7.25 show emission restriction and emission tax scenarios in BUEMS-MACRO model and TIMES-MACRO model respectively.

As it is indicated above, the initial GDP levels of the two models are different from each other. For the purpose of comparison, TIMES-MACRO initial GDP level has been taken based on BUEMS-MACRO initial GDP level.

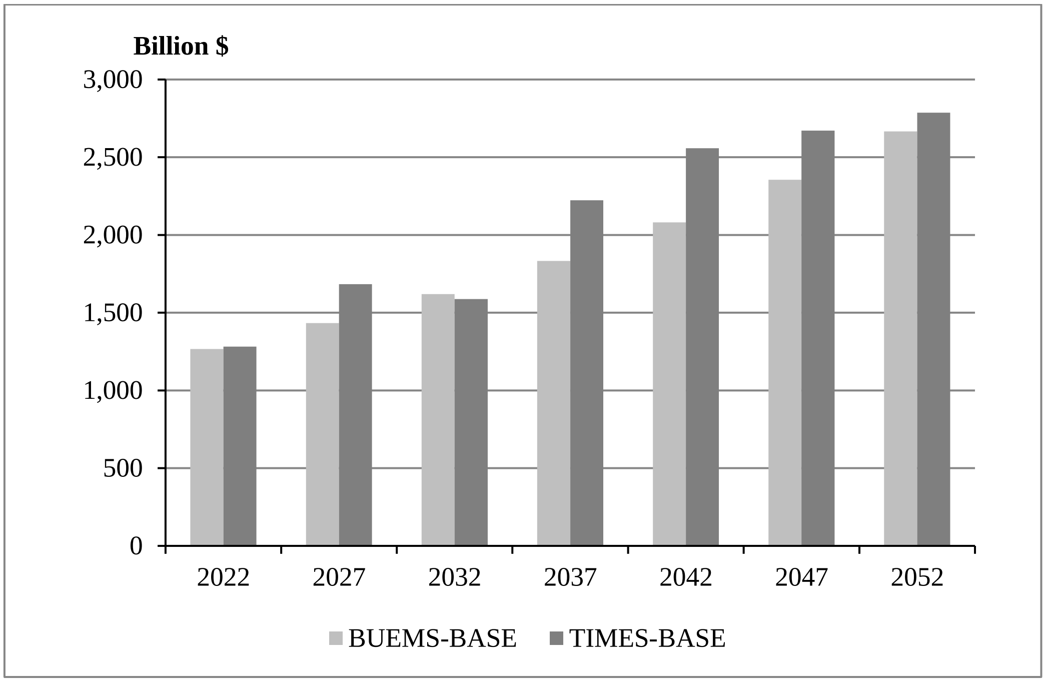

Figure 7.23. BUEMS-MACRO and TIMES-MACRO GDP levels predicted in the Base scenarios.

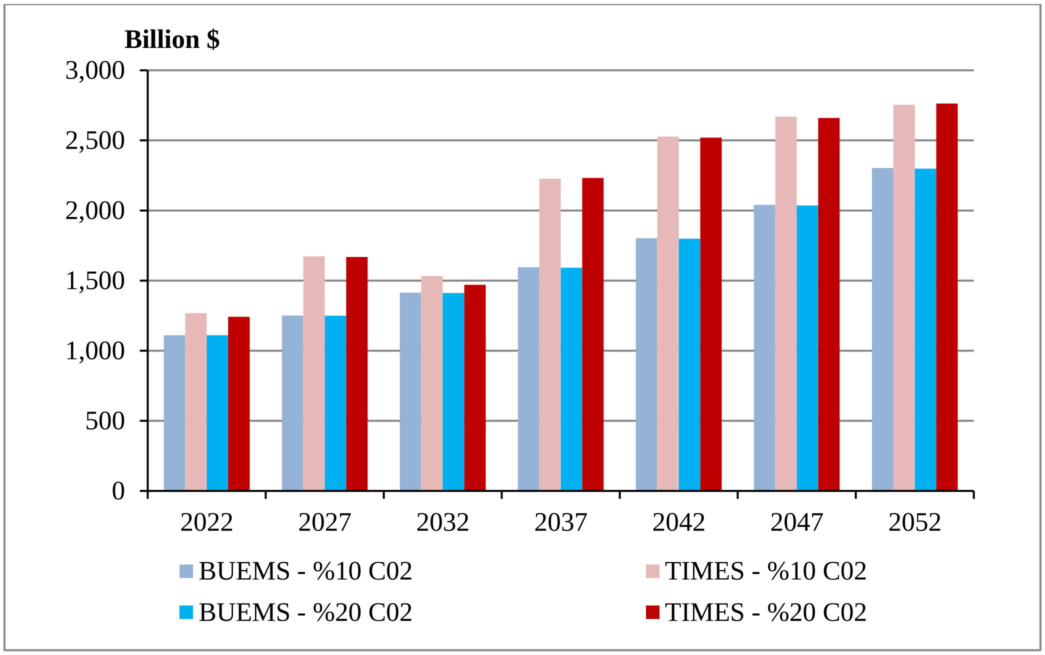

Figure 7.24. BUEMS-MACRO and TIMES-MACRO GDP levels predicted in the C0$_2$ emission restriction scenarios.

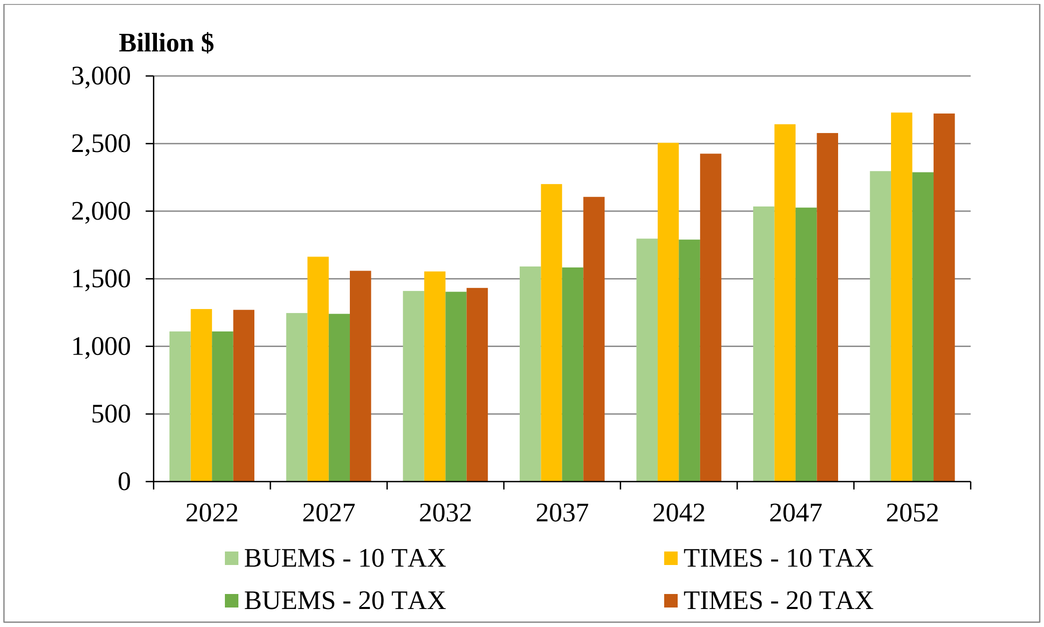

Figure 7.25. BUEMS-MACRO and TIMES-MACRO GDP levels predicted in the emission tax scenarios.

While taking all these differences into account, higher GDP levels are observed in TIMES-MACRO model compared to BUEMS-MACRO model. The results show that the average difference in GDP levels between these two models is 12% for both Base scenario and emission restriction and tax scenarios. This is mainly the results of having higher end-use energy demand levels in TIMES-MACRO model compared to BUEMS-MACRO model.

Table 7.7 shows % gdp losses in TIMES-MACRO emission scenairos compared to TIMES-MACRO Base scenario, and Table 7.8 shows % gdp losses in BUEMS-MACRO emission scenairos compared to BUEMS-MACRO Base scenario.

Table 7.7. % GDP losses predicted in TIMES-MACRO emission scenairos compared to TIMES-MACRO Base scenario.

Scenario Name	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
TIMES-MACRO %10C0$_2$	0.38%	0.90%	0.52%	0.52%	0.46%	0.46%	0.48%
TIMES-MACRO %20C0$_2$	1.17%	2.24%	1.44%	1.36%	1.24%	1.24%	1.25%
TIMES-MACRO 10 TAX	0.04%	0.26%	0.15%	0.16%	0.14%	0.15%	0.15%
TIMES-MACRO 20 TAX	0.15%	0.55%	0.30%	0.32%	0.29%	0.29%	0.30%

Table 7.8. % GDP losses predicted in BUEMS-MACRO emission scenairos compared to BUEMS-MACRO Base scenario.

Scenario Name	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
BUEMS-MACRO %10C0$_2$	1.19%	1.33%	1.48%	1.69%	1.96%	2.20%	2.42%
BUEMS-MACRO %10C0$_2$	1.33%	1.49%	1.67%	1.88%	2.16%	2.40%	2.62%
BUEMS-MACRO 10 TAX	1.55%	1.65%	0.78%	2.00%	2.25%	2.48%	2.70%
BUMES-MACRO 20 TAX	2.05%	2.07%	2.18%	2.34%	2.61%	2.87%	3.09%

8. CONCLUSION

In this thesis, the main goal is to build an optimization model that links energy system with rest of the economy. In this regard, the model in this thesis provides relations between the energy and the economy.

BUEMS has a bottom-up structure that represents the energy system with a technology rich description. BUEMS models the Turkish energy system in detail and has an open structured framework that allows any further scenarios analysis. The model uses GAMS programming language and linear model methodology with CPLEX solver.

However, BUEMS does not address the macroeconomic part of the energy system. Energy demands in the BUEMS model are determined exogenously in the absence of price changes. However, in the real economy, energy prices affect energy demands. From this perspective, in this thesis, the Macro module has been proposed with the top-down modeling approach as a linkage model to the BUEMS model.

To link energy and economy system each other, two different models, the BUEMS and the Macro models, are used. They are together referred to as BUEMS-MACRO. The main advantage of this method is high flexibility. In this regard, the model can be solved with alternative production functions easily without running energy supply model every time. Furthermore, in this method, non-linear functions are collected in a small model which can be solved in a short period of time.

The production function that is used in the Macro module is a nested CES function with capital, labor and energy as input factors for Turkey. The elasticity of substitution (esub=0.3) is taken from Karali (2006).

In this thesis, both BUEMS and BUEMS-MACRO model results are indicated. The energy prices which are obtained from the BUEMS Base scenario are used in the Macro model. According to these energy prices, the Macro model calculates the gross output, the GDP, investment and consumption levels for the each period. The production growth rate determines energy demands endogenously, and endogenous energy demands are used in the BUEMS-MACRO Base model. It should be noted that the ratio for energy costs between the consecutive periods in the BUEMS model should be consistent with the production growth rate in the Macro module. In this study, two models have been run several times until the equality between these two ratios has been obtained.

The main conclusion in this study is that, endogenous demands in the BUEMS-MACRO model are lower than the exogenous demands in the BUEMS model. This is because in the Macro model, demands are under the effects of price changes. In this study, the macro analysis has been performed between the years 2022 and 2052. For this reason, total energy demands of the BUEMS-MACRO model remain unchanged for the years 2012 and 2017 (first two periods), and then decrease compared to the BUEMS model until the end of the planning horizon.

The energy system of Turkey is highly dependent on fossil fuels and it is expected that coal will continue to be the dominant energy source for Turkey in the near future. The Base scenario results of both BUEMS and BUEMS-MACRO Base models indicate that coal is the main energy resources due to its relatively cheap price throughout the planning horizon. However, since coal has the most carbon-content fossil and is widely used especially to generate electricity, environmental concerns have been raised about the negative impacts of coal on the nature. In the scope of this thesis, environmental impacts of alternative scenarios are also analysed under the emission restriction and emission tax scenarios.

Under both emission restriction and emission tax scenarios, energy supply levels decrease compared to the Base scenario while end-use energy demands remain unchanged in the BUEMS model. As a result of this, it is concluded that the emission restriction and the emission tax scenarios are both more effective than the Base model, since the same end-use energy demand is met by less total energy supply. Accordingly, the model tends to use more renewable energy when emission scenarios are applied. However, when it comes to compare these two types of scenarios each other in terms of their efficiency levels, a certain judgement can not be made, since the results presented in this thesis show that while the total supply levels can be higher in some emission restriction scenarios, they also may be higher in other emission tax scenarios as well according to the restrictions on the amount of CO_2 consumed and the taxes applied per kiloton of CO_2 emissions.

The emission restriction and emission tax scenarios are treated differently in the BUEMS-MACRO scenarios than the BUEMS model. As it is indicated before, the end-use energy demands are generated endogenously in the Macro module according to the energy prices. For this reason, as emission scenarios are applied, the energy prices change and end-use demands change as well. It is observed from this study that, as limits on the amount of CO_2 emissions and taxes paid on per kiloton CO_2 consumptions get higher, the model tends to shrink its economy. As a result of that, lower demands are observed in the emission scenarios compared to the Base Macro scenario. It should be noted that, emission scenarios which are run under the BUEMS-MACRO model also shift from fossil fuels to renewable energies like BUEMS model.

Future work based on this study may be conducted in several areas. BUEMS and BUEMS-MACRO models both can be run under the different emission scenarios, such as lower and higher emission restriction levels and taxes. Moreover, end-use energy demands, energy supply prices, costs (investment, operational& maintenance, distribution, transmission, etc.), upper and lower bounds on variables and technologies can be changed, new bounds can be introduced into the model and new analyses can be achieved based on the related changes in the model.

Another possible further work of this thesis study is that different elasticity of substitution levels can be used for the CES function or different nesting structure can be used instead of capital-labor and energy. Furthermore, different types of production functions can be realized in the calculation of gross output.

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