

DESIGN AND DEVELOPMENT OF A LARGE SCALE ENERGY MODEL

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ABSTRACT

DESIGN AND DEVELOPMENT OF A LARGE SCALE ENERGY MODEL

Interest on the sustainability of energy systems has recently increased with the emerging need to mitigate global warming in a global environment experiencing continuous increases in energy demand. Global warming is mainly the product of carbon dioxide (CO₂) gases that are emitted to the atmosphere by burning fossil fuels such as coal, oil, and natural gas. In response to reducing the global warming impacts, policy makers and researchers have been giving particular interests on reducing CO₂ emissions, securing energy supplies, enabling alternative energy sources, increasing energy efficiency, while striving to maintain stable energy prices at reasonable levels. Energy modeling has been a frequently applied tool in national, regional and global energy planning since the early 70ies. Energy models at the national scale typically mimic the dynamics and relationships of energy demand and supply to provide valuable guidance for policy makers. From this point of view, this thesis study describes a new bottom-up, large-scale energy modeling framework focusing on the mechanisms and relationships that would mimic the energy sector as a whole. The new framework is built as a straight forward, flexible, general purpose, optimization modeling framework. All the complex relationships of producing, transforming, transmitting and supplying energy resources according to the demand mechanisms are represented with a deep technological detail. The new framework is validated by comparing the results of a base scenario with another model developed under a similar energy modeling framework (MARKAL) which is run under the same data set and assumptions. The base run results are also compared with the latest confirmed statistics. Then the model is run under different scenario assumptions, after being calibrated according to the Turkish national energy sector data. Results of the Base scenario are compared with other alternative scenarios. Scenario analysis study is used to analyze the impacts of alternative approaches on energy system dynamics such as energy supplies, emissions, and energy costs.

ÖZET

GENİŞ ÖLÇEKLİ BİR ENERJİ MODELİ TASARIMI VE GELİŞTİRİLMESİ

Küresel ısınmayı azaltmaya yönelik olarak son dönemde ortaya çıkan gelişmeler, sürdürülebilir enerji sistemlerine olan ilgiyi artmıştır. Küresel ısınma temelde, kömür, petrol, doğal gaz gibi fosil yakıtların yanması sonucu atmosfere yayılan karbon dioksit (CO₂) gazının bir sonucudur. Karar vericiler ve araştırmacılar, küresel ısınmanın etkilerini azaltmak amacıyla, özellikle CO₂ salımının azaltılması, enerji kaynaklarının güvenceye alınması, alternatif kaynaklarının geliştirilmesi, ve enerji verimliliğinin artırılması gibi konulara dikkat çekmekte, ancak bunları yaparken enerji fiyatlarını makul ölçülerde tutmanın önemini vurgulamaktadırlar. Bu bağlamda, bu tez çalışması enerji sektörü tüm mekanizma ve ilişkilerini yansıtmaya odaklanan yeni geniş ölçekli bir enerji modelleme sistemini tanıtmaktadır. Yeni modelleme platformu anlaması kolay, sade ve değiştirilmeye açık bir yapıda tasarlanmış olup, genel amaçlı bir optimizasyon modelidir. Sistemde, talep mekanizmalarına göre şekillenen enerji kaynağı arz ve üretimlerine ait ilişkiler büyük bir teknolojik detay kullanılarak yansıtılmaktadır. Yeni modelleme platformunun doğruluğu, baz senaryo sonuçlarının benzer başka bir enerji modelinin (MARKAL) aynı veri seti ve şartlar altında ürettiği sonuçlarla karşılaştırılması ile kanıtlanmıştır. Baz senaryo sonuçları ayrıca en son yayınlanan istatistiklerle de karşılaştırılmıştır. Türkiye ulusal enerji sektörü verileri ile kalibre edilen model daha sonra farklı senaryo analizleri için kullanılmıştır. Olağan şartlar altındaki durumun devamını yansıtan senaryoya (baz senaryo) ait sonuçlar alternatif senaryo sonuçları ile karşılaştırılmıştır. Senaryo analizi çalışması, alternatif yaklaşımların enerji arzı, emisyonlar, enerji maliyetleri gibi enerji system dinamikleri üzerindeki etkisini görmeyi amaçlamaktadır.

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LIST OF SYMBOLS

af	Annual availability factor
af_tid	Scheduled outage for electricity generation technologies
a _{ij}	Input-output coefficient
baseload	Maximum share of the night time demand for electricity
be	Scale parameters for energy supplies in CES production function Macro Module
bel	Scale parameters for electricity in CES production function of Macro Module
b _{dm}	Scale parameters for energy demands in CES production function of the MARKAL framework
bound_x_fix	Fix bound on technology activity/capacity/investment/supply
bound_x_lower	Low bound on technology activity/capacity/investment/supply
bound_x_upper	Up bound on technology activity/capacity/investment/supply
c	Energy conversion technology in the BUEM framework / Conversion technology in the MARKAL framework
capunit	Unit conversion factor
cdf	Capacity depreciation factor
ce	Electricity generation technology in the BUEM and MARKAL frameworks
ceh	Electricity and LTH generation technology in the MARKAL framework

cf	Capacity utilization factor
ch	LTH generation technology the BUEM and MARKAL frameworks
C_E	Consumptions on energy goods
C_NE	Consumptions on non-energy goods
cost_inv	Annual investment cost of a technology
cp	Process technology in the BUEM framework
crf	Capital recovery factor
C	Consumption in the Macro Module of the BUEM and MARKAL frameworks
cum	Cumulative capacity of a resource technology
D	Damage reducing output in Integrated Assessment Models
d	Demand technology
decay	Maximum decay of capacity between consecutive periods
decay_s	Maximum decay of supply between consecutive periods
decomcost	Decommissioning cost per unit of capacity
delivent	Unit delivery cost of an energy carrier
demand	Demand for an energy service
disanncost	Discounted total annual cost
disannenv	Annual total of discounted environment costs
disanninv	Annual total of discounted investment costs

disannother	Annual total of discounted other costs
disannsupply	Annual total of discounted supply costs
discount	Discount rate
dtraninv	Unit investment cost for transmissiom of LTH
dtranom	Unit operational cost for transmissiom of LTH
E	Energy input in the Macro Module of the BUEM framework
e	Energy source/carrier
EC	Annual energy cost in the Macro Module
edistin	Unit investment cost for distribution of electricity
edistom	Unit operational cost for distribution of electricity
eff	Efficiency rate
E_i	Aggregated export level of sector i in Input-Output model
elc_gen	Total electricity generation
elm	Electricity-loss maximum ratio
ELS	Electricity input in the Macro Module of the BUEM framework
emis_bound_upper	Upper bound on total emission
emisact	Emission emitted per unit of activity
energy_elc_cap	Level of installed capacity
energy_elc_cons	Level of energy source processed to generate electricity
energy_elc_gen	Level of electricity

energy_f_cons	Level of energy source processed in a sector
energy_supply	Total supply level of any energy source
envact	Emission from a unit technology activity
envcap	Emission from technology capacity
envcost	Emission cost per unit emission
envinv	Emission from technology investment
envsep	Emission from supply
ereserv	Peak reserve factor for total electricity generation capacity
etraninv	Unit investment cost for transmission of electricity
etranom	Unit operational cost for transmission of electricity
fixom	Fixed operation and maintenance cost
fraclife	Fraction of life to number of years in a period
growth	Maximum growth of capacity between consecutive periods
growth_l	Labor force growth parameter
growth_s	Maximum growth of supply between consecutive periods
import_share	Share of import
inpent	Level of input requirement per unit of activity
inv_cost	Investment cost per unit of new capacity
INV	Investment
K	Capital

L	Labour
life	Life time
limit	Limit fraction on activity of a multiple output technology
m	Set of technologies
maent	Level of input requirement per unit of activity of a demand technology
M_i	Aggregated import level in a Input-Output Model
moent	Output level of an energy carrier produced by a demand technology
nyrsper	Number of years per period
out_ent(dm)	Level of demand satisfied by unit activity of a demand technology
outent	Level of output generation per unit of activity
peakcon	Fraction of the plant's capacity that should be credited towards the peaking requirement
pri_df	Net discount factor
pri_disc	A factor to annualize and discount the investment cost
pri_inv	Annualized and discounted unit investment cost
qhr	Fraction of the year represented by each time slice
qhr(z)(y)	Season/time-of-day compound
qhr(y)	Day/night share of operation for an electricity generation technology

qhr(z)	Fraction of the year represented by seasons
r_act	Activity level of a technology
r_cap	Capacity level of a technology
r_em	Emission level
r_inv	Investment level on a technology
r_lout	Amount of an energy carrier produced by a multiple output technology
r_supply	Supply level of a supply technology
r_tczyh	Activity level of an electricity and LTH generation technology
r_tezy	Activity level of an electricity generation technology
r_thz	Activity level of a district heat generation technology
r_tsep	Supply level of a supply technology
resid	Level of residual capacity
s	Primary supply technology
salvcost	Unit salvage cost
scost	Unit supply cost
sex	Export technology
sign	Determinant of import/export
sim	Import technology
smn	Mining technology
srn	Renewable technology

start	Year in which the technology will be available
startyrs	Shift from the first year of the model
t	Period
T	Temperature
totcost	Net present value of the total cost for all periods
undannenv	Annual total of unddiscounted environment costs
undanninv	Annual total of unddiscounted investment costs
undannother	Annual total of unddiscounted other costs
undannsupply	Annual total of unddiscounted supply costs
unit_penalty_cost	Penalty cost paid on per tons of CO ₂ emissions
udf	Discount factor for consumption
v	Emission type
varom	Variable operation and maintenance cost
α	Cost for reducing emissions in Integrated Assessment Models
α_i	Value shares in a typical CES production function
λ_i	Technical coefficients in a typical CES production function
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
BP	British Petroleum
BASE	Business As Usual
BUEM	Bottom-Up Energy Model
CCS	Carbon Capture and Storage Technologies
CES	Constant Elasticity of Production
CETA	Clean Energy Technology Association Model
CGE	Computable General Equilibrium Model
CIMS	Canadian Integrated Modelling System
CO ₂	Carbon Dioxide
DICE	Dynamic Integrated Model of Climate and the Economy
E3 ME	Energy-Environment-Economy (E3) Model
EC	European Commission
EFOM	Energy Flow Optimization Model
EIA	U.S. Energy Information Administration
EM1	Emissions Restrictions Scenario 1
EM1 Macro	Emissions Restrictions Scenario with Macro Model 1
EM2	Emissions Restrictions Scenario 2

EM2 Macro	Emissions Restrictions Scenario with Macro Model 2
ENVEES	Energy-Economy-Environment Model
EPPA	MIT Emissions Prediction and Policy Analysis Model
ERIS	Energy Research and Investment Strategies Model
ERM	Environmental Resources Management Model
ESCAPE	Energy Systems Center for Analysis and Policy Evaluation Model
esub	Elasticity Of Substitution
ETSAP	Energy Technology Systems Analysis Program
FORTTRAN	IBM Mathematical Formula Translating System
FUND	Climate Framework for Uncertainty, Negotiation and Distribution Model
GAMS	General Algebraic Modeling System
G-CUBED	A Multi-Sector Intertemporal General Equilibrium Model
GDP	Gross Domestic Production
GEM-E3	Global Energy Model
GREEN	Tool for Assessing the Life Cycle Climate Performance Model
HERMES	Harmonized European Research for A Multinational Economic and Energy System Model
IA	Integrated Assessment Models
ICAM	Integrated Climate Assessment Model
IEA	International Energy Agency

IIAM	Indian Institute of Management Model
IMAGE 2.0	Energy-Industry System Model
IMP	Import Restriction Scenario
IO	Input-Output Models
LEAN	Lean Management for the Energy Model
LEAP	Long-Range Energy Alternatives Planning System Model
LP	Linear Programming
LTH	Low Temperature Heat
MARKAL	Market allocation Model
MARKAL-ED	Market allocation Model Combined with a Micro Model -Stepwise Demand Function
MARKAL-MACRO	Market allocation Model Combined with a Macro Model
MARKAL-MICRO	Market allocation Model Combined with a Micro Model
MDM (UK)	Multisectoral Dynamic Model
MEPA	Massachusetts Environmental Policy Act Model
MERGE 3	Integrated Assessment Model for Global Climate Change
MESSAGE	Model For Energy Supply Systems And Their General Environment
MIDAS	Multinational Integrated Demand and Supply Model
MINICAM	Mini-Climate Assessment Model
MIS	Macroeconomic Information System Model

NEMS	National Energy Modeling System of USA
NLP	Non-Linear Programming
PE1	Emissions Penalty Scenario 1
PEU4 Macro	Emissions Non-Linear Penalty Scenario With A Penalty Fine of 235 TL
PE2	Emissions Penalty Scenario 2
PE Macro	Emissions Penalty Scenario With Macro Model
POLES	Prospective Outlook on Long-Term Energy Systems Model
POLES	Global Energy Supply, Demand, Prices Forecasting Model
PRIMES	The Primes Energy System Model
QUEST	A Macroeconometric Model for EUC Countries
RICE	Regional Integrated Model of Climate and the Economy
SCREEN	Hybrid Bottom-Up Computable General Equilibrium Model
SGM	Second Generation Model
SLICE	Stylized Integrated Assessment Model of Climate and the Economy
TIMES	The Integrated MARKAL-EFOM System
TES-BUEM	Turkish Energy System Application of the BUEM Framework
TES-MARKAL	Turkish Energy System Application of the MARKAL Framework
WARM	Waste Reduction Model
WIAGEM	World Integrated Assessment General Equilibrium Model
WORLDSCAN	A Model for International Economic Policy Analysis

1. INTRODUCTION

Enormous increase in the worldwide demand for energy services in recent years, as well as the developments in the various energy system dynamics such as energy supply security, alternative resources, efficiency, and environmental concerns require rigorous and creative energy policy implementations on global, regional, and national levels. Proper energy policies and planning have pivotal influences on sustainable development of energy systems.

The International Energy Agency (IEA, 2008) forecasts that world primary energy demand between now and 2030 will increase by 1.5% per year from just over 12000 million tonnes of oil equivalent (Mtoe) to 16800 Mtoe - an overall increase of 40%. The increase is mainly related with population growth and economic development. The world population is projected to rise by 1.4 billion and the world real income is projected to rise by 100% over the next 20 years according to Energy Outlook 2030 of BP. The largest increase in the energy demand is expected to take place in developing countries (such as China and India). The shares of global energy consumption in these countries are estimated to grow at an average annual rate of 3 percent from 2004 and 2020 (EIA, 2007). From this point of view, it is obvious that depletion of energy sources (especially oil and gas) in the coming years will be dramatic. Therefore, targets such as improving energy efficiencies, reducing dependence on fossil fuels, stimulating development of new energy technologies and resources, and their impacts on energy system cost structure are crucial. In addition, an international obligation towards the reduction of CO₂ emissions to counter global warming is the other critical issue that the countries need to deal with. Reflecting on these problems, comprehensive national energy strategies that surround the energy issues are needed. Thus, interest in energy policy modeling has considerably increased.

In recent years, various kinds of global and national energy, environment, and climate models have been proposed. These models have different features and are often based on different methodological approaches. However, even though most of them are useful in predicting future trends, in practice, vast data needs, inflexible structures, and “black box” treatment of some relationships make them difficult to deploy. The modeling

structures are generally invisible or not well-documented, so it is not always trivial to understand the dynamics. From this perspective, the purpose of this thesis is to define, develop, and implement a new large-scale bottom-up energy-modeling framework with an agenda of transparent and straight forward structure designed to rethink the capabilities and limitations of the existing models. The flexible structure of this modeling approach also allows the user to implement refinements and modifications to suit the needs of particular analysis. Compared to similar frameworks, the new modeling framework features simpler relations, reduced data requirements, an open-structure and ability to incorporate various relations such as non-energy costs, indirect energy impacts, and energy import dependences.

The thesis also contains a thorough description of the new modeling framework along with a full-scale application on the Turkish energy sector. The modeling application identifies the Base case energy projections of Turkey, associated CO₂ emissions, and system costs. In addition, there is a specific section that focuses on a small-scale macro model, which is developed with the purpose of producing energy demands of the main model endogenously. On the other hand, behavior of the energy system dynamics under different assumptions and circumstances are the major focus of the scenario analysis part.

Chapter 2 presents a literature survey on existing energy models, underlying approaches, and a major classification. Chapter 3 provides a detailed description of a similar modeling framework (MARKAL) that has inspired the new framework. Chapter 4 describes the new framework together with variable types and definitions, objective function contents, constraint types, classes, definitions, parameters, and representations. Chapter 5 compares the new modeling framework with an existing framework (MARKAL) while emphasizing strengths and weak points. Chapter 6, on the other hand, is for the model application. A Turkish Energy Sector model has been developed based on the new framework as a case study analysis. The initial purpose has been the validation of the new framework. After the validation, it is used for scenario analysis. The section initially describes the current energy situation of Turkey, and then presents the features of the model, calibrated under the Turkish energy system data. Validation of the new modeling framework is also represented in this section. A MARKAL model, which has been run under the same assumptions and circumstances of Turkish energy sector, is used as a

validation mechanism for the new framework. The model results are compared with the latest confirmed statistics as well. Chapter 7 presents the results of the Base scenario and several other energy/environment scenarios, while emphasizing and comparing their efficiency, share of zero carbon fuels, import dependence, electricity generation, emissions, and cost structure characteristics. Major conclusions of the study are provided in the final chapter.

2. ENERGY POLICY MODELING LITERATURE

Energy policy modeling has been a frequently applied tool in national, regional and global energy planning since the early 70ies. Energy models at the national scale typically mimic the dynamics and relationships of a nation's energy demand and supply to provide valuable guidance for policy makers. These dynamics and relations are often influenced by many external parameters such as governmental policies, environmental enforcements (Bosello *et al.*, 1998), technological innovations (Nakicenovic *et al.*, 1998), and physical resource limitations (IEA, 2008). Each external parameter may require a different perspective, analysis, or modeling tool (Bauer and Quintanilla, 2000). Computational difficulties and data collection needs are also challenging the modelers.

Energy models basically mimic the interactions between consumers and suppliers of energy. Typically, energy sector models seek the satisfaction of the consumers' energy demands based on supply, technology, economy, environmental characteristics and limitations, under some (generalized) cost minimization/utility maximization objective (Figure 2.1).

The methodological diversities and developments over the past four decades have generated a wide literature on energy modeling (Fisher-Vanden *et al.*, 1993; Lazarus *et al.*, 1997; Loulou *et al.*, 2004a; Loulou *et al.*, 2004b; Nordhaus, 1994; Schrattenholzer, 1981). Models differ from each other mainly with respect to their disaggregation levels, energy sector representations, regional scopes, and time horizons. However, the most significant differentiation comes from the level of disaggregation (Hourcade *et al.*, 2006). The technologically disaggregated models, namely bottom-up models, are flow optimization or partial equilibrium representations of the energy sector. They provide a detailed technological representation and typically include no or very limited interactions with the macroeconomic system. On the other hand, the aggregated models, namely top-down models, have a macroeconomic perspective and mainly focus on the relations of the energy sector with other sectors of the economy. They represent sectoral economic activities through aggregate production functions. However, their energy-economy interactions have a limited representation of the energy system.

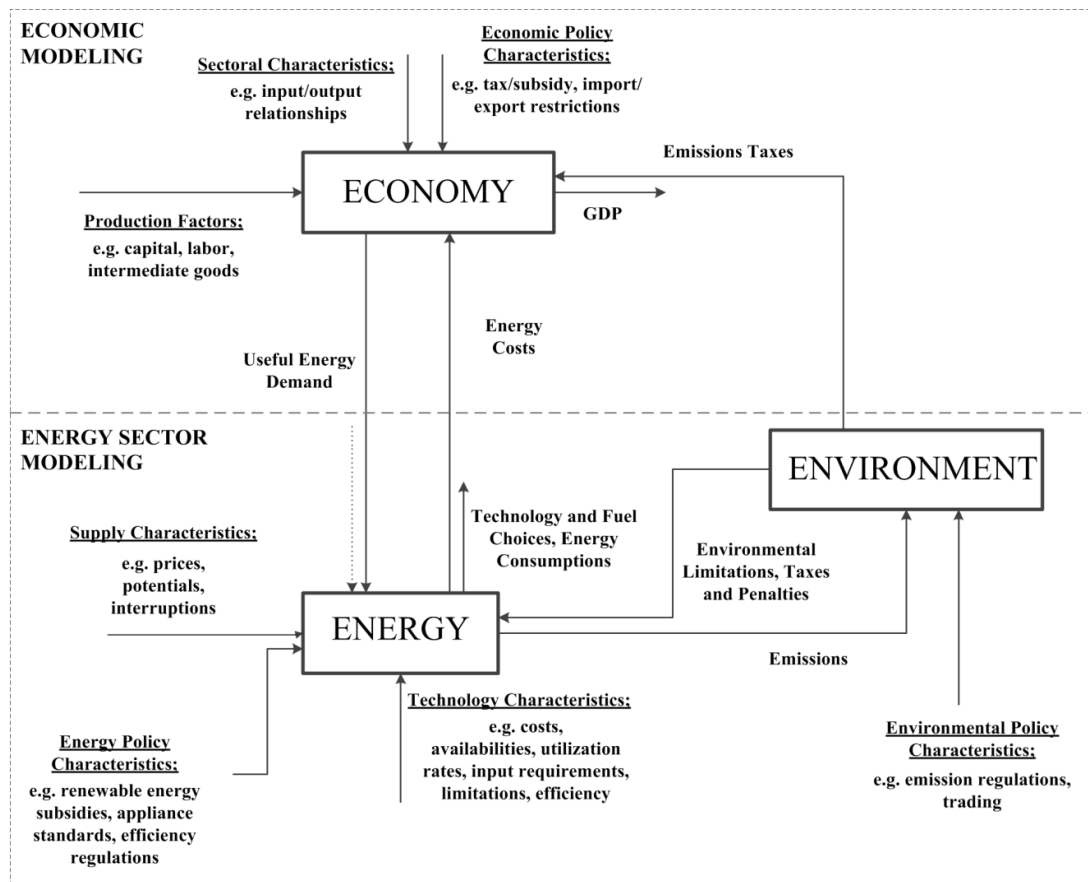


Figure 2.1. Main components of energy policy models.

Top-down and bottom-up models are listed as the two basic approaches in energy modeling literature. They both have advantages and disadvantages and are criticized in several aspects. Top-down models, for example, are mostly criticized for not capturing the necessary detail of the energy sector and underrepresenting the complex interactions among demand and supply options (IPCC, 2001; Jaccard *et al.*, 2003). These models are typically not capable of integrating technological innovations with the necessary level of detail, so the advanced future technologies and fuel options are not sufficiently well represented. Bottom-up models, in contrast, are built with deep technological detail including technical performances and cost structures of future technologies (Böhringer and Rutherford, 2008). However, in this case the feedback mechanism between the energy sector and the rest of the economy is typically lacking. The third modeling avenue combining those two approaches is hybrid models. This group of models combines technological explicitness of bottom-up models with the economic comprehensiveness of top-down models (Hourcade *et al.*, 2006).

Energy sector models have been around for more than four decades, and have undergone major changes over that period. (Bosello *et al.*, 1998) and (Nakata, 2004) classify energy models in several different categories. Table 2.1 displays an extended version of their findings (see (Van der Voort, 1984), (Van der Voort *et al.*, 1985): EFOM-ENV, (Messner and Strubegger, 1995), (Messner *et al.*, 1996): MESSAGE III, (Manne A. and Richels, 1992): MERGE 3, (Nordhaus, 1994): DICE, (Peck and Teisberg, 1992): CETA, (Barns D. *et al.*, 1992): ERM, (CEC, 1991): QUEST, (Barker, 1994; Nordhaus and Yang, 1996): RICE, (Barker, 1994): MDM, (Barker and Zagame., 1995): E3ME, (Rotmans *et al.*, 1994), (CRU, 1992): ESCAPE, (Alcamo, 1994): IMAGE 2.0, (Capros and Karadeloglu, 1992): HERMES/MIDAS, (Tol, 1997): FUND, (Bareto and Kypreos, 2000), (Capros and Chryssochoides, 2000): ERIS, (Bernstein *et al.*, 1997): IIAM, (Dowlatabadi, 1998): ICAM, (Rowe and Hill, 1989): IEA, (Gjerde *et al.*, 1998): G-CUBED, (Fisher-Vanden *et al.*, 1993): SGM, (Yang *et al.*, 1996): EPPA, (Brenkert A.L., 2003 #96): MINICAM, (Kolstad, 1994): SLICE, (IIASA, 1994), (Kemfert, 2002): WIAGEM, (Loulou *et al.*, 2004a): MARKAL, (Loulou *et al.*, 2004b): MARKAL-MACRO, (EIA, 2009): NEMS, (Murphy *et al.*, 1997): CIMS, (Kumbaroğlu and Madlener, 2003): SCREEN, (Arikan and Kumbaroglu, 2001): ENVEES, (Loulou *et al.*, 2005): TIMES, (Lazarus *et al.*, 1997): LEAP, (Smith *et al.*, 2010): GCAM, (Burniaux and Truong, 2002): GTAP-E.

Classification is done according to the models' regional representation and disaggregation levels. The top-down/bottom-up disaggregation is further sub-divided as follows: input-output (IO), integrated assessment (IA), computable/applied general equilibrium (CGE/AGE), and econometric models. Bottom-up models are categorized as linear (LP) and nonlinear (NLP) programming models.

Table 2.1. Classification of energy policy models.

		National	EU	Global	Global-regionalized
Top-Down Models	IO Models	MIS MEPA			
	IA Models		ESCAPE	DICE RICE SLICE CETA GCAM	IMAGE 2.0 (13 world regions) RICE (6 world regions) FUND (9 world regions) MERGE 3 (5 world regions) ERIS (9 world regions)) IIAM (26 world regions) ICAM (7 world regions) MINICAM (9 world regions) GCAM (14 world regions)
	CGE/AGE Models	Conrad (D) Bovemberg-Goulder (USA) Jorgenson-Wilcoxon (USA)	GEM-E3 LEAN HERMES	GTAP-E	ERM (9 world regions) EPPA (12 world regions) SGM (20 world regions) GREEN (12 world regions) G-CUBED (8 world regions) Whalley-Wigle (6 world regions) WIAGEM (25 world regions)
	Econometric Models	MDM	QUEST - WARM E3 ME		WORLDSCAN POLES
Bottom-Up Models	LP/NLP Models	MARKAL TIMES MESSAGE III EFOM-ENV LEAP	MIDAS MARKAL PRIMES		TIMES IEA-MARKAL (10 world regions)
Hybrid Models		MARKAL-MACRO NEMS ENVEES SCREEN	MARKAL-MACRO HERMES-MIDAS		CIMS

2.1. Top-Down Models

Top-down models adopt an economy-wide perspective. This kind of models can support policy makers in assessing the macroeconomic impacts (such as overall change in GDP, consumption, investments, imports and foreign exchange) of particular market instruments such as carbon tax on energy system or subsidies on renewable energy generation. However, energy-economy interactions have a limited representation of the underlying energy system. The energy sector like any other sector is mostly represented in an aggregate way. There are typically no technological details of energy production or conversion and cannot incorporate different assumptions about how discrete energy technologies and costs will evolve in the future.

Top-down models are divided into four major categories: input-output models (IO), integrated assessment models (IA), computable general equilibrium models (CGE), and macro-econometric models. However, conventional top-down models are mostly based on the general equilibrium framework (Nakata, 2004). Those four modeling types are discussed in the following subsections in detail.

2.1.1. Input-Output Models

Input-output analysis was developed by Wassily Leontief in the late 30's (Leontief, 1936). These models are based on a system of linear equations that represent an economy as a number of industries. Input-output analysis shows the process, by which inputs in one industry sector produce outputs for consumption or for input into another industry sector. Each industry uses the outputs of another industry as input to produce its own output. For example, the automotive sector needs outputs from steel, glass, rubber, energy/electricity, and plastic sectors to produce cars and trucks. Therefore, demand for the automotive sector affects the demands for steel, glass, rubber, energy/electricity and plastic production sectors.

Total demand for a sector i is the summation of two separate groups of demands; demands from other production sectors which is the intermediate demand and demand

from final consumer which is the final demand. Total demand equation for sector i , then, is given by Leontief as (Leontief, 1986):

$$X_i = \sum_{j=1}^n X_{ij} + Y_i \quad (2.1)$$

where X_i represents the total demand for sector i . X_{ij} is the intermediate demand for sector i demanded by sector j and Y_i is the final demand for sector i demanded by final consumer. n is the total number of sectors that sector i has interactions.

On the other hand, the intermediate demand, X_{ij} , is assumed to be directly proportional to sector j 's output:

$$X_{ij} = a_{ij} * X_j \quad (2.2)$$

where a_{ij} is the input-output coefficient, which gives the level of input from sector i that is required per unit of production in sector j .

An input-output coefficient is the quantity of input divided by the quantity of output. This way, an input-output coefficients matrix can be derived for each combination of input and production processes. Therefore, the classical approach of the input-output models is mainly based on the construction of an input-output matrix A , which represents the level of input/output ratio between sectors (Figure 2.2). The coefficients are determined according to the initial year relationships of inputs and outputs.

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2n} \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ a_{31} & a_{32} & a_{33} & \dots & a_{3n} \end{bmatrix}$$

Figure 2.2. A typical input-output matrix.

An input-output matrix is often used to show the effect of a change in production of a final good on the demand for inputs. For example, one can estimate how much additional steel, glass, rubber, energy/electricity, plastic and other inputs will be required to increase the automotive sector's production by a certain percentage.

A simple IO model can be extended to encompass interregional input-output relationships. In this case, the basic IO model equation is modified to capture interregional input-output interactions by considering import and export variables. Suppose M_i and E_i represent the aggregated import and export levels of sector i with the other regions. Then, total input is,

$$X_i + M_i = \sum_{j=1}^n X_{ij} + Y_i + E_i \quad (2.3)$$

The input-output analysis has been frequently deployed in the literature to model and analyze the economic, environmental, and other impacts of the energy sector's activities. For example, Using a single-region input-output model, Jacobsen (2000) examines the relation between trade patterns and the energy consumption in Danish manufacturing industries. His results show that manufacturing sectors, such as chemicals or paper production, can be affected in opposite directions as a result of changes in trade patterns. Another interesting aspect of his analysis is the dependence of the results on the aggregation level of the input-output data: impacts of trade pattern on energy consumption obtained from a 27-sector model differ significantly from those obtained from a 117-sector model. This dependence is due to the aggregation of disaggregated sectors with very different trade developments and energy intensities.

(Ozkan *et al.*, 2004) analyze the effects of different energy sources on the Turkish agriculture sector for the period 1975-2000 with input-output analysis. They point out that human and animal power has been mostly substituted with electricity and diesel fuel after the industrialization of Turkish agriculture sector. Therefore, there is a need to promote development of new technologies and use of alternative energy sources. Similarly, (Liu *et al.*, 2010) use energy input-output analysis to investigate energy intensities, exports, and

imports of China. Their results show that international trade plays an important role in both economic growth and energy consumption of China..

The MIS (Macroeconomic Information System) modeling framework is one of the popular IO model, used in energy analysis (Kemfert and Kuckshinrichs, 1997). Taking GDP growth rate as a given figure, the MIS framework describes the development of different industrial and service sectors in detail. However, the MIS is considered as a static modeling framework since many other significant relationships such as macroeconomic effects, demand-supply relations, cost differences, etc. are ignored.

The IO models are considered as simple linear models, representing rough approximations of the inputs required. However, they are mostly criticized for missing the feedback mechanism between energy demand and supply (Rosenbluth, 1968). Many relationships/effects, which can severely change the results, such as price changes, wage dynamics, and supply limitation are not considered in the analysis. Since there is no feedback mechanism, the impact of an exogenous stimulus on a sector can only be seen on the input-output path. However, in a real system, all sectors are related and there are many cross impacts. Furthermore, the model assumes that the input/output coefficients which are estimated for the initial period, are valid for each time period (Rosenbluth, 1968). To eliminate these deficiencies, input-output models are frequently combined with detailed econometric models and run iteratively (Rey, 1998). Econometric models may have effects on resource availabilities, financial boundaries, production capacities, export & import limitations, and many other factors. These models generally maximize utility or minimize cost by implementing the demand data, produced in input-output analysis. On the other hand, input/output coefficients are improved by the information produced in economic models. For example, (Ozkan *et al.*, 2005), repeat the same study, they did earlier with an IO model (mentioned above), by using input-output econometric analysis. The input-output model of the first study is combined with a macroeconomic model using a Cobb-Douglas production function, in which renewable and nonrenewable energy sources are perfect substitutes. The results indicate the same conclusion in principle. This time, they insist on the effects of non-renewable energy usage on global warming.

The MEPA (Massachusetts Economic Policy Analysis) modeling framework, on the other hand, is one of the first regional frameworks including a static input-output approach in addition to its macroeconomic relationships (Stevens *et al.*, 1981). The MEPA framework is initially developed as a macroeconomic model which includes supply relationships, industrial location responses to changing costs, and a production function allowing substitution among inputs (Treyz *et al.*, 1977). Then, it is conjoined with a static input-output model. MEPA modeling approach has general applicability to policy analysis and planning studies that require the detailed regional interindustry interactions captured by a disaggregated input - output model and the cost, price, supply, location, and demand interdependencies which are endogenous in the best regional forecasting and policy simulation models.

2.1.2. Integrated Assessment Models

An integrated assessment (IA) model is defined as a combination of scientific and socio-economic aspects of climate change (Bernstein *et al.*, 1997; Capros and Chryssochoides, 2000; Dowlatabadi, 1993; Edmonds and Reilly, 1983; Manne *et al.*, 1995; Rotmans, 1990; Tol, 1997). The purpose of this modeling approach is to assess the impacts of climate change control policies over a wide knowledge from multiple disciplines (Tol, 2002; Weyant *et al.*, 1996).

Weyant *et al.* (1996) pointed three major drivers for integrated assessment models: (i) assess various impacts of climate change control policies, (ii) constructively force multiple dimensions of the climate change problem into the same framework, and (iii) quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind.

A basic production function for an IA model at period t is defined as follows (Traeger, 2009):

$$Y_t = \frac{1 - \alpha_t}{D_t} * A_t * K_t^\gamma * L_t^{(1-\gamma)} \quad (2.4)$$

which is actually a Cobb-Douglas type production function, where K_t and L_t are Capital and Labor, respectively. The exponent γ is interpreted as the value share of capital in the value added aggregate. A_t is an exogenous technological progress parameter, D_t is damage reducing output, and α_t is the cost of emission reductions, which is estimated as a function $\alpha_t(\omega_t)$ of the emission control rate, ω_t . Damage is obtained as a quadratic function of temperature:

$$D_t = a_0 + a_1 * T_t + a_2 * T_t^2 \quad (2.5)$$

where T_t is the temperature at period t .

On the other hand, L_t is an exogenous estimate and K_t is the sum of existing but depreciated capital of the previous period and the new investments, I_t .

$$K_{t+1} = (1 - \delta) * K_t + I_t \quad (2.6)$$

$$I_t = Y_t - C_t \quad (2.7)$$

where C_t is the consumption at period t . In addition, emissions from production at period t is defined as follows (Traeger, 2009):

$$E_t = \sigma_t * (1 - \omega_t) * A_t * K_t^\gamma * L_t^{(1-\gamma)} \quad (2.8)$$

where σ_t is the ratio of uncontrolled industrial emissions to output. The objective function of the IA models is the welfare maximization. A basic welfare function for an IA model at period t is defined as follows (Traeger, 2009):

$$W = \sum_t \frac{1}{1 + \rho^t} * L_t * \frac{\left(\frac{C_t}{L_t}\right)^{1-\theta}}{1 - \theta} \quad (2.9)$$

where ρ is utility discount rate and θ is consumption elasticity of marginal utility.

IA models have two primary purposes: (i) seek to find the optimal policy which trades off expected costs and benefits of climate change control or the policy which maximizes welfare of achieving a particular goal, (ii) simulate the effect of an efficient level of carbon abatement on the world economy. However, they are mostly criticized for offering contrasting results that depends on critical assumptions about transmission channels between policies and relevant variables (Cantore, 2009).

The most frequently debated assumption is the utility discount rate (Arrow *et al.*, 1996; Cline, 1992; Nordhaus, 1994). The discount rate is critical since small changes in the yearly rate may have a great impact when compounded over decades. In models which allow for economic response to policy, if a low rate of discount is used, welfare increases. Due to increasing welfare, investment rates become higher (since anything not consumed should be invested in IA models) and hence capital and uncontrolled emissions are higher. However, emissions should be affected by consumption instead of investment.

The second critical assumption is the assumed amount of economic growth in greenhouse gas (GHG) intensive industries. Most IA models tie GHG emissions to industrial production either implicitly through emissions projections, which are based on the growth in industrial production or explicitly through an actual model of industrial production (Tol, 2002). However, economic growth is, at the same time, directly affected from advances in technology and population growth. IA models miss those links between economic growth and population growth and advances in technology. However, as demonstrated in (Kelly and Kolstad, 1996), without growth in population and advances in technology, there will not be enough emissions to drive any climate change.

On the other hand, there is a wide range of approaches to IA modeling of climate change. Examples of IA models include the DICE model of Nordhaus (1994), the MERGE model of Manne *et al.* (1995), the CETA model of Peck and Teisberg (1992), GCAM model of Smith *et al.* (2010), and the IMAGE 2.0 model of Alcamo (1994).

The DICE (Dynamic Integrated Climate Change Model) framework is a highly aggregated model with a one-sector, one-region representation (Nordhaus, 1994). The

model links a production model for world output, a module of utility maximization by a representative consumer, a climate module and an impact module of climate change and CO₂ emission abatement costs. However, the high level of aggregation is often criticized for bringing uncertainties to data and parameters (Funtowicz and Ravetz, 1994). The model of (Edmonds and Reilly, 1983), by contrast, is a global model, but less aggregated. Its energy module takes into account nine primary energy sources and their corresponding CO₂ emission factors (Van den Bergh, 1999).

The MERGE (An Integrated Assessment Model for Global Climate Change) framework is developed to analyze global warming issues (Manne *et al.*, 1995). This macroeconomic general equilibrium model includes five regions of world. The model has a detailed climate module and an elaborated damage assessment module. Production factors are combined in a Cobb-Douglas production function for each of the five regions; capital and labor are combined into a composite input, and energy and non-energy are combined into a composite input.

The CETA (A Model for Carbon Emissions Trajectory Assessment) modeling framework is a regionalized world model that explicitly includes energy carriers, like coal, oil, natural gas, and nuclear (Peck and Teisberg, 1992). The CETA framework is capable of analyzing uncertainty and has been used to calculate the expected value of perfect information (Van den Bergh, 1999).

The GCAM (Global Change Assessment Model) framework is a global model disaggregated into 14 geopolitical regions, explicitly linked through international trade in energy commodities, agricultural and forest products, and other goods such as emissions permits (Smith *et al.*, 2010). It is a dynamic-recursive market equilibrium model. The scale of human activities is determined by the interaction between labor force, determined by work-aged population, labor participation and unemployment rate assumptions and the price of energy services. An important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded within the agriculture-land-use system model.

The IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect) model is an IA model that includes a very detailed analysis of land use (Alcamo, 1994). The model is based on a macroeconomic analysis of future demands for various food products in 13 model regions and includes a detailed analysis of future energy demands and emissions of GHGs (Van den Bergh, 1999).

2.1.3. Computable General Equilibrium Models

Since the beginning of the 1990's CGE modeling has become a widely used tool for analysis of energy and environmental policy issues (Barns D. *et al.*, 1992; Bovenberg and Goulder, 1996; Capros *et al.*, 1995; Conrad, 1999; Fisher-Vanden *et al.*, 1993; Gjerde *et al.*, 1998; Jorgenson *et al.*, 1992; Kemfert, 2002; Whalley and Wigle, 1992; Yang *et al.*, 1996). 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. Mostly, these production functions distinguish between the input factors capital, energy and labor and their substitution elasticities have to be given exogenously (Kemfert, 1998). Therefore, each sector is represented by a production function, which is designed to simulate the potential substitutions between the main factors of production. A most typical one is the Constant Elasticity of Production (CES) function, which is a type of production function that displays constant elasticity of substitution. In other words, production has a constant percentage change in factor (e.g. labor and capital) proportions due to a percentage change in marginal rate of technical substitution.¹

An example of a CES production function is as follows (Uzawa, 1962):

$$Y = \alpha_0 \left(\sum_{i=1}^n \alpha_i * X_i^\rho \right)^{1/\rho} \quad (2.10)$$

¹ Marginal Rate of Technical Substitution (MRTS) is the amount by which the quantity of one input has to be reduced ($-\Delta x_2$) when one extra unit of another input is used ($\Delta x_1 = 1$), so that output remains constant. $MRTS(x_1, x_2) = -\frac{\Delta x_1}{\Delta x_2}$, where $MRTS(x_1, x_2)$ is Marginal Rate of Technical Substitution of the input x_1 for x_2 .

where Y is the gross output, n is the number of inputs to production and $\alpha_0, \alpha_i, i = 1, \dots, n$, $\alpha_0 > 0, 0 \leq \alpha_i \leq 1$, are the technical coefficients. ρ is the parameter that controls the elasticity of substitution, σ , according to $\sigma = 1/(1 - \rho), \rho \geq -1$. Elasticity of substitution represents the ease or difficulty of substituting one production factor for another while maintaining the same level of output. This user-defined parameter makes the model fully responsive to price effects.

CES production functions most suitable to energy-economy models generally have the following three-input form (Kemfert, 1998):

$$Y_s = \alpha_0 * (\alpha_k * K_s^\rho + \alpha_l * L_s^\rho + \alpha_e * E_s^\rho)^{1/\rho} \quad (2.11)$$

where K , L , and E represent capital, labor, and energy, respectively.

The parameters $(\alpha_0, \alpha_k, \alpha_l, \alpha_e)$ are calibrated for each sector such that inputs and outputs reproduce a base year historical data. However, it is difficult to defend the validity of some of the parameter values.

CES production functions generally provide a well fit to the economy. However, for some specific sectors like oil refineries, Fixed-coefficient (Leontief) Production function is more suitable. The function is in the form of (Varian, 1992),

$$Y = \lambda_0 * \min(X_1/\lambda_1, \dots, X_m/\lambda_m) \quad (2.12)$$

where Y is the gross output, m is the number of inputs to production and $\lambda_0, \lambda_i, i = 1, \dots, m$ are the technical coefficients. Fixed-coefficient production function implies that for a single unit of output, we need λ_i units of $X_i, i = 1, \dots, m$. There is no flexibility and substitution opportunity between input factors. The coefficient, λ_i , is the fixed input requirement in order to produce a single unit of output. In other words, if Y units of output are desired to produce, $\lambda_i * Y$ units of $X_i, i = 1, \dots, m$ are needed. Consequently, an increase in any one of the factors without increasing the others will lead to absolutely no increase in output, Y .

There have been many efforts to study energy-economy-environment interactions using CGE models. Examples in this regard are the OECD model GREEN of Burniaux *et al.* (1992), the EU model GEM-E3 of Capros *et al.* (1995), the SGM model of Fisher-Vanden *et al.* (1993), HERMES model of Mot *et al.* (1989), and GTAP-E Model of Burniaux and Truong (2002).

The GREEN (A Global Model for Quantifying The Costs of Policies to Curb CO₂ Emissions) framework is a global CGE model and has been developed to assess the economic impacts of limitations on CO₂ emissions (Burniaux *et al.*, 1992). The global economic activity is divided into 12 regions and the model is used to analyze the impacts of emission constraints in the OECD member countries. This modeling framework is counted as a recursive dynamic model. These kinds of models are a sequence of static models with rules for determining the amount of savings. Thus, the total amount of new capital constructed in each time period. In GREEN's dynamic structure, for example, two kinds of capital goods coexist in each period; old capital installed in previous periods, and new capital resulting from current period investment (Van den Bergh, 1999).

The GEM-E3 (Computable General Equilibrium model for Studying Economy-Energy- Environment Interactions) modeling framework is a multi-regional, multi-sectoral CGE model that covers the interactions between energy, economy, and environment (Capros *et al.*, 1995). Production is modeled through CES production functions involving many factors (all intermediate products and two primary factors; capital and labor). At the same time, consumers can endogenously decide the structure of their demand for goods and services. The GEM-E3 also explicitly considers market clearing mechanisms, and related price formation in the economy, energy and environment markets. Following a micro-economic approach, it formulates the supply or demand behavior of the economic agents regarding production, consumption, investment, employment and allocation of their financial assets (Van den Bergh, 1999).

The SGM (Second Generation Model) framework is specifically designed to analyze the climate problem caused by energy consumption (Fisher-Vanden *et al.*, 1993). It is composed of a set of 14 multi-sector regional CCE models. This modeling framework

includes a time frame of 1990 through 2050, in five year time steps. Each production process is represented by a constant elasticity of substitution or Leontief production function.

The HERMES (Harmonized Econometric Research for Modeling Economic Systems) framework has been developed to analyze economic development in the various European member states (Mot *et al.*, 1989). The production function incorporates capital, energy, labor and intermediate goods in nested CES and Cobb-Douglas production functions (with capital being nested with energy and labor with intermediate goods). The HERMES modeling framework includes a full specification of wage and price formation, employment and expenditure categories. However, the specification of energy demand in the model is rather elementary and no specific attention is paid to emissions of pollutants (Van den Bergh, 1999).

The GTAP (Global Trade Analysis Project Model) framework is a multi-regional applied general equilibrium model, representing the global economy, including bilateral trade patterns, and a global bank linking total savings to total investment. In each region, a representative agent maximizes her own utility (Hertel and Tsigas, 1997). The GTAP-E model is an energy-environmental version of the standard GTAP which allows for the possibility of inter-fuel and inter-factor substitution both in the production structure of firms and in the consumption behavior of private households and government sector (Burniaux and Truong, 2002). GTAP-E allows capturing and highlighting the macroeconomic effects arising from changes in energy-environmental policy strategies.

In addition, (Jorgenson *et al.*, 1992) particularly analyzed the impact of environmental regulations on economic growth by using a CGE model. The base case of their model is based on the environmental regulation framework of the 1970s and early 1980s. (Conrad and Schroder, 1993) develop a different CGE application to measure the inefficiency of the regulations on air quality standards, by introducing taxes which encourage air quality improvements.

2.2. Bottom-Up Models

Compared to top-down models, bottom-up models represent the energy system with a technology rich description and put the emphasis on the correct description of energy sources and technologies (Capros, 1993; Capros and Karadeloglu, 1992; Fishbone L.G. *et al.*, 1983; Loulou *et al.*, 2004a; Schrattenholzer, 1981; Van der Voort *et al.*, 1985). Bottom-up energy system models are partial equilibrium representations of the energy sector. They provide a great number of discrete energy technologies to capture substitution of energy sources on the primary and final energy level, process substitution, or efficiency improvements. Each energy consuming technology is identified by a detailed description of input-output structures, cost dynamics, and other technical and economic characteristics. However, such models often neglect the macroeconomic impacts of energy policies. Bottom-up energy system models are typically cast as optimization problems, which compute 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.

2.2.1. Partial Equilibrium Models

Partial equilibrium models are driven by demand curves, which results in the simultaneous determination of quantities and prices. This simplified analysis focuses on a small part of the total economy, often on a two-commodity world. The determination of the price of a good is eased by looking at the price of one good and assuming that the prices of all other goods remain generally constant. In contrast to general equilibrium models, partial equilibrium models imply that only a few markets are considered at a time (while general equilibrium is determined on all markets simultaneously). Therefore, partial equilibrium theory limits the scope of the analysis. Basically, it is assumed that there are two goods: a composite commodity, which represents all goods other than the good of interest and the good of interest. By holding prices and quantities of other goods fixed, the possibility that the events in a specific market affect other markets' equilibrium prices and quantities is ignored. Those models either maximize net surplus or minimize net cost by computing a partial equilibrium. There is a variety of partial equilibrium models such as the EFOM

model of Van der Voort *et al.* (1984), the MARKAL model of Fishbone and Abilock (1981), the MESSAGE model of Schrattenholzer (1981), the MIDAS model of Capros and Karadeloglu (1992), and the PRIMES model of Capros (1993).

The EFOM (Energy Flow Optimization Model) framework (Van der Voort *et al.*, 1985) strives for bottom-up analysis on national scale. This modeling framework is widely used to evaluate new technologies and assess energy environment policies. The development of national energy systems are subject to energy and environment constraints such as the availability of fuel supplies, penetration rates of certain technologies, emission standards, and emission limitations under a cost minimization objective (Nakata, 2004). It was originally written in FORTRAN programming language. Later a GAMS (General Algebraic Modeling System) module is developed in order to improve the user friendliness, portability, and computational power and speed of the model.

The MARKAL (Market allocation Model) framework is a bottom-up, dynamic linear optimization model of the energy system of an economy (Fishbone and Abilock, 1981). The model was originally designed for the evaluation of the possible impacts of new energy technologies on national or regional systems with a cost minimization objective. The MARKAL incorporates a full range of energy processes, exploitation, conversion, transmission, distribution and end-use technologies. Besides the standard MARKAL LP modeling framework, the MARKAL family of models includes the MARKAL-MACRO framework (a relatively new NLP model that combines the technological detail of standard MARKAL with the general economic perspective of MACRO, a long-term neoclassical growth model), and the MARKAL-MICRO (NLP) and MARKAL-ED (LP) frameworks (which have a partial equilibrium model not representing the rest of the economic system, but allowing demands to be reduced in response to higher energy prices). The models are developed based on the GAMS optimization modeling interface. The basic philosophy behind the modeling approach developed in this thesis is mostly inspired by the MARKAL. Thus, some of the relations have similar modeling philosophy in concept. Chapter 3 is set up as a specific chapter discussing the MARKAL structure and modeling in detail. In addition, in Chapter 5, the framework developed in this thesis is compared with the MARKAL framework, thus highlighting the motivation behind the new framework and discussing its main features.

The TIMES (The Integrated MARKAL - EFOM System) framework is a bottom-up, linear, dynamic optimization model of energy systems that may be applied local, national, or regional scales (Loulou *et al.*, 2005). This framework shares the same basic modeling paradigm with the MARKAL framework. It provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. Producers and consumers of commodities such as energy carriers, materials, and energy services come to equilibrium each period. The result is a supply-demand equilibrium that maximizes the net total surplus. However, there are some structural differences in the two modeling frameworks that will affect the characteristics of the model results (such as energy carrier consumption mechanisms, parameter implementations, variable structures, etc.). These differences do not affect the basic paradigm common to the two frameworks, but rather some of their technical features and properties.

The MESSAGE (Model for Energy Supply Systems and Their General Environment) framework is a bottom-up model, which minimizes the total discounted costs of supplying a given set of energy demands over a period (Schrattenholzer, 1981). The modeling framework is specifically applied for multi-regional studies for medium to long-term energy planning, energy policy analysis, and scenario development purposes. The main subject of the MESSAGE framework is defined as the balancing of demand for secondary (or final) energy and supply of primary energy resources via diverse technologies (Schrattenholzer, 1981). The model is based on the FORTRAN programming language.

The MIDAS (Multinational Integrated Demand and Supply Model) framework is a large-scale bottom-up energy system planning and forecasting model (Capros and Karadeloglu, 1992). MIDAS is a country level simulation modeling framework performing dynamic simulation of energy systems, which are represented by combining engineering process analysis and econometric formulations. The energy demand submodule features an econometric forecasting system and uses relative energy prices to estimate energy demand and fuel substitutions by sector, at a disaggregated level. The energy supply submodule combines econometrics with process analysis in formulating the energy supply behavior. The supply side has a narrow scope that consists of five interconnected submodules, namely electricity generation, petroleum refining, natural gas and synthetic gas production and distribution, coal mining and coke-oven plants. Compared to other modeling

frameworks discussed earlier, the MIDAS can be considered as a small scale one because of its limited technology diversity and reduced details in energy demand and supply sides.

PRIMES is a price driven partial equilibrium modeling framework developed for the energy-environment analysis in the European Union member states (Capros, 1993). The framework focuses on market related mechanisms influencing the evolution of energy demand and supply and technology penetration in the market. The current version of the modeling framework (formulated as a non-linear mixed complementarily problem and solved on GAMS) is fully operational and calibrated on the 1995 data set for all European Union member states. On the other hand, the PRIMES differs from other optimization energy modeling frameworks categorized under bottom-up approaches (such as MARKAL and EFOM) by explicitly considering energy price formation. The framework also improves upon the econometric formulations of the econometric-type energy models (such as POLES and MIDAS).

2.3. Hybrid Models

The limitations of top-down and bottom-up approaches have led to development of integrated frameworks. These group of models combine technological explicitness of bottom-up models with the economic comprehensiveness of top-down models (Hourcade *et al.*, 2006). Examples in this field are the NEMS 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. Gritsevskiy and Schrattenholzer (2003), the ETA-MACRO model of Manne (1977) and MDM 3M model of Barker and Peterson (1987).

The NEMS (National Energy Modeling System) framework features a hybrid modeling of energy system of an economy, which is specific to the U.S. energy markets (DOE, 2009). These models have modular structures, operating with different objectives. Supply and conversion modules generate the local production, import, and cost values that are needed by four demand modules. Demand modules are constrained by resource base characteristics, industry infrastructure and technology, and world market conditions. An

integrating module is used to transform information between the modules in each iteration. Supply, demand, and conversion modules provide feedback to one another in an iterative manner and the NEMS is solved for equilibrium in phase with a macroeconomic activity model run separately. Gross domestic product (GDP) is the main output of the macroeconomic activity model. Therefore, on one hand, there is GDP driving energy consumption. On the other hand, there are energy prices and other energy system activities that influence economic growth and activity (mainly GDP, income, industrial output, housing starts, employment, and interest rates).

Merging the MARKAL modeling framework with a single sector MACRO module, which maximizes national utility function, results in a new modeling framework, called the MARKAL-MACRO (Manne and Wene, 1992). Due to the non-linear structure of the MACRO module, the MARKAL-MACRO is a hybrid non-linear optimization framework. The MARKAL-MACRO approach aims at maximizing consumer welfare over the planning horizon, while controlling aggregate investment, and providing least-cost energy system configurations to meet the endogenously determined demands for energy services.

On the other hand, the HERMES modeling framework, has been linked to the MIDAS modeling framework for several energy specific studies (Capros and Karadeloglou, 1992). The MESSAGE modeling framework is combined with a single sector macro module in a few studies (A. Gritsevskiy and Schrattenholzer, 2003).

The ETA-MACRO modeling framework has a two-way linkage between the energy sector and the general economy (Manne, 1977). The ETA is a detailed energy process model that specifies a menu of electric and non-electric technologies, as well as their costs, availabilities, and performance characteristics. The Macro module is a single sector representation of the macro-economy that uses a constant elasticity of substitution production function allowing substitution between capital, labor, and energy. Together, these maximize discounted utility subject to a set of constraints such as economic growth rates, limits to capital turnover, and energy supply (Dowlatabadi and Oravetz, 2006; Jaccard *et al.*, 2003).

Moreover, (Vögele *et al.*, 2009) developed a different hybrid approach by linking the input-output modeling framework MIS (instead of a macro module) and the bottom-up modeling framework IKARUS (Instruments for Greenhouse Gas Reduction Strategies) - MARKAL. In this study, the MIS framework supplies data about the development of the different industry and service sectors and the IKARUS-MARKAL modeling framework calculates the energy demand of these sectors and the cost-optimal energy production structure. The researchers focus on the question of whether a given emission target (such as the Kyoto targets) can be reached by assuming a desired growth rate and taking technological restrictions into account. In addition, they examine the economic impacts of CO₂ mitigation strategies on industrial growths.

3. THE MARKAL MODELING FRAMEWORK

3.1. General Scope and The Objective

MARKAL is a dynamic, bottom-up, large-scale, linear optimization modeling framework for energy systems (Loulou *et al.*, 2004a). This technology rich framework is designed to be deployed on a multi-period horizon to minimize the total discounted energy system cost. MARKAL models seek an intertemporal partial equilibrium on energy markets. Quantities and prices of various fuels and other necessary commodities of the energy sector come to equilibrium in each period, while endeavoring that the net total cost of supplying all levels of energy services are minimized over a number of constraints. In addition, MARKAL also considers new technologies that will be available in the future. Accordingly, the optimization results can include new advanced technologies that may be deployed in the future if they become competitive.

The MARKAL framework incorporates a full range of energy processes, exploitation, conversion, transmission, distribution and end use technologies. Over these technologies, the least cost way of satisfying energy demands are searched and the levels of fuel usages, costs, and emissions at optimum are obtained (Figure 3.1).

Modeling structure of a MARKAL model is defined over sets, technologies, and equations. The number of equations is based on the number of technologies provided into the system. Any item that produces/supplies or processes energy forms is represented as a technology.

Energy sources, technologies, emissions, and demands are mounted into the model one by one according to their characteristics. Those characteristics determine in which set the energy source, technology, or demand will be. Normally, MARKAL's set structure is static, which means it does not change from one implementation to another. However, the model also allows the user to create new sets by a filtering mechanism. The filtering mechanism needs a common feature to search the qualitative data (e.g. input energy

carrier, technology definitions) and form a new set. Qualitative data represents the lists of energy sources, technologies, sets, demands, and emissions. Quantitative data, in contrast, contains the parameter levels specific to each technology and time period. The filtering mechanism is usually applied for specific scenario applications.

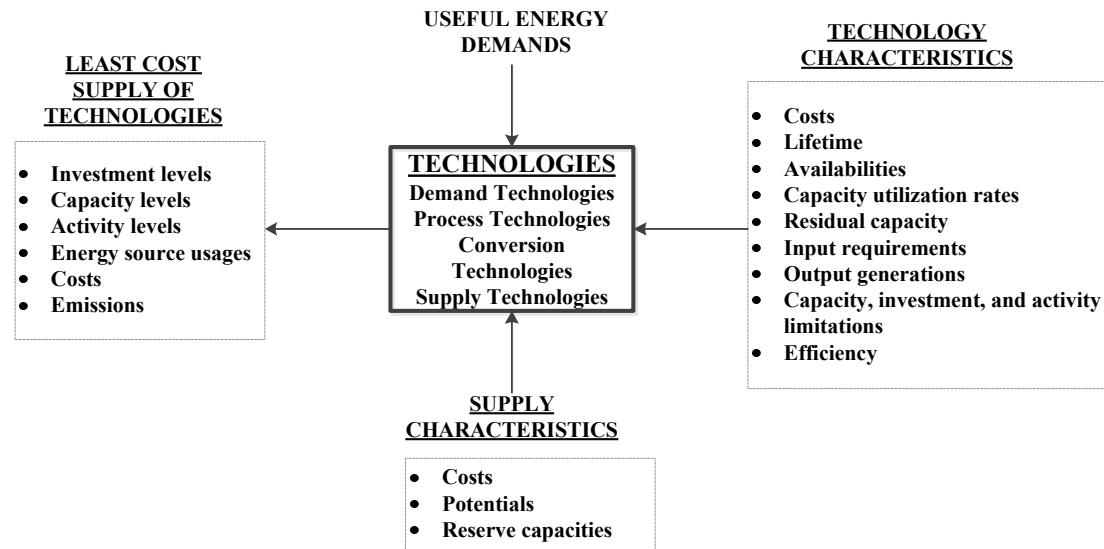


Figure 3.1. Main components of a MARKAL model.

Energy sources, supplied by the resource technologies, are either processed by the process technologies, which primarily contain the conversion and refinery technologies, or used directly by the end-use technologies. On the other hand, the process technologies change the form of the energy source and prepare it according to the end-use technology requirements. Finally, the end-use technologies transform energy sources to the energy services (Figure 3.2). In other words, they transform the final energy of an energy system to the useful energy of energy demand. These technologies are usually called demand technologies.

Energy sources are named as energy carriers in the MARKAL framework. Therefore, to be consistent with the MARKAL modeling literature, energy sources are called “energy carriers” in this section.

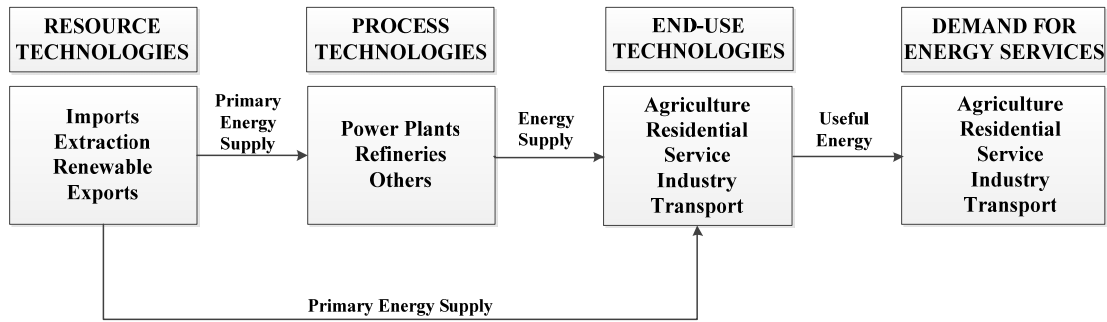


Figure 3.2. Technology relations of a MARKAL model.

Time horizon is divided into a defined number of time periods and number of years in a period is considered identical in each model period. The model allows seasonal (namely summer, winter, intermediate) and day time (namely day, night) analysis of electricity generation technologies by considering the demand share for each time slice. Time-slices are recognized by only for technologies producing electricity (seasonal and diurnal) or low-temperature heat (LTH) (seasonal), both of which may not be easily stored and thus require a finer time disaggregation than other energy carriers (Loulou *et al.*, 2004a). As a result, these two energy carriers are disaggregated into six or three time-slices respectively during each time period (to be individually balanced regarding their supply capabilities and demand needs of the related energy carriers). In addition, a peak requirement is imposed for these two energy carriers, which forces sufficient additional capacity to be installed to meet the peak demand.

The MARKAL approach, like most partial equilibrium models, assumes perfectly competitive markets for energy carriers (Loulou *et al.*, 2004a). The result is a supply - demand equilibrium that minimizes the net total discounted cost of the energy system over a certain time horizon. However, constraints reflecting special considerations, such as limitations on technology penetration, residual capacity implementations, etc. may disturb this perfectly competitive market assumption.

3.2. The Modeling Structure

3.2.1. Sets

3.2.1.1. Set of Energy Carriers. MARKAL models include several types of energy carriers such as fossil fuels, synthetic fuels, nuclear energy, renewable energy resources, heat, and electricity (as can be seen from Table 3.1), which flow between system technologies. As explained in the previous subsection, electricity and LTH have different parameter structures than the other energy carriers. The parameters, especially costs, associated with transmission and distribution of electricity and LTH are considered as well. All energy carriers, other than electricity and LTH, are called standard energy carriers.

Table 3.1. Set of energy carriers in the MARKAL modeling framework.

Set of Energy Sources, <i>e</i>		
Standard	Fossil Fuel	Liquid
		Solid
		Gaseous
	High Temperature Heat	
	Nuclear	
	Renewable	
	Synthetic	Liquid
		Solid
		Gaseous
Electric		
Low Temperature Heat (LTH)		

3.2.1.2. Set of Technologies. Resource, process, conversion, and demand technologies form the technology set of the MARKAL modeling framework (as can be seen from Table 3.2). The technologies of the model are linked to each other via energy carriers.

Table 3.2. Sets of technologies in the MARKAL modeling framework.

Sets of Technologies ²		
Resource, s	Non-domestic, s_{nd}	Export
		Import
	Domestic, s_d	Extraction (Mining)
		Renewable
Process, p	Energy	
Conversion, c	Electric, not LTH, ce	Standard
		Base Loaded
		No Load Management
	Electric and LTH, ceh	Standard
		Base Loaded
		No Load Management
	LTH, not Electric, ch	
Demand, d		

The Set of Resources and Sinks contains all the resource technologies that supply energy carriers to the system. Resource technologies provide energy carriers without any processing requirements. They are like energy carrier storages supplying the energy forms to the system with a unit cost. Mining (Extraction), Imports, Exports, and Renewable Energy Technologies constitute the subsets of this set. Mining technologies are associated with domestic extraction; import technologies are for imported fuels, and renewable energy technologies are for renewable energy resources (such as wind, biomass, etc.). On the other hand, export technologies are considered as the sinks of the system. They capture the energy carriers, but contribute the total cost function in a negative way (a minus cost), in other words as an income. The resource technologies are treated separately and distinctly from the rest of the technologies, and have fewer parameters. Each resource technology provides a single energy carrier to the system with attributes that specify its cumulative resource availability, cost of procurement, and bounds on its annual production activity. They may also require the consumption of various energy carriers in order to operate. There may be different resource technologies that produce the same energy carrier. Those

² Process, conversion, and demand technology sets are collected under the umbrella set k for the simplicity of equation representations.

technologies operate with different parameter structures specific to each other. Especially, differentiation in unit supply cost is the reason for differentiation in total costs in respect to total supplies from the technologies.

The Set of Process Technologies groups the technologies that process energy carriers to produce other energy carriers, except those technologies producing electricity or LTH. The MARKAL modeling framework applies separate sets for electricity and LTH generating technologies that are discussed in the following subsection. Apart from the input requirements and output production ratios, a process technology has up to three types of cost attributes attached to it: investment cost (per unit of new capacity), fixed annual maintenance cost (per unit of existing capacity), and variable operating cost (per unit of activity). Each process technology is further characterized by its life time, the period in which it initially becomes available, and its discount rate (used to compute the annualized investment cost). Its operation may also be guided by bounds expressed in absolute terms or maximum growth rate per period. Finally, each process technology may have emission coefficients attached to each of its three variables: investment, capacity, and activity.

The Set of Conversion Technologies is associated with the technologies that can produce electricity, LTH, or both. Thus, conversion technologies consist of three primary subsets: technologies producing electricity; technologies producing low temperature heat; and coupled production technologies (producing both heat and electricity). The members of these sets are tracked for each of the relevant time segments (six for electricity, three for heat), whereas all other energy carriers are tracked only via annual flows. Each conversion technology has the same attributes mentioned earlier for process technologies, plus a few more describing the seasonal and diurnal availability of the capacity. For example, solar technologies are not available during the night and wind power may vary by season. In addition, each conversion technology has a peaking attribute defining its ability to contribute to the peaking demand requirements. In addition, baseloaded power plants tend to operate continuously (e.g., nuclear, hydro, or large fossil-fired) and are usually set to operate at the same levels day and night, within a season.

The Set of Demand or End-Use Technologies contains all end-use technologies, i.e. those which transform final energy of the system to useful energy that satisfies the energy demand. It is implicitly assumed that a demand device operates at a level proportional to its capacity, and therefore activity is explicitly derived from the capacity variable. Each demand technology has the same attributes mentioned earlier for process technologies, except the ones described on activities.

3.2.1.3. Set of Demands. Demands in the MARKAL modeling framework are grouped under six different sub categories (as can be seen from Table 3.3). Each demand service must be assigned to one of these six main end-use demands. Within each of these categories there may be any number of sub sectors representing specific demand for energy services. For example, in the residential demand set, there may be space conditioning (both heating and cooling), lighting, or hot water demand.

Table 3.3. Sets of energy demands in the MARKAL modeling framework.

Sets of Demands, <i>dm</i>
Agricultural Demand, <i>dam</i>
Commercial Demand, <i>dcm</i>
Industrial Demand, <i>dim</i>
Residential Demand, <i>drm</i>
Transport Demand, <i>dtm</i>
Non-Energy Demand

3.2.1.4. Set of Emissions. Elements of the emission set identify the environmental indicators that are to be tracked according to the activity, capacity, or new investments in technologies. Therefore, the MARKAL modeling framework uses three different emission factors; emission per unit of activity, emission per unit of capacity, and emission per unit of new investment.

3.2.1.5. Set of Time Segments. Elements of the time set identify the seasonal and diurnal divisions of some technologies. They are recognized only by technologies producing electricity (seasonal and diurnal) and LTH (seasonal).

Electricity and LTH are the energy carriers that may not be easily stored and thus require a finer time disaggregation than other energy carriers (Loulou *et al.*, 2004a). These two energy carriers are disaggregated into six and three time-slices respectively during each time period (to be individually balanced regarding their supply capabilities and demand needs of the related energy carriers). Moreover, a peak requirement is imposed for these two energy carriers, which forces sufficient additional capacity to be installed to meet the peak demand.

Table 3.4. Sets of time segments in the MARKAL modeling framework.

Sets of Time Segments, w	
Season, z	Summer
	Intermediate
	Winter
Day, y	Day
	Night

In addition, time horizon is divided into a defined number of time periods (which is represented by t). The number of years in a period, on the other hand, is considered identical in each model period (and represented by y).

3.2.2. Variables

Decision variables in the MARKAL modeling framework are primarily associated with supply levels, investments on technology capacities, technology capacity levels, and technology operation levels. All technologies, except resource technologies, have an investment and a capacity variable for each period, $r_{inv}(m, t)$ and $r_{cap}(m, t)$, respectively. Operating/activity level of process technologies and conversion technologies are represented with different variables: $r_{act}(p, t)$ for process technologies;

$r_{tezy}(ce, w, t)$ for electricity generation technologies; $r_{tzh}(ch, z, t)$ for LTH production technologies; $r_{tczyh}(ceh, w, t)$ for combined heat and power plants. Demand technologies do not have an activity variable, instead they are assumed to operate at a level appropriate to their capacities. On the other hand, resource technologies have supply variables, $r_{tsep}(s, t)$. The amount of an energy carrier produced by a mixing process technology that generates multiple outputs (e.g. refinery) is represented by a unique variable, $r_{lout}(p, t)$. There is also an emission variable related with each emission type v , $r_{em}(v, t)$. The values of all variables are optimized for each period.

3.2.3. Constraints and Relationships

A MARKAL model is calibrated on an initial period, which is usually a past period, over which the model has no freedom, and for which the quantities of all variables are fixed at their historical values. The main variables to be calibrated are: the capacities and operation levels of all technologies, as well as the extracted, exported and imported quantities for all energy carriers. The associated emission levels are also cross checked. The calibration procedure also affects the decisions for future periods. For example, existing capacities and remaining lifetime of some of the technologies at and after the initial period can be set at the calibration phase. Since such technologies are already in place and have set capacities, the model does not need to make any investment decision; only the operating and maintenance decisions have to be made. However, it is free to “not use” the existing capacity of a technology and invest on alternative technologies if it helps to reduce the total cost being tracked.

The MARKAL framework equations are separated into two types: (i) constraint equations that reflect some conditions that need to be satisfied during the optimization process, (ii) non-constraint equations that are used for accounting and reporting purposes. These equations are outlined in detail in the following subsections.

3.2.3.1. The MARKAL Objective Function - The Total Discounted System Cost.

MARKAL's objective function is the minimization of the total system cost, which is the totality of discounted annual costs of each period. Total discounted annual cost of period t is summed over all technologies, all demand segments, all pollutants, and all input fuels of the various costs incurred, namely; annual supply costs (including fuel delivery, extraction, and import costs), annualized investment costs, annual operation costs (including fixed and variable technology operation costs), minus revenue from exported energy carriers, plus taxes and emission costs. The total discounted annual costs, then, are summed over all periods to calculate the total cost of the system.

$$\min \text{ totcost} = \sum_t \text{disannncost}(t) \quad (3.1)$$

where

- $\text{disannncos}(t)$: total discounted annual cost at period t ,
- totcost : total system cost.

Discounted costs which are the components of the objective function are discussed in detail in the following subsections. In addition to them, undiscounted versions are defined and tracked as well for possible accounting and reporting purposes. Therefore, the system costs described below are displayed in both discounted and undiscounted forms.

3.2.3.2. Total Annual Cost. Total annual cost is the summation of total annual supply cost, total annualized investment cost, total annual operation cost, total annual tax payment and total annual emission cost. Total annual supply cost is a net cost including the negative costs (revenue) associated with export activities.

(i) *Total Annual Undiscounted Cost:* This cost function is constructed with the purpose of tracking the total annual undiscounted cost of period t . Undiscounted costs of annual supplies, investments, operation and maintenance, emissions and taxes are summed at each period t .

$$\begin{aligned} undanncost(t) = undannsupply(t) + undanninv(t) \\ + undannother(t) + undannenv(t) + undanntax(t) \end{aligned} \quad (3.2)$$

where

- *undannenv(t)*: annual total of undiscounted environment costs at period *t*,
- *undanncost(t)*: total annual undiscounted cost of period *t*,
- *undanninv(t)*: annual total of undiscounted investment costs at period *t*,
- *undannother(t)*: annual total of undiscounted other costs at period *t*,
- *undannsupply(t)*: annual total of undiscounted supply costs at period *t*,
- *undanntax(t)*: annual total of undiscounted tax payments at period *t*.

(ii) *Total Annual Discounted Cost*: The annual undiscounted costs defined above are properly discounted to the initial year or a user defined year in the first period. Discount factor works in two steps (Loulou et al., 2004a): (i) discounts cost within the period, (ii) and then rediscounts the cost, which is already discounted to the beginning of the period, to an initial or user defined discount year. Details of the discount process are given in Section 3.2.3.3.

$$\begin{aligned} disanncost(t) = disannsupply(t) + disanninv(t) \\ + disannother(t) + disannenv(t) + disanntax(t) \end{aligned} \quad (3.3)$$

where

- *disannenv(t)*: annual total of discounted environment costs at period *t*,
- *disanncost(t)*: total annual discounted cost of period *t*,
- *disanninv(t)*: annual total of discounted investment costs at period *t*,
- *disannother(t)*: annual total of discounted other costs at period *t*,
- *disannsupply(t)*: annual total of discounted supply costs at period *t*,
- *disanntax(t)*: annual total of discounted tax payments at period *t*.

3.2.3.3. Total Annual Supply Cost. Annual supply cost includes all supply related costs of the system. Domestic resource supply costs and import/export resource supply costs are considered separately. If supply of an energy carrier needs another energy carrier as an input, delivery cost of the input energy carrier is taken into consideration as well. In addition, transmission and distribution costs, associated with electricity or LTH, are also added to the supply cost.

A sign parameter is used for import and export technologies. The underlying reason is the implementation of export costs as revenues. Export technologies negatively contribute to the total cost function, which means they act like an income and reduce the total system cost. If the sign parameter is negative, then it is an export technology with a minus cost. If the sign parameter is positive, then it is an import technology with an additional cost.

(i) *Total Annual Undiscounted Supply Cost:* Annual undiscounted supply cost of the system is a non-constraint equation which is constructed with the purpose of tracking the undiscounted supply cost of period t . The first summation mark in the relationship represents the total cost of supplying domestic resources at period t . Unit supply cost of each resource technology is multiplied by the total supply level of that resource technology at period t , and then summed through the domestic resource set, s_d . If there is an input requirement associated with the supply of domestic resource, delivery cost of the input is also considered. The same cost structure is used for import and export technologies as well. However, import and export technologies are distinguished from each other by the sign parameter as discussed above. In addition, if the energy carrier is electricity, the electricity transmission and distribution costs are added. Those costs are defined for per unit of electricity, thus are applied on both imported (variable is $r_{tsep}(s, t)$) and generated electricity (variables are $r_{tezy}(ce, w, t)$ and $r_{tczyh}(ceh, w, t)$). The transmission cost is appropriate for LTH generation as well. On the other hand, the MARKAL system considers that LTH cannot be supplied by import technologies (i.e. cannot be imported). Input delivery costs of electricity/LTH generation technologies (e.g. coal, diesel, etc.) are also considered in the electricity supply costs.

$$\begin{aligned}
undannsupply(t) = & \sum_{s_d} (scost(s, t) \\
& + \sum_e inpent(s_d, e, t) * delivent(s_d, e, t)) * r_tsep(s, t) \\
& + \sum_{s_{nd}} sign(s) * (scost(s, t) + (etranom(e, t) + edistom(e, t)) \\
& + \sum_e inpent(s, e, t) * delivent(s, e, t)) * r_tsep(s, t) \\
& + \sum_{ce, w} (etranom(e, t) + edistom(e, t) \\
& + \sum_e inpent(ce, e, t) * delivent(ce, e, t)) * r_tczy(ce, w, t) \\
& + \sum_{ch, z} (dtranom(e, t) \\
& + \sum_e inpent(ch, e, t) * delivent(ch, e, t)) * r_thz(ch, z, t) \\
& + \sum_{ceh, w} (etranom(e, t) + edistom(e, t) + dtranom(e, t) \\
& + \sum_e inpent(ceh, e, t) * delivent(ceh, e, t)) * r_tczyh(ceh, w, t)
\end{aligned} \tag{3.4}$$

where

- $delivent(s, e, t)$: unit delivery cost of energy carrier e to technology s , at period t ,
- $dtranom(e, t)$: unit transmission cost of energy carrier e (if the energy carrier e is LTH) at period t ,
- $edistom(e, t)$: unit distribution cost of energy carrier e (if the energy carrier e is electricity) at period t ,
- $etranom(e, t)$: unit transmission cost of energy carrier e (if the energy carrier e is electricity) at period t ,
- $inpent(s, e, t)$: energy carrier e requirements of resource technology s at period t ,
- $sign(s)$: sign parameter (which is -1 if the technology s is an export, +1 if the technology s is an import),
- $scost(s, t)$: unit supply cost of technology s at period t .

(ii) *Total Annual Discounted Supply Cost*: Annual discounted supply cost is the properly discounted form of annual undiscounted supply cost discussed above. The only difference is the implementation of discount factor, $pri_df(t)$.

$$disannsupply(t) = pri_df(t) * undannsupply(t) \quad (3.5)$$

where

$$pri_df(t) = \sum_{y=1}^{nyrsper} \frac{(1 + discount)^{(1-y)}}{(1 + discount)^{-startyrs + nyrsper * (t-1)}} \quad (3.6)$$

Discount factor works in two steps (Loulou *et al.*, 2004a): (i) discounts the cost within the period, (ii) and then rediscounts the cost, which is already discounted to the beginning of the period, to an initial or user defined discount year.

Supply cost is an annual cost rather than a period cost (since all costs are provided annually). $(1 + discount)^{(1-y)}$ is used to calculate the discounted cost of each year (y) in the period. This formula contains the basic present value computation with respect to a specific global model discount rate applied to any cost realized in a specific time.³ The cost of each year in the period, then, is summed to obtain the total discounted cost of the period. $nyrsper$ gives the number of years in period t . Finally, $(1 + discount)^{-startyrs + nyrsper * (t-1)}$ discounts the total discounted period cost to the beginning of the planning horizon by reapplying the basic present value formula. $startyrs$ represents the shift from the first year of the model to the relative to which all discounted costs are to be calculated (default value of the MARKAL modeling framework is 2.5). Thus, $-startyrs + nyrsper * (t - 1)$ gives the number of years to which all discounted costs are to be calculated.

³ Present value is the current worth of a future sum of money or stream of cash flows given a specified rate of return. Future cash flows are discounted at the discount rate. The present value formula is $PV = FV * (1 + i)^{-n}$, where PV is the present value, FV is the future value, i is the discount rate, and n is the number of years.

3.2.3.4. Total Annual Investment Cost. Total annual investment cost is the summation of annualized investment costs of the system technologies at period t . Therefore, the investment costs are initially annualized based on the lifetime of the technologies to determine their representation in an “annualized payments” format.

The investment cost of each technology k is annualized with the capital recovery factor, $crf(k)$. The actual investment cost of period t (which includes the investment costs of electricity/LTH transmission and distribution systems as well if it is a conversion technology) is normally calculated over newly invested capacities. Then, this cost is spread over the lifetime of the technology with the capital recovery factor (Loulou *et al.*, 2004a). Capital recovery factor is a product of technology discount rate and lifetime and calculated based on Equivalent Annual Cost formula.⁴

$$crf(k) = \frac{discount}{1 - (1 + discount)^{-life(k)}} \quad (3.7)$$

where

- $crf(k)$: capital recovery factor of technology k ,
- $discount(k)$: technology discount rate. If there is not a discount rate exogenously associated with the technology, the global model discount rate is used.
- $life(k)$: lifetime of technology k .

(i) *Total Annual Undiscounted Investment Cost*: Annual investment cost of technology k at period t is the totality of the new investment realized in this period and the old investments realized in the past periods but still available in the current period. Since the investment cost is annualized according to lifetime of the technology, there should be no associated cost when its lifetime is over. Once the investments of technology k that are still available at period t are determined, they are summed to find the total capacity and associated investment cost.

⁴ The equivalent annual cost (EAC) is the cost per year of owning and operating an asset over its entire lifetime. The cost is calculated as: $EAC = AP * \frac{Discount\ Rate}{1 - (1 + Discount\ Rate)^{-number\ of\ periods}}$ where AP is the asset price at the beginning of the period.

Whether a technology investment is alive or not in a period depends on its lifetime and the period in which the investment is occurred. $(t - t_k')$, in which $t_k' = \max\{0, t - \text{lifetime of technology } (k)/\text{nyrsper}\}$, gives the interval for available investments (among all capacity additions of technology k realized up to period t) of technology k at period t . This way, the retired capacity additions of technology k at the previous periods are not included in the period t 's total capacity.

$\text{undanninv}(t)$ is totality of undiscounted annual investment costs of all technologies at period t (summed over technology set k).

$$\text{undanninv}(t) = \sum_k \sum_{h=t_k'}^t \text{cost_inv}(k, h) * r_inv(k, h) \quad (3.8)$$

where $\text{cost_inv}(k, h)$ is the annualized investment cost of technology k at period h , including the unit investment cost and electricity/LTH transmission and distribution system investment costs (if applicable). Capital recovery factor, which is the annulization factor, is calculated as discussed above. In addition, if the technology lifetime is not a multiplier of the number of years in a period, the last period's cost does not cover the period, but a fraction of it. The fraction rate, $\text{fraclife}(k)$, is exogenously determined based on the lifetime of the technology and the number of years in a period. The rate is equalized to 1 if lifetime of technology k is a multiplier of the number of years in a period, otherwise $\frac{\text{life}(k)}{\text{nyrsper}} - t$ is used as the fraction rate.

$$\begin{aligned} \text{cost_inv}(k, t) = & \text{crf}(k) * (\text{inv_cost}(k, t) + \text{edistinv}(k, t) \\ & + \text{etraninv}(k, t) + \text{dtraninv}(k, t)) * \text{fraclife}(k) \end{aligned} \quad (3.9)$$

where

- $\text{crf}(k)$: capital recovery factor for technology k ,
- $\text{dtraninv}(k, t)$: unit investment cost for LTH transmission system of technology k at period t ,

- $edistinv(k, t)$: unit investment cost for electricity distribution system of technology k at period t ,
- $etraninv(k, t)$: unit investment cost for electricity transmission system of technology k at period t ,
- $fraclife(k)$: the last period fraction rate,
- $inv_cost(k, t)$: unit investment cost of technology k at period t .

(ii) *Total Annual Discounted Investment Cost*: Annual discounted investment cost is the summation of all annualized and discounted investment costs of the system at period t . Thus, the investment costs of the technologies are initially annualized and discounted.

The actual investment cost includes the same cost items discussed above in the undiscounted cost section. The only difference in here is the implementation of salvage cost. Salvage cost, which is the future value of the technology k at the time its lifetime is over, is considered as a component of the actual investment cost as well. However, since this cost is revenue to the system, it is applied with a minus sign. Once the actual investment cost is obtained, it is annualized and discounted.

Annualization and discount factors are aggregated under the same parameter, $pri_disc(k, t)$. Annualization is done based on the capital recovery factor. Discounting, on the other hand, is done based on the basic present value formula as discussed earlier in $pri_df(t)$ case.

$$pri_disc(k, t) = crf(k) * (1/(1 + discount))^{(-startyrs + nyrsper*(t-1))} \quad (3.10)$$

where $(1 + discount)^{-startyrs + nyrsper*(t-1)}$ is the formula that discounts the annualized cost to the beginning of the planning horizon.

Discounted annual investment cost, $disanninv(t)$, is the totality of the discounted annual investment costs of all technologies at period t (summed over technology set k).

$$disanninv(t) = \sum_k pri_inv(k, t) * r_inv(k, t) \quad (3.11)$$

where $pri_inv(k, t)$ is the annualized and discounted investment cost of technology k at period t .

$$pri_inv(k, t) = pri_disc(k, t) * (inv_cost(k, t) + edistinv(k, t) + etraninv(k, t) + dtraninv(k, t) - salvinv(k, t)) \quad (3.12)$$

where $salvinv(k, t)$ is the unit salvage cost of technology k at period t . Salvage cost is calculated according to the following formula in the MARKAL framework.

$$salvinv(k, t) = \frac{1 - (1 + discount)^{-nyrsper*t + \frac{life(k)}{nyrsper} * npers - 1}}{(1 + discount)^{nyrsper*(npers+1-t)} - 1} * (inv_cost(k, t) + edistinv(k, t) + etraninv(k, t) + dtraninv(k, t)) \quad (3.13)$$

where $npers$ is the number of elements in the period set.

3.2.3.5. Total Annual Other Operational Cost. Annual other operational cost is the sum of all fixed and variable operation and maintenance costs of the system (Loulou *et al.*, 2004a).

Fixed costs are calculated over capacities and variable costs are over activities. Since the process, electricity, and LTH technologies are separated in activity variables, variable costs are calculated in four parts; one for process technologies and three for conversion technologies. Variable operation and maintenance costs of electricity/LTH transmission and distribution systems are considered as well. In addition, input delivery cost to process and demand technologies is considered in this cost formula (whereas input delivery cost to resource and conversion technologies are considered in supply cost formula).

In the MARKAL modeling framework, input requirement of demand technology d is named $maent(d, e, t)$, instead of $inpent(d, e, t)$. Demand technologies do not have an activity variable. Instead, a capacity utilization factor, which shows the fixed proportion of the actual capacity to be used, determines the active capacity of the demand technology. In addition, in case activity and capacity of a demand technology differentiate in units, a converter parameter is used.

(i) *Total Annual Undiscounted Other Operational Costs*: Annual undiscounted other operational cost of the system is a cost item which is defined with the purpose of tracking the undiscounted other operational costs of period t . Fixed operation and maintenance cost is applied on capacities for each system technology. Variable operation and maintenance cost, on the other hand, is applied on technology activities, which are represented differently depending on the set that the technology belongs to (e.g. $r_act(p, t)$ for process technologies, $r_tezy(ce, w, t)$ for electricity generation technologies, $r_thz(ch, z, t)$ for LTH generation technologies, $r_tczyh(ceh, w, t)$ for electricity/LTH generation technologies, $capunit * cf * r_cap(d, t)$ for demand technologies).

$$\begin{aligned}
 undannother(t) = & \sum_{p'=p \cup c \cup d} fixom(p', t) * r_cap(p', t) \\
 & + \sum_p (varom(p, t) + \sum_e inpent(p, e, t) * delivent(p, e, t)) * r_act(p, t) \\
 & + \sum_{ce, w} (varom(ce, t) * r_tezy(ce, w, t)) + \sum_{ch, z} (varom(ch, t) * r_thz(ch, z, t)) \\
 & + \sum_{ceh, w} (varom(ceh, t) * r_tczyh(ceh, w, t)) \\
 & + \sum_d capunit(d) * cf(d, t) \\
 & * \left(\sum_e maent(d, e, t) * delivent(d, e, t) + varom(d, t) \right) * r_cap(d, t)
 \end{aligned} \tag{3.14}$$

where

- $capunit(d)$: conversion factor to change the unit of capacity according to unit of annual production activity (if the unit of activity is different than capacity in demand technologies, it is used, otherwise it is set to unity).
- $cf(d, t)$: capacity utilization factor d at period t ,
- $fixom(k, t)$: fixed operation and maintenance cost per unit capacity of technology k at period t ,
- $maent(d, e, t)$: input e requirements of technology d at period t ,
- $varom(k, t)$: variable operation and maintenance cost per unit activity of technology k at period t .

(ii) *Total Annual Discounted Other Operational Costs*: Annual discounted other operational cost is the properly discounted form of annual other operational cost discussed above. The only difference is the implementation of the discount factor, $pri_df(t)$. $pri_df(t)$ is the same parameter calculated in Section 3.2.3.3.

$$disannother(t) = pri_df(t) * undannother(t) \quad (3.15)$$

3.2.3.6. Total Annual Environmental Cost. Annual environmental cost is the summation of all environmental costs of the system technologies. This cost is mostly used in scenario applications. In a standard MARKAL base model, there is no environmental cost.

(i) *Total Annual Undiscounted Environmental Costs*:

$$undannenv(t) = \sum_v env_cost(v, t) * r_em(v, t) \quad (3.16)$$

where $envcost(v, t)$ is the unit emission cost per emission v at period t .

(ii) *Total Annual Discounted Environmental Costs:*

$$disannenv(t) = \sum_v pri_df(t) * undannenv(t) \quad (3.17)$$

The cost relationships, discussed up to now, illuminate the dynamics of the objective function. However, the minimization objective, at the same time, is subject to a number of constraints. The following subsections describe the constraint sets of the MARKAL modeling framework.

3.2.3.7. Balance Constraints. These relationships guarantee that total usage (consumption and export) of an energy carrier, except electricity and LTH, cannot exceed its total supply (extraction, import, and production) levels. For example, gasoline consumed by vehicles plus gasoline exported to other regions must not exceed gasoline produced from refineries plus gasoline imported from other regions (Loulou *et al.*, 2004a).

Left hand side of a balance constraint represents the technologies supplying or producing the energy carrier. Energy carriers are supplied either by import technologies or domestic production technologies (such as extraction facilities). Production of an energy carrier can be from any system technology other than resource technologies (e.g. product of process technologies (including multiple output technologies like refineries), side product of electricity/LTH generation technologies, or side product of demand technologies). The right hand side of the equation, on the other hand, represents the technologies consuming or exporting the energy carrier. Consumption technologies can be any type of system technology (e.g. resource, process, electricity/LTH generation, demand technologies).

$$\begin{aligned}
& \sum_s r_{tsep}(s, t) + \sum_p outent(p, t) * r_{act}(p, t) + \sum_p r_{lout}(p, t) \\
& + \sum_{ce, w} outent(ce, t) * r_{tezy}(ce, w, t) + \sum_{ch, z} outent(ch, t) * r_{thz}(ch, z, t) \\
& + \sum_{ceh, w} outent(ceh, t) * r_{tczyh}(ceh, w, t) \\
& + \sum_d moent(d, t) * capunit(d, t) * cf(d, t) * r_{cap}(d, t) \\
& \geq \sum_s inpent(s, t) * r_{tsep}(s, t) + \sum_p inpent(p, t) * r_{act}(p, t) \\
& + \sum_p r_{lout}(p, t) + \sum_{ce, w} inpent(ce, t) * r_{tezy}(ce, w, t) \\
& + \sum_{ch, z} inpent(ch, t) * r_{thz}(ch, z, t) + \sum_{ceh, w} inpent(ceh, t) * r_{tczyh}(ceh, w, t) \\
& + \sum_d maent(d, t) * capunit(d) * cf(d, t) * r_{cap}(d, t) / eff(d, t)
\end{aligned} \tag{3.18}$$

where

- $capunit(d)$: conversion factor to change the unit of capacity according to unit of annual production activity,
 - $cf(d, t)$: capacity utilization factor d at period t ,
 - $eff(d, t)$: efficiency rate (of input usage) of demand technology d at period t ,
 - $inpent(p, t)$: input requirements of process technology p at period t ,
 - $maent(d, t)$: input requirements of technology d at period t ,
 - $moent(d, t)$: level of output generation by demand technology d at period t .
- MARKAL model allows energy carrier production from demand technologies.
- $outent(p, t)$: level of output generation by technology k at period t .

Electricity and LTH balance constraints have the same structure. Additionally, they are related with each individual time of day and season time segments. Electricity and LTH constraints can be found in Appendix A.

3.2.3.8. Satisfaction of Demand. These constraints ensure that all demands for energy services are satisfied (Loulou *et al.*, 2004a). Total activity of demand technologies servicing a particular demand must be at least equal to the demand, dm , itself. For example, residential space heating demand may be satisfied by a combination of several types of heating devices (e.g. coal, electricity, etc.).

$$\sum_d out(dm)(d, t) * capunit(d) * cf(d, t) * r_cap(d, t) \geq demand(dm, t) \quad (3.19)$$

where

- $out(dm)(d, t)$: fraction of the output from demand technology d that services the particular demand dm at period t ,
- $demand(dm, t)$: demand for energy service dm at period t .

3.2.3.9. Capacity Transfer. These constraints ensure that capacity of any technology in a period is the summation of its residual capacity (due to facilities and technologies that existed and were operational before the start of the planning horizon and that are alive at the current period) and the new investment of current and prior periods that are still in place (Loulou *et al.*, 2004a).

Since whether an investment is alive or not in a period depends on the lifetime of the technology and the period in which the investment is occurred, the investment should be eliminated from the total capacity when its lifetime is over. Once the available investments of technology k at period t are determined, they are summed to obtain the total capacity.

$$(t - t_k'), t_k' = \max\{0, t - lifetime\ of\ technology\ (k)/nyrsper\} \quad (3.20)$$

gives the interval for available investments of technology k at period t .

$$r_cap(k, t) = \sum_{h=t_k'}^t r_inv(k, h) + resid(k, t) \quad (3.21)$$

where $resid(k, t)$ is the level of residual capacity of technology k at period h .

3.2.3.10. Cumulative Limit on Resource Technologies. These constraints guarantee that total supply level of any resource cannot exceed its cumulative capacity over the entire planning horizon (Loulou *et al.*, 2004a). Cumulative capacity can be reserve capacity of mining resources or contract limitations for import/export activities.

$$\sum_t nyrsper * r_tsep(s, t) \leq cum(s) \quad (3.22)$$

where $cum(s)$ is the cumulative resource limit applied on resource technology s .

3.2.3.11. Decay/Growth Limit on Resource Technologies. These relationships ensure that supply level of any resource technology cannot be lower/greater than previous period's supply level multiplied by a decay/growth rate parameter (Loulou *et al.*, 2004a).

$$r_tsep(s, t + 1) - r_tsep(s, t) * decay_r(s, t)^{nyrsper} \geq 0 \quad (3.23)$$

$$r_tsep(s, t) * growth_r(s, t)^{nyrsper} - r_tsep(s, t + 1) \geq 0 \quad (3.24)$$

where

- $decay_r(s, t)$ is the maximum decay rate of supply level s between period t and period $t + 1$,
- $growth_r(s, t)$ is the maximum growth rate of supply level s between period t and period $t + 1$.

3.2.3.12. Decay/Growth Limit on Capacity. These relationships ensure that capacity of any technology cannot be lower/greater than previous period's capacity level multiplied by a decay/growth rate parameter (Loulou *et al.*, 2004a). As such, these constraints reflect possible physical or practical limitations on short time (one period) increases or decreases on capacity.

$$r_cap(k, t + 1) - r_cap(k, t) * decay(k, t)^{nyrsper} \geq 0 \quad (3.25)$$

$$r_cap(k, t) * growth(k, t)^{nyrsper} - r_cap(k, t + 1) \geq 0 \quad (3.26)$$

where

- $decay(k, t)$ is the maximum decay rate of technology k 's capacity between period t and period $t + 1$,
- $growth(k, t)$ is the maximum growth rate of technology k 's capacity between period t and period $t + 1$.

3.2.3.13. Use of Capacity. These relationships ensure that activity level of any technology cannot exceed its available capacity (Loulou *et al.*, 2004a). Since the activity levels of process and conversion technologies are represented with different variables ($r_act(p, t)$, $r_tezy(ce, w, t)$, $r_thz(ch, z, t)$, and $r_tczyh(ceh, w, t)$), four different structures are used. However, the basic relationship is all the same: the activity of any technology at period t must be less than or equal to its available capacity at this period.

Constraints related with electricity technologies include all individual parameters related with time of day and season time segments, $qhr_{zy}(w)$. Similarly, constraints related with LTH technologies include all individual parameters related with season time segments, $qhr_z(z)$. The availability of power plants is also adjusted with the scheduled outage/maintenance fraction. This way, the constraint eliminates the portion of the capacity that is unavailable due to the scheduled outage.

The “Use of Capacity” relationship is not valid for demand technologies, since there is no activity variable specified for them. Instead, activity is always assumed to be directly

proportional to the installed capacities. The proportion is determined by the capacity utilization factor, which is exogenously placed into the model.

$$(i) \quad r_{act}(p, t) \leq af(p, t) * r_{cap}(p, t), \forall p \quad (3.27)$$

$$(ii) \quad r_{tezy}(ce, w, t) \leq capunit(ce) * qhr_{zy}(w) * af(ce, t) \\ * (1 - af_{tid}(ce, t)) * r_{cap}(ce, t), \forall ce \quad (3.28)$$

$$(iii) \quad r_{thz}(ch, z, t) \leq capunit(ch) * qhr_z(z) * af(ch, t) * r_{cap}(ch, t), \forall ch \quad (3.29)$$

$$(iv) \quad r_{tczyh}(ceh, w, t) \leq capunit(ceh) * qhr_{zy}(w) * af(ceh, t) \\ * (1 - af_{tid}(ceh, t)) * r_{cap}(ceh, t), \forall ceh \quad (3.30)$$

where

- $af(k, t)$: annual availability factor of technology k at period t ,
- $af_{tid}(c, t)$: scheduled outage/maintenance rate for technology c at period t ,
- $qhr_{zy}(w)$: fraction of the year represented by each time segment w (combination of season (z) and time-of-day (y)),
- $qhr_z(z)$: fraction of the year represented by each season z .

3.2.3.14. Limitation for Flexible Output Technologies. These constraints guarantee that production level of an energy carrier from a multiple output technology cannot exceed the amount that the multiple output process is actually outputting (Loulou *et al.*, 2004a).

Those type of technologies have two different decision variables; one representing the level of energy carrier e produced by multiple output technology k at period t , $r_{lout}(k, e, t)$, one representing the activity level of multiple output technology k at period t , $r_{act}(k, t)$. On the other hand, $outent(k, e, t)$ is the output level of energy carrier e produced by a unit activity of technology k at period t . Thus, $r_{act}(k, t)$ and $outent(k, e, t)$ together produce the level of energy carrier e that the multiple output process is actually outputting.

$$r_lout(k, e, t) - outent(k, e, t) * r_act(k, t) = 0 \quad (3.31)$$

3.2.3.15. Efficiency of Flexible Output Technologies. On the other hand, the relation below ensures that sum of all outputs from a flexible mixing process respects the overall efficiency of that process. For such processes, sum of energy carriers produced is limited to a maximum share, $limit(k, t)$, of the process activity.

$$limit(k, t) * r_act(k, t) = \sum_e r_lout(k, e, t) \quad (3.32)$$

3.2.3.16. Electricity and LTH Peak Reserve Constraints. In the MARKAL modeling framework, a peak requirement is imposed for electricity and LTH. That requirement is used to force sufficient additional capacity to be installed to meet the peak demand. Thus, this relationship ensures that there is always enough capacity in place to meet the highest electricity/LTH demand of the day. Electricity and LTH peaking constraints differ from each other due to the level of time disaggregations (electricity has six time segments, LTH has three time segments). However, other than this, the relation is the same. The constraint below describes the electricity peaking relations. LTH Peak Reserve Constraint, on the other hand, is given in Appendix A.

A peak contribution parameter is used to determine the fraction of each electricity supply and generation option that should be credited towards the peaking requirement at period t (Loulou *et al.*, 2004a). The left hand side of the relation represents the total electricity that is credit towards the peaking requirement. The level of total electricity at period t is defined as the summation of import and national generations, which are increased with a reserve margin. The impact of overall efficiency of the electricity infrastructure is considered as well. The right hand side of the relation, on the other hand, represents the total electricity demands of the system technologies that consume or export electricity. The MARKAL framework considers that electricity generation plants do not consume electricity. Thus, there is no associated consumption figure in the relation. On the other hand, $inpent(ce, t) * r_tezy(ce, w, t)$ is used for electricity storage facilities, not to represent electricity generation plants that consume electricity.

$$\begin{aligned}
& \frac{teent(e, t)}{(1 + ereserv(e, t))} * (\sum_s peakcon(s, t) * qhr_{zy}(w) * r_{tsep}(s, t) \\
& + \sum_c peakcon(c, t) * capunit(c) * qhr_{zy}(w) * af(c, t) * r_{cap}(c, t) \\
& \geq \sum_s inpent(s, t) * qhr_{zy}(w) * r_{tsep}(s, t) \\
& + \sum_p inpent(p, t) * qhr_{zy}(w) * r_{act}(p, t) \\
& + \sum_{ce} inpent(ce, t) * r_{tezy}(ce, w, t) \\
& + \sum_{ch} inpent(ch, t) * (\frac{qhr_{zy}(w)}{qhr_z(z)}) * r_{thz}(ch, z, t) \\
& + \sum_d maent(d, t) * capunit(d) * cf(d, t) * qhr_{zy}(w) * r_{cap}(d, t)) / eff(d, t)
\end{aligned} \tag{3.33}$$

where

- $ereserv(e, t)$: peak reserve factor for electricity at period t ,
- $peakcon(c, t)$: the fraction of the technology c 's capacity that should be credited towards the peaking requirement at period t . Many types of generating equipment are predictably available during peak load and thus have a peak coefficient equal to 1 in the MARKAL, whereas others such as wind turbines or solar plants are assigned peak coefficients less than unity since they are on average only fractionally available at peak times. For example, a wind turbine typically has a peak coefficient of 0.25 or 0.3, whereas a hydropower plant, a gas plant, or a nuclear plant typically has a peak coefficient equal to unity.
- $teent(e, t)$: overall efficiency of the electricity infrastructure at period t .

3.2.3.17. Electricity Baseload Constraint. These constraints guarantee that baseload power plants operate at the same level throughout the day and night and only a fraction of the total night time demand for electricity is met by such plants (Loulou *et al.*, 2004a). Such classes of power plants (e.g. hydro, large coal-fired, nuclear) cannot be easily started/shutdown/restarted, but instead tend to be run at full capacity almost all of the time (Loulou *et al.*, 2004a). Thus, even when the night time demand is lower than the total generation capacity of baseload plants, they should still operate. These constraints ensure that a percentage of the total night time demand is met by non-baseload plants, so if there is an unplanned decrease of night-time demand, non-baseload plants would be the ones to be shut down. On the other hand, since there is no day/night division for baseload power plant activities, the time segments decreases to three (only seasonal division).

The left hand side of the relation represents the night-time electric generation from baseload plants. Since those plants have non-stop production during the day, they only have day-time generation variables; $r_{tezy}(ce, z, D', t)$ and $r_{tczyh}(ce, z, D', t)$ (where D' means “day” and is used for 24 hours-time). The night time production of these variables is determined with the night-time fraction parameter, $qhr_{zy}(z, N')$. The total night-time production from non-baseload plants, on the other hand, is represented at the right hand side of the relationship.

$$\begin{aligned}
& (1 - baseload(e, t)) * teent(e, t) * qhr_{z_y}(z, 'N') \\
& * (\sum_{s \cap baseload} r_{tsep}(s, t) + \sum_{ce \cap baseload} r_{tezy}(ce, z, 'D', t) \\
& + \sum_{ceh \cap baseload} \left(ceh_{z_y}(ce, z, 'D', t) * \left(\frac{1}{elm(ceh)} - 1 \right) * r_{tczyh}(ce, z, 'D', t) \right) \\
& \leq teent(e, t) * baseload(e, t) * (\sum_{s \cap nonbaseload} qhr_{z_y}(z, 'N') * r_{tsep}(s, t) \\
& + \sum_{ce \cap nonbaseload} r_{tezy}(ce, z, 'N', t) \\
& + \sum_{ceh \cap nonbaseload} \left(ceh_{z_y}(ce, z, 'N', t) * \left(\frac{1}{elm(ce)} - 1 \right) \right. \\
& \left. * r_{tczyh}(ce, z, 'N', t) \right)
\end{aligned} \tag{3.34}$$

where

- $baseload(e, t)$: fraction of the highest night demand for electricity that can be met by baseload plants at period t ,
- $ceh_{z_y}(ce, w, t)$: units of electricity loss per unit of heat gained in a coupled heat and electricity technology ceh at time-division w and period t ,
- $elm(c)$: electric loss maximum, which is the fractional loss beyond which the total electricity production may not be reduced.

3.2.3.18. Annual Reservoir Management Constraint. This relationship imposes a limit on annual activity of a hydropower plant based on its available capacity. Annual activity of the plant is calculated as the summations of activities belong to each time-segment in this year (represented in the left hand side of the relationship). This activity is bounded with a limit of the annual available capacity (represented in the right hand side of the relationship). Seasonal activity of a hydropower plant is controlled with a similar constraint as well.

$$\begin{aligned} \sum_w r_{tezy}(ce, w, t) \\ \leq capunit(ce) * araf(ce, t) * af(ce, t) * r_{cap}(ce, t) \end{aligned} \quad (3.35)$$

where

- $araf(ce, t)$: fraction of the capacity that limit the annual activity of the hydropower plant ce at period t .

3.2.3.19. Emission Constraint. These constraints define the total emissions of type v . Emissions are assumed to be proportional to supply levels of supply technologies, and activity, capacity, and investment levels of other technologies.

$$\begin{aligned} r_{em}(v, t) = & \sum_s envsep(s, v, t) * r_{tsep}(s, t) \\ & + \sum_p envact(p, v, t) * r_{act}(p, t) + \sum_{ce} envact(ce, v, t) * r_{tezy}(ce, t) \\ & + \sum_{ch} envact(ch, v, t) * r_{thz}(ch, t) + \sum_{ceh} envact(ceh, v, t) * r_{tczyh}(ceh, t) \\ & + \sum_p envcap(p, v, t) * r_{cap}(p, t) + \sum_{p'} envinv(p, v, t) * r_{inv}(p, t) \end{aligned} \quad (3.36)$$

where

- $envact(k, v, t)$: quantity of emission type v per unit of activity of technology k at period t ,
- $envcap(k, v, t)$: quantity of emission type v per unit of capacity of technology k at period t ,
- $envinv(k, v, t)$: quantity of emission type v per unit of investment of technology k at period t ,
- $envsep(s, v, t)$: quantity of emission type v per unit of supply from technology s at period t .

The relationship below is optionally used to limit the emissions. It is not active in a standard MARKAL base model.

$$\sum_t nyrsper * r_em(v, t) \leq cumem(v) \quad (3.37)$$

where $cumem(v)$ is the cumulative upper bound on emission type v .

3.3. The MARKAL-MACRO Model

The MARKAL framework also features an extension to address the interactions between the energy sector and the general economy. In this framework extension, called the MARKAL-MACRO system, energy demands of various sectors are model variables that are aggregated as an “Energy” input into a general economy production function whose other primary inputs are “Capital” and “Labor”. This is a major difference from the basic MARKAL framework in which all sectoral demands are treated as exogenous parameters to be inputted by the user. The MACRO framework uses the aggregate energy that is provided by the original MARKAL model, while the MARKAL module simultaneously uses the energy demand coming from the MACRO module (Loulou *et al.*, 2004b). Thus, the MARKAL-MACRO system indirectly facilitates the price elasticity of demand for energy services by linking energy representation/cost of the MARKAL module with energy demand of the MACRO module. During applications, the two models are solved iteratively. In each iteration, energy demand is produced according to the energy representation/cost information passed from the MARKAL module. The MACRO model is

a typical one-sector neoclassical growth model. This model maximizes utility subject to a national budget constraint (Allen, 1968). National output is produced by a single sector, which is represented by a nested production function with a constant elasticity of substitution among its three inputs namely capital, labor and energy.

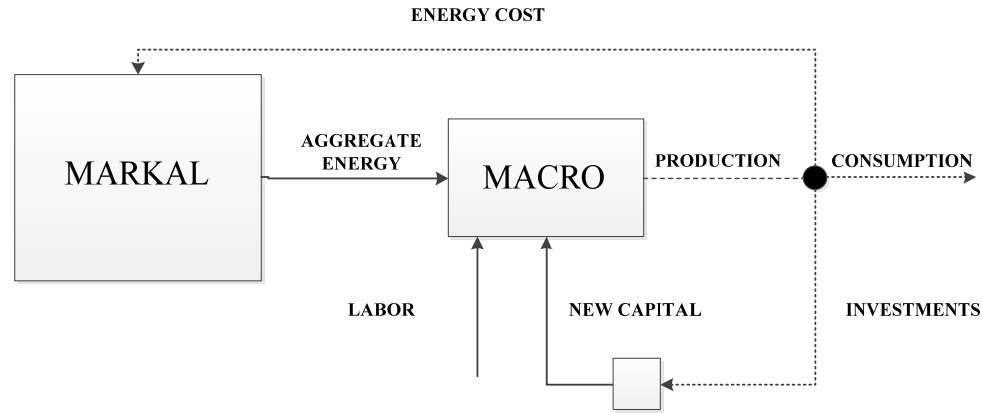


Figure 3.3. The MARKAL-MACRO flows.

The MARKAL and the MACRO modules are designed to be calibrated separately. MARKAL calibration is done by energy statistics obtained from past performances of the energy sector, while the MACRO module is calibrated according to macroeconomic statistics. The main parameters of the MACRO module that are calibrated are related to consumption, national production, investment, and capital accumulation levels and rates. Those levels and rates are also calibrated by initial year bounds and set to fixed values. Initial year's energy cost and demand are set to be the same in the MARKAL and the MACRO modules.

The MACRO system addresses the general economic consideration (that are to be linked to the energy sector considerations) through the following non-linear optimization problem.

The utility function is the discounted sum of the logarithms of consumption, C_t , at each period (Loulou *et al.*, 2004b). udf_t is the discount factor.

$$\max \sum_t udf_t * \ln C_t \quad (3.38)$$

The Simple Keynesian Function establishes a relation between consumption, C_t , investment, INV_t , annual energy cost, EC_t , and production, Y_t (Parke, 2006). EC_t is passed from the MARKAL module, while optimization determines C_t and INV_t .

$$Y_t = C_t + INV_t + EC_t \quad (3.39)$$

The production function is a CES function. The first term within the brackets is a value added aggregate, in which capital, K_t , and labor, L_t , may be substituted directly for each other in Cobb-Douglass fashion. The second term indicates that the energy demand services for demand dm at period t , $D_{dm,t}$, defined and determined in the MARKAL module may also substitute for one another. Finally, the two aggregates (labor-capital on one hand, and energy on the other) may substitute for each other, although with a different elasticity than the lower level substitution of labor and capital (Loulou *et al.*, 2004b). The exponent α is interpreted as the value share of capital in the value added aggregate, whereas the exponent ρ is directly related to the elasticity of substitution ($esub$) between the two aggregates via $\rho = 1 - \frac{1}{esub}$. akl and b_{dm} are distribution parameters.

$$Y_t = (akl * K_t^{\rho * \alpha} * L_t^{\rho * (1 - \alpha)} + \sum_{dm} b_{dm} * D_{dm,t}^{\rho})^{1/\rho} \quad (3.40)$$

The underlying relationship between new investment, INV_t , and the existing capital stock, K_t , is given by the Capital Accumulation Function (Philippidis *et al.*, 2011):

$$K_t = (1 - \partial) * K_{t-1} + \frac{nyrsper}{2} * (tarv * INV_{t-1} + INV_t) \quad (3.41)$$

where ∂ is the rate of depreciation of the capital stock and $tarv$ is the exponent where $tarv = (1 - depr/100)^{nyrsper}$ ($depr$ is the depreciation rate at period t and $nyrsper$ is the number of years per period). This equation ensures that total capital in the current

period reflects the capital in the previous period, minus depreciation, plus new investment (Loulou *et al.*, 2004b).

The MACRO framework does not include any endogenous dynamics for labor. Labor is exogenously specified as an index with growth rate $growv_t$ (Loulou *et al.*, 2004b).

$$L_0 = 1, L_{t+1} = (1 + growv_t)^{nyrsper} * L_t \quad (3.42)$$

The links between the MARKAL and MACRO modules are set in several critical features such as demand, capacity, and annual energy cost (Loulou *et al.*, 2004b). The energy demands, $D_{dm,t}$, determined in the MACRO module provide the physical link from the MACRO to the MARKAL modules. The other link between the two modules equates the MACRO variable energy cost, EC_t , with the MARKAL expression of the annual energy cost. The MACRO module also imposes an upper bound on technological capacity increase between two successive periods. Thus, excessive rapid market penetration of technologies are damped.

4. THE DESCRIPTION OF THE BUEM MODELING FRAMEWORK

The methodological diversities and developments of modeling frameworks over the past four decades have lead to a wide literature on energy modeling. These models have different features and are often based on different approaches. However, even though most of them are useful in predicting future trends, in practice, vast data needs, inflexible structures, and “black box” treatment of some relationships make them difficult to deploy. From this perspective, the BUEM (Bottom-Up Energy Model) framework is designed as a simple, flexible, general purpose, linear optimization modeling framework. The purpose of building this modeling framework has been to focus on the mechanisms and relationships that would mimic the energy sector as realistically as possible, but without unnecessary, insignificant detail that would primarily hinder data compilation and result analysis phases. All the complex relationships of supplying and producing energy sources according to the demand mechanisms are duely represented in this approach with sufficient technological detail.

An important advantage of the framework is its simplicity in the representation of the complexity of outside world. Complicated linkages of any energy related technology and facility, either in itself or with other technologies and facilities, are simplified in a comprehensive way. However, resulting models at the same time, represent all the necessary relations. This way, the rigid, extremely detailed, and quite confusing structure of other modeling frameworks, such as the MARKAL and NEMS, are simplified and the data requirements are reduced.

The flexibility of the framework comes from the ability and ease of adding new relations/constraints to the system. Most of the other modeling frameworks have well-defined rigid structures or interfaces that prevent the user from adding new relations (which are not defined or placed into the modeling framework in functional forms as parts of system equations) to the system. This framework, on the other hand, provides a suitable environment to build new relations based on what the user wishes to analyze and on scenario requirements.

The framework is designed to have the ability to perform national or sectoral analysis. The main modeling system is a unified structure of submodules and this modular structure allows the user to work either on narrow scope projects (such as focusing on the energy consumption of a specific sector) or wide scope projects (like focusing on national energy consumption). That gives the framework its ability to support specific energy studies, e.g. hybrid vehicle share in transport sector, or more general policies, e.g. import dependence of a country for energy.

The modeling structures and relations are built over linear equations, which make the generated models computable and easy to track for errors and interpret the results.

The modeling framework includes two parts; the Bottom-Up Module and the Macro Module. The Bottom-Up module is to cover all aspects of the energy system from the energy supply side to the demand side. In other words, an energy sector specific model with an exogenous energy demand data set, is aimed at this stage. On the other hand, the Macro module is to be used to build a feedback mechanism between the energy sector and the demand for energy from all sectors and sub sectors of the economy. This way, energy demands are linked to the prices and some key economic factors such as the GDP, the total production, consumption, and investments. These two modules have their own objectives. Therefore, they can work separately as well.

4.1. The Bottom-Up Energy Modeling Framework

The BUEM Bottom-Up approach is designed as a new large-scale energy model with a bottom-up perspective. The purpose has been to create an energy policy analysis tool to investigate the application of various alternative energy policies that may focus on technology assessments, emissions, carbon penalties, import dependencies, efficient technology penetration rates, share of renewable energy sources, and so on. The need to represent energy supply and consumption profiles and their differences regarding base to alternative scenarios are the main drivers of this study.

The framework aims at the development of a bottom-up linear programming optimization model having the objective of minimizing the total energy system cost over a set of constraints. All constraints are to be satisfied in each period and energy supply levels satisfying the period's demands are determined accordingly. Thus, energy supply and demand are equated in each period. This equilibrium is to be reached under the least-cost energy supply and production combinations. Figure 4.1. summarizes the BUEM modeling framework as a whole.

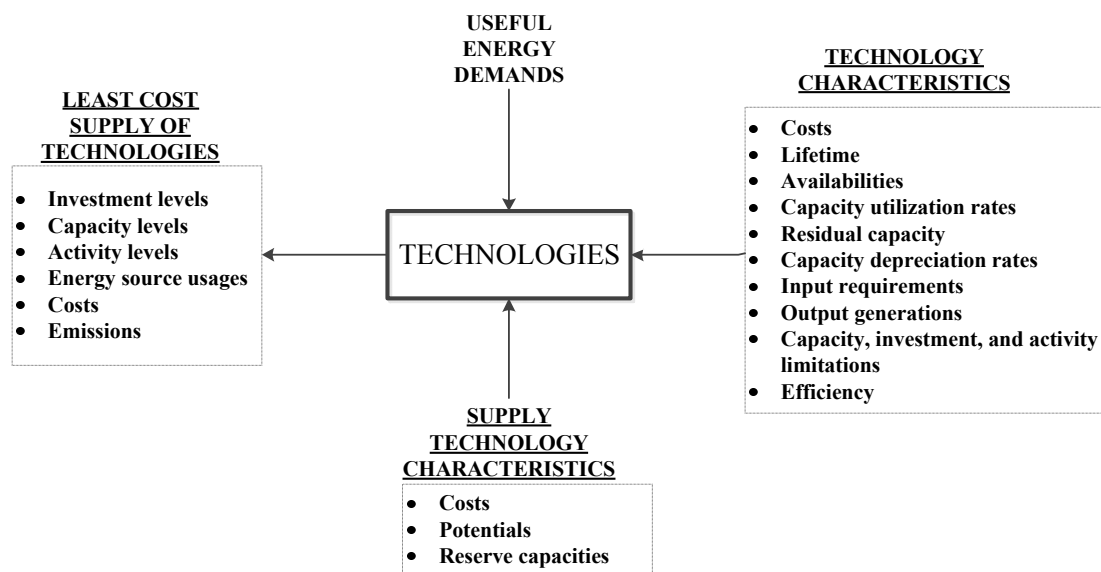


Figure 4.1. Basic BUEM framework structure.

Any mechanism processing, converting or transmitting an energy source is referred to as a technology. Therefore, industrial processes, electricity generation facilities, vehicles, electrical appliances, etc. are all represented as technologies in this framework. Each technology has its own parameter structure that helps to determine its contribution to the total discounted annual system cost and its other impacts on to the system (such as resource consumptions, energy source requirements, and environmental impacts). Costs, availability factors, limitations, input requirements, and levels of output generated per technological activity are the main parameters that contribute to the determination of the least-cost supply options. The technologies are linked to each other via energy source conversions; energy sources link one technology to another and create the backbone of the

structure. From this point of view, any output energy form from a technology is an input energy form to another technology.

The technologies supplying or producing energy sources are divided into two groups. The first group is the “Supply Technologies”. This group includes those technologies that supply the energy sources to the system, such as imported fuels (e.g. coal, oil, synthetic energies, etc.), extracted fuels (e.g. mining of coal, natural gas, etc.) or renewable energy sources, with a unit cost and limitations on supplies. Those technologies do not need any input energy source to operate.

The second group is the “Energy Conversion Technologies”. This group includes those technologies that generate an energy source by using another energy source as an input. Electricity generation facilities, hydrogen energy production plants, petroleum refineries, ethanol/methanol production facilities can be given as examples of technologies under this group. For each energy conversion technology, a technology investment, a technology capacity, and a technology activity variable is defined. Investment, operation, and maintenance costs, technology availability factors, limitations on technology investment, capacity or activity, input requirements per unit technology activity, output generation per unit technology activity, and lifetime are defined as the main parameters.

The third group is the “Demand Technologies”. This group includes those technologies that convert energy sources to meet demand requirements (vehicles, space heating devices, refrigerators.etc.). In other words, they use energy sources as inputs to satisfy system demands. Each demand technology has a parameter list including investment, operation, and maintenance costs, capacity utilization factor, limitations on technology capacity and investment, efficiency rate, lifetime, input requirements per unit technology activity, and level of demand satisfied per unit technology activity. System demands are directly (and solely) linked to demand technologies. Those demands are determined outside of the model and exogenously placed to the system. In the second phase of this study, however, the ways of producing the demands endogenously is discussed. This model extension is treated in Section 4.2.

The optimization process collects all the information from the system and provides the least cost fuel-technology combination that satisfies the specified demand with respect to minimization cost objective (Figure 4.2). Demand technologies' input requirements impulse the optimization procedure and the system communicates with the connected technologies. If the connected technology is an energy conversion technology, optimization process evaluates the technology options that might provide the necessary inputs to the conversion technology. This mechanism is continued until a supply technology is reached. If the demand technology is directly related to a supply technology, then it is a one-chain optimization decision. If it is not, all the intermediate technologies are evaluated until a supply technology is reached. Then, all the information from bottom to top is collected and the final optimum decision is made by evaluating the net cost of each option that satisfies the specified demand. The optimization process covers all demand items in an integrated fashion.

For example, demand technologies that serve to residential heating such as coal-fired boilers, natural-gas fired boilers, electricity heating devices, etc. are used to satisfy the residential heating demand requirement (Figure 4.3). Each demand technology is considered in the overall optimization setting. The cost structure, efficiency rate, capacity utilization factor, output generation level, and lifetime (which are directly obtained from the technology parameter list) enter the evaluation process. Additionally, their input requirements (together with the costs and requirements of further inputs along to the chain) are also considered in this optimization. For example, coal type characteristics such as supply prices and maximum availabilities are considered in the evaluation process. Similar reasoning is applied to natural gas-fired boilers. For electricity-fired boilers, on the other hand, different options of electricity generation are evaluated before providing the net (and the least) price of electricity heating. Accordingly, a net cost for each heating demand technology is obtained. After evaluating all options based on net costs, the least cost way of satisfying the residential heating demand is determined. Sometimes a combination of demand technologies may serve (give the least cost) for a specific demand. For example, 80% of the heating demand can be satisfied by coal-fired boiler, while the remaining 20% is shared between natural gas and electricity (e.g. 12% natural gas, 8% electricity).

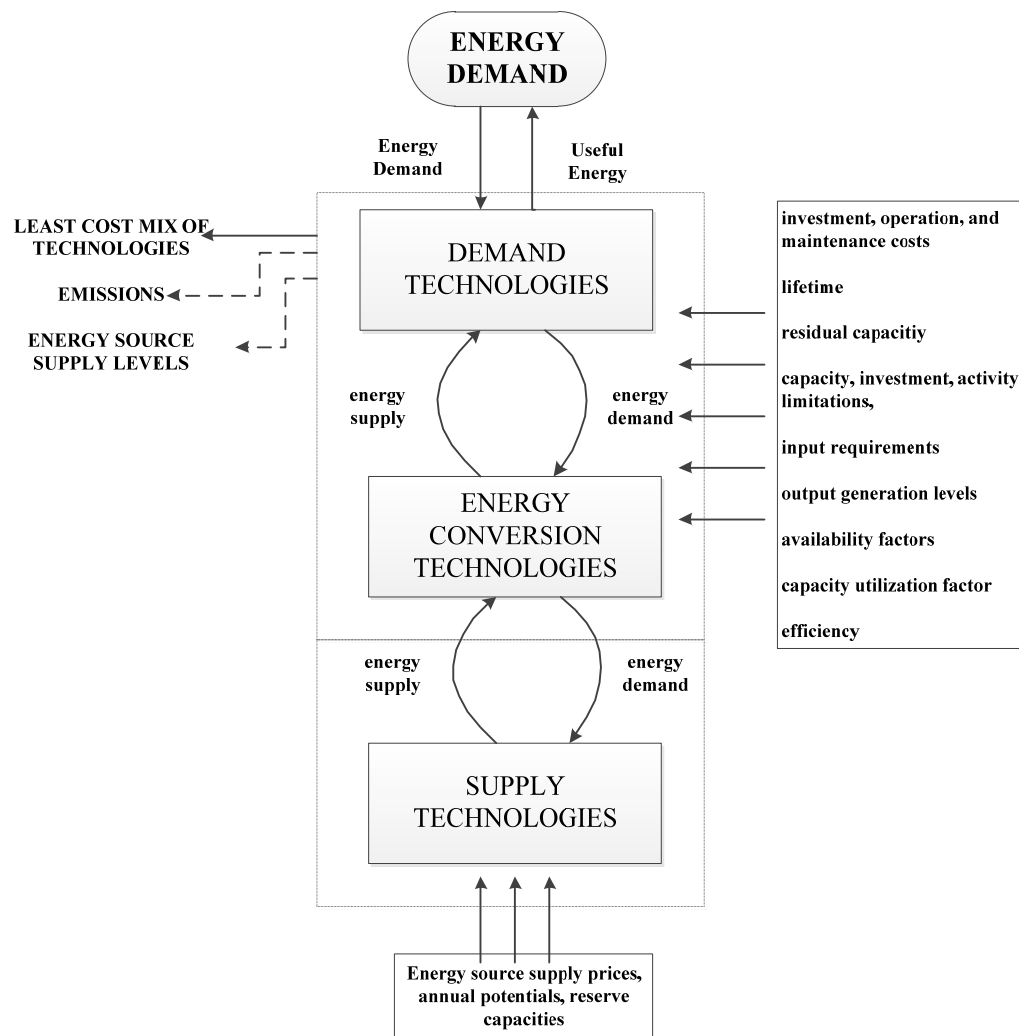


Figure 4.2. Relationships and interdependencies among energy technologies.

Supply technologies provide energy sources to the system without any input requirement. Each energy conversion technology, on the other hand, processes an energy source as an input to produce another energy source as an output. Demand technologies finally process the input energy sources to produce output demands. This way, the model relates the supply side and the demand side of the energy system over many intermediate technologies (an example is displayed in Figure 4.4). From this perspective, an energy system model is built on three submodules, namely supply, energy conversion, and demand submodules. Technology characteristics are structured based on the module the technology belongs to. In other words, each technology in a module features the same specifications and dynamics. The submodules and the feedback mechanisms among them are discussed in the following subsections in detail.

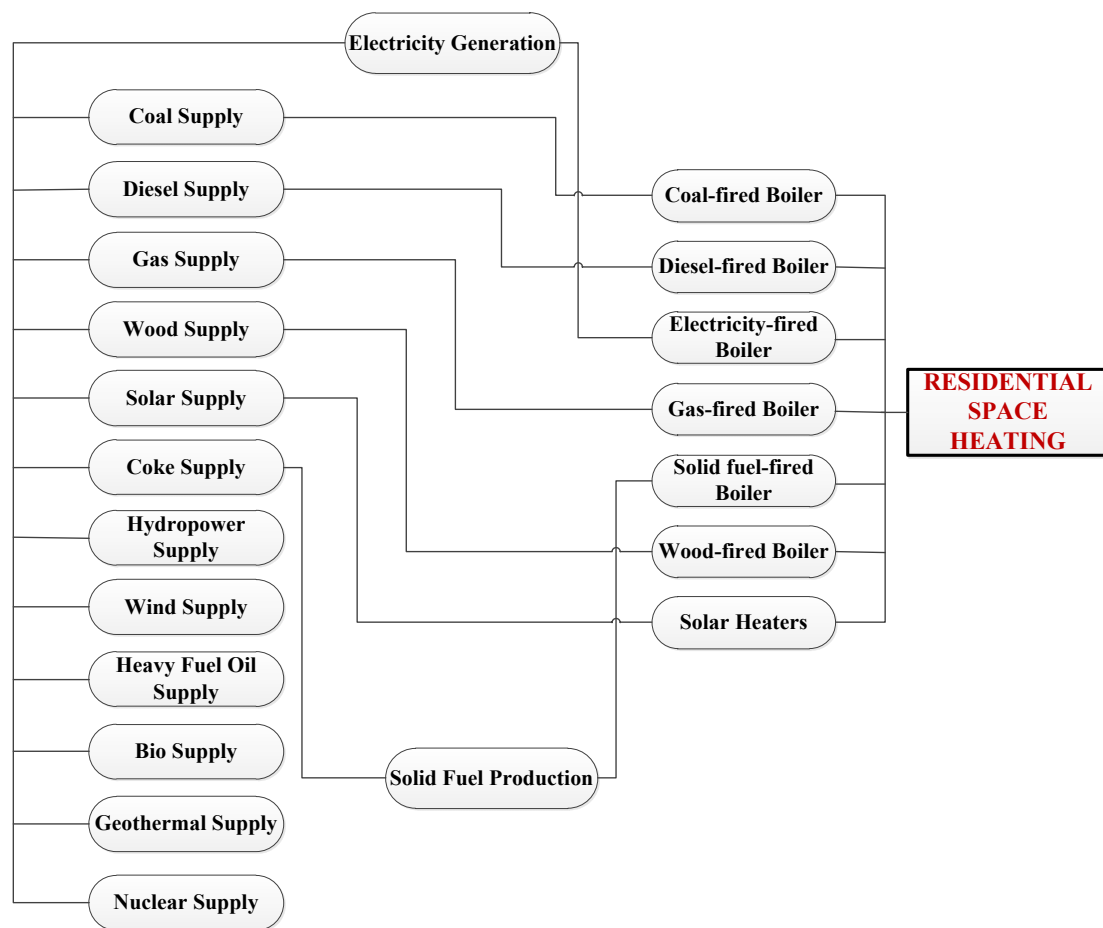


Figure 4.3. Energy technologies and related energy flows regarding residential heating.

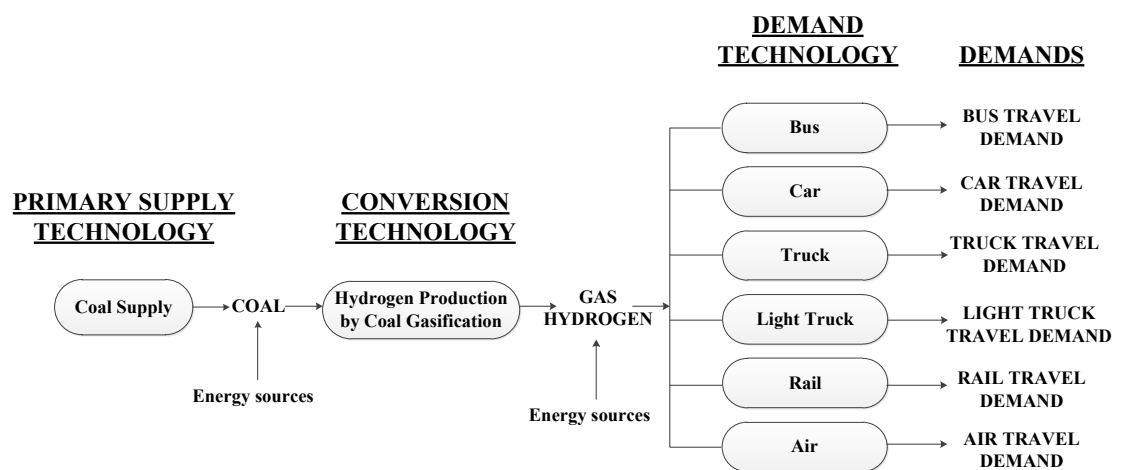


Figure 4.4. Schematic overview of input-output relations.

4.1.1. The Supply Submodule

This submodule consists of the supply technologies that are responsible for supplying energy sources to the energy sector. Without any energy source, it is not possible to build a meaningful energy model. In the developed framework, energy sources are either imported or supplied domestically. Imported sources are brought the system by import technologies. Domestic resource alternatives, on the other hand, include mining and renewable energy resources (as can be seen from Table 4.1). All supply technologies (import, mining, and renewable technologies) have similar characteristics; the division aims to create separate sets of technologies that will be already available in the scenario analysis phases (e.g. to apply scenarios such as imposing import limitations for energy consumption). Export technologies, which act like energy sinks (just consuming energy without producing anything) are also provided in the developed framework.

Table 4.1. Supply technologies.

Supply Technologies
Import Technologies
Mining Technologies
Renewable Technologies
Export Technologies

Realization levels of the supply technologies form one of the main decision variable sets of the model. These variables are represented by “*r_supply*” abbreviations in the model constraints and typical units used for them are PJ/year. Each supply technology is related with a unit supply cost and annual and cumulative bound limitations on supply levels. Annual bounds can be used for setting annual availabilities on renewable energy resources (such as wind and water) or annual purchase contracts on import/export activities. Cumulative bounds, on the other hand, limit the total supply of a supply technology over the planning horizon. These bounds are especially useful in applying reserve capacity of mining resources or contract limitations for import/export activities. In addition, decay and growth bounds can be used to limit the decay and growth of supply between consecutive periods.

Supply technologies are designed in a way that they cannot provide more than one energy source to the system. However, different supply options for the same energy source may be provided. For example, there may be different types of mines that produce the same energy source (e.g. coal and natural gas) with different prices; or different renewable energy resources that supply the same energy source (such as wind and water) with different annual availabilities. Those differences are represented as the multiple technologies producing the same energy source, but with different parameter structure. Key parameters of supply technologies may be summarized as follows:

- *bound_s_lower/bound_s_fix/bound_s_upper*: annual supply bound; lower bound, fixed bound, and upper bound,
- *cum*: cumulative (overall supply) resource limitation on supply,
- *decay_s/growth_s*: maximum decay (or growth) rate of supply between the consecutive periods,
- *inpent*: level of input requirement per unit supply (e.g. coal extraction facilities may need electricity for lighting),
- *scost*: unit supply cost.

Supply technologies may operate at any level (if there is no specified upper bound) or choose not to operate (if there is no specified lower bound) depending on the optimization decision.

4.1.2. The Energy Conversion Submodule

Energy conversion technologies transform an energy source to another energy source according to demand requirements. They are the intermediate process technologies that reconfigure or transform the energy sources and basically need input energy sources to supply new energy sources to the system.

Most of the technologies in this module belong to electricity generation facilities. LTH generation facilities create another important group. On the other hand, petroleum refineries and productions of some other fuels such as ethanol, methanol, coke, or

hydrogen can be given as examples of the technologies in the third group. Therefore, energy conversion technologies are divided into three sub groups (as can be seen from Table 4.2). The technologies that produce electricity are called “Electricity Generation Technologies”. The technologies that produce LTH are called “LTH Generation Technologies”. The technologies that produce the remaining energy sources (some of which are mentioned above) are called “Process Technologies”.

This division becomes important especially in the modeling of electricity and LTH generation sectors. For example, peak load and reserve capacity investments significantly affect the installed capacity levels and electricity generation rates. They are needed to be carefully placed into the system. Those kinds of electricity/LTH specific equations are not applicable for the process technologies. In addition, operation level of electricity generation technologies is divided into two time-segments, namely day and night. Time-segments are recognized by only for technologies producing electricity, which may not be easily stored and thus require a finer time disaggregation than other energy carriers. This way, the supply capabilities and demand needs of electricity are individually balanced in each time segment.

Table 4.2. Energy conversion technologies.

Energy Conversion Technologies
Electricity Generation Technologies
LTH Generation Technologies
Process Technologies

Another key decision variable set in the developed framework is associated with periodic capacity investments in various conversion technologies and how much of the available capacity to activate in order to generate the desired level of output energy source. Capacity level is a cumulative variable. It grows with new investments and decreases with depreciation each period. Thus, new investment level, capacity level, and activity level of conversion technologies are to be determined each period. These variables are represented as “ r_{inv} ”, “ r_{cap} ”, and “ r_{act} ”, respectively. Typical units are displayed in PJ/year, same as for supply technologies.

New investment on a technology is generated based on several parameters, such as unit investment and operational costs, discount rates for the investment expenses, lifetime, depreciation rate, annual limitations on capacity, activity, and investment, input requirement per unit activity and related fuel expenses, output generation level per unit activity, and annual availability of the capacity. The investment is assumed to take place at the beginning of the period, and so is fully available to the model in the period in which the investment takes place. Thus, once the new investment is determined, the capacity of the current period is obtained. Any existing or newly created capacity is assumed to be available in the following period (minus a predetermined loss percentage due to depreciation). Depreciation rates and lifetimes of technologies are important parameter sets to be estimated.

The system also considers the residual capacity of a technology that was invested prior to the start of the planning horizon but still exists at the current period. Thus, those technologies become readily available in the system without any investment cost. The residual capacity concept is especially useful in calibrating the initial year (Residual capacity and new capacity are calibrated separately at the initial year). This way, the investment costs of existing technologies are not considered (since they were already available at the start time of the planning horizon). Instead, only the initial years' investments are considered. For example, diesel vehicle park of the initial year's transport sector is the collection of the capacity coming from the previous years and the new capacity invested in the initial year. The system only pays for the initial year's diesel vehicle investments. The existing capacity coming from the previous years are considered as paid before the planning horizon starts. Activity level is determined based on the annual availability of the capacity, which is the fraction of the year that the capacity is available to operate. All or some of the capacity can be activated based on the annual availability factor. On the other hand, technology activity cannot exceed available capacity.

Key parameters of conversion technologies may be summarized as follows. The applications and impacts of these parameters in the BUEM relationships are discussed in the following subsections in detail.

- *af*: annual availability factor of the technology,
- *baseload*: the highest percentage of the baseload power plants in total electricity generation,
- *bound_x_lower/bound_x_fix/bound_x_upper*: annual bounds on capacity/activity/investment; lower bound, fixed bound, and upper bound,
- *capunit*: unit conversion factor. This parameter is used to do unit conversion between capacity and activity of technologies (if capacity and activity units are different).
- *cdf*: capacity depreciation rate. This parameter determines the share of the capacity that would be depreciated. If it is not activated, the invested capacity would last until its life is over.
- *decay_c/growth_c*: maximum decay/growth rate of capacity between consecutive periods,
- *decomcost*: decommissioning cost per unit of capacity. Decommissioning cost is the future expenses of the technology at and beyond the time its useful lifetime is over. At the end of its lifetime, a technology may need to be decommissioned, decontaminated, and demolished so that the site is made available for other uses. This parameter is only valid for nuclear plants in the developed framework. For nuclear plants, the term decommissioning includes all clean-up of radioactivity and progressive dismantling of the plant.
- *discount*: discount rate. This parameter is used to discount system costs.
- *dtraninv*: unit investment cost for LTH transmission system of LTH generation technology,
- *dtranom*: unit transmission cost of LTH from LTH generation technology,
- *edistinv*: unit investment cost for electricity distribution system of electricity generation technology,
- *edistom*: unit distribution cost of electricity from electricity generation technology,
- *etraninv* : unit investment cost for electricity transmission system of electricity generation technology,
- *etranom*: unit transmission cost of electricity from electricity generation technology,

- *emisact*: level of emission emitted per unit of technology activity,
- *emissep*: level of emission emitted per unit of technology supply,
- *ereserv*: peak reserve factor for electricity generation,
- *fixom*: fixed operation and maintenance cost per unit of capacity,
- *inpent*: level of input requirement per unit of technology activity,
- *invcost*: investment cost per unit of new capacity addition,
- *life*: useful lifetime of the technology,
- *outent*: level of output generation per unit of technology activity,
- *peakcon*: the fraction of the technology m 's capacity that should be credited towards the peaking requirement at period t ,
- *qhr_(q)*: fraction of the year represented by time-of-day segment. q is “d” if it is for day time, “n” if it is for night time,
- *resid*: residual capacity. This capacity only includes the predefined capacities that were invested prior to the start of the planning horizon.
- *salvcost*: salvage cost per unit of capacity. Salvage cost is defined as the remaining value of the technology at the time its useful lifetime is over.
- *startyrs*: the first year in which the technology would be available to operate,
- *teent*: transmission efficiency of electricity,
- *varom*: variable operation and maintenance cost per unit of activity.

4.1.3. The Demand Submodule

This module includes the demand technologies that satisfy the final demand requirements. They are directly linked to the system demands. However, system demand requirements (e.g. tonnes of steel production, billion vehicle km, etc.), which are not generally in energy units, are initially needed to be converted to final energy demand requirements. The output generation parameter is used to do the unit conversion. This parameter actually defines the level of demand satisfied per unit activity of demand technology, but at the same time considers the unit conversions. In other words, it gives the level of demand met by one PJ technology activity. This way, demand technologies convert demand requirements into energy requirements.

Similar to other technologies, demand technologies may invest on additional capacity in each period. However, there are no defined operating levels, nor the associated activity variables, for them. Instead, a capacity utilization factor is assigned to each technology. This factor determines the level of capacity that is in use, which implies that the activity of the related demand technologies is to be fixed at a certain percentage of the capacity. Thus, investment and capacity levels are the only variables related to this technology group.

Regarding new investments and capacities in consecutive periods, the structural relationships are set up in a manner similar to that of the energy conversion technologies. Treatment of the residual capacity is also handled in a similar manner. In addition, efficiency rates of the input usage are taken into consideration. These parameters describe how efficiently each demand technology uses the energy input to produce useful energy demand. For example, if a diesel car technology works with a 0.37 efficiency, the input requirement of the technology is increased by a factor of $1/0.37$.

Demand technologies are grouped in sectors (as displayed in Table 4.3). In this way, it becomes possible to apply sector specific constraints and do sectoral analysis.

Table 4.3. Demand technologies.

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

Parameters of the demand technologies are generally similar to those of the energy conversion technologies. The only differences are the capacity utilization factor and efficiency rate parameters, which are discussed above. Capacity utilization factor is used instead of annual availability factor (of energy conversion technologies). However, the logic behind them is totally different. Annual availability factor shows the maximum share of the capacity that will be available in the period, while capacity utilization factor shows the

share of the capacity that is in use in the period. On the other hand, efficiency rate of a technology is represented by a specific parameter in demand technologies, while input/output ratio is used as an indicator of efficiency in energy conversion technologies. Therefore, the key parameters of this submodule that differentiates from energy conversion technologies are as follows:

- cf : capacity utilization factor,
- eff : efficiency rate (of input usage) of demand technologies.

4.1.4. Sets of the Energy Modeling Framework

In the developed framework, system equations are applied over the predefined set displayed in Table 4.4. Every relationship (constraint) is defined over a set or a group of sets. Most of the sets are formed over technologies based on common features. Each technology in the set must satisfy the requirements indicated by the related constraints (linear equations or inequalities). There are also specific sets for energy sources, (e), demand services, (dm), and emissions, (v). Each energy source, demand service, and emissions of the associated sets must satisfy the requirements indicated by the related constraints as well. However, the number of such constraints is few compared to technology set constraints.

Table 4.4. Sets of the BUEM modeling framework.

Set Abbreviation	Description
m	Any technology of the model
s	Supply Technology
sim	Import Technology
smn	Mining Technology
srn	Renewable Technology
sex	Export Technology
c	Energy Conversion Technology
ce	Electricity Generation Technology
ch	LTH Generation Technology
cp	Process Technology
d	Demand Technology
da	Agriculture Sector Demand Technology
dr	Residential Sector Demand Technology
ds	Service Sector Demand Technology
di	Industry Sector Demand Technology
dt	Transport Sector Demand Technology
$k (c \cup d)$	Energy Conversion and Demand Technologies
e	Energy source
dm	Demand service
v	Emission type
t	Time period
y	Year
q	Time segment

4.1.5. Variables of the Energy Modeling Framework

System variables are specific to the submodule and the set that the technology belongs to. Model constraints are constructed over the variable relationships. As mentioned above, energy conversion technologies have investment, capacity, and activity variables. Supply level is the only single variable of the supply technologies and demand technologies only have investment and capacity variables (as displayed in Table 4.5).

Table 4.5. Decision variables of the BUEM modeling framework.

Variable	Description
$r_supply(s, t)$	Supply Level of Supply Technology s
$r_supply(sim, t)$	Supply Level of Import Technology sim
$r_supply(smn, t)$	Supply Level of Mining Technology smn
$r_supply(srn, t)$	Supply Level of Renewable Technology srn
$r_supply(sex, t)$	Supply Level to Export Technology sex
$r_inv(c, t)$	Investment level of Energy Conversion Technology c
$r_inv(ce, t)$	Investment Level of Electricity Generation Technology ce
$r_inv(ch, t)$	Investment Level of LTH Generation Technology ch
$r_inv(cp, t)$	Investment Level of Process Technology cp
$r_cap(c, t)$	Capacity Level of Energy Conversion Technology c
$r_cap(ce, t)$	Capacity Level of Electricity Generation Technology ce
$r_cap(ch, t)$	Capacity Level of LTH Generation Technology ch
$r_cap(cp, t)$	Capacity Level of Process Technology cp
$r_act(c, t)$	Activity Level of Energy Conversion Technology c
$r_act(ce, t)$	Activity Level of Electricity Generation Technology ce
$r_act(ch, t)$	Activity Level of LTH Generation Technology ch
$r_act(cp, t)$	Activity Level of Process Technology cp
$r_inv(d, t)$	Investment Level of Demand Technology d
$r_inv(da, t)$	Investment Level of Agriculture Sector Demand Technology da
$r_inv(dr, t)$	Investment Level of Residential Sector Demand Technology dr
$r_inv(ds, t)$	Investment Level of Service Sector Demand Technology ds
$r_inv(di, t)$	Investment Level of Industry Sector Demand Technology di
$r_inv(dt, t)$	Investment Level of Transport Sector Demand Technology dt
$r_cap(d, t)$	Capacity Level of Demand Technology d
$r_cap(da, t)$	Capacity Level of Agriculture Sector Demand Technology da
$r_cap(dr, t)$	Capacity Level of Residential Sector Demand Technology dr
$r_cap(ds, t)$	Capacity Level of Service Sector Demand Technology ds
$r_cap(di, t)$	Capacity Level of Industry Sector Demand Technology di
$r_cap(dt, t)$	Capacity Level of Transport Sector Demand Technology dt
$r_em(v, t)$	Emission Level of Emitter v

4.1.6. Functional Form of a Typical Energy Model

The bottom-up model structure is primarily formed by the energy system constraints covering energy and environment relations. The objective function of the model is the minimization of the total discounted system cost aggregated over all periods. Most of the equations are applied over technology sets. According to the set a technology belongs to, active constraints can be defined. In other words, a constraint which is specific to a set or sets is applied to each technology in the set or sets. Therefore, total number of the constraints in the model is simply related with the total number of technologies. Functional relationships are divided into two categories based on their status in the model; (i) constraint equations that reflect some conditions that need to be satisfied during the optimization process, (ii) non-constraint equations that are used for accounting and reporting purposes. Sometimes, reported quantity is employed as an input to another relationship.

Another classification may be based on the purpose of the mathematical relationships. In other words, the relationships are categorized according to what the constraint is responsible for. From this perspective, there are six groups of constraints in the model: (i) Cost constraints, (ii) Regular performance constraints, (iii) Electricity performance constraints, (iv) Emission constraints, (v) Accounting constraints, (vi) Scenario constraints.

4.1.7. Cost Constraints

4.1.7.1. The BUEM Objective Function - The Total Discounted System Cost. The objective function of a BUEM model is the minimization of the total cost of the system, which is the totality of the discounted annual costs of each period. The total cost includes each cost item of the BUEM framework that are summed over the planning horizon. Besides discounted costs, undiscounted costs are also reported for accounting purposes. In addition, each cost item is tracked by sector as well.

The objective function of a BUEM model is as follows.

$$\min \text{ totcost} = \sum_t \text{disanncost}(t) \quad (4.1)$$

where

- *disanncost*(*t*): total discounted annual cost of period *t*,
- *totcost*: total discounted system cost.

Primary cost items considered the total cost of the system (namely annual supply cost, annualized investment cost, annual operational other costs, environmental cost, revenue from exported energy sources) are discussed in detail in the following subsections.

4.1.7.2. Total Annual Cost. Total annual cost is the summation of each annual cost item of period *t*. These items are grouped under five major categories: (i) total fuel supply cost of the system, (ii) total investment cost of the system, (iii) total other operational cost of the system, (iv) total environmental cost of the system, and (v) total additional costs of the system. Total fuel supply cost is the summation of all the expenses of supplying energy sources to the system at period *t*. Each supply expense is an annual cost, so none of them needs to be annualized. However, investment cost is not an annual expense and needs to be annualized. Thus, each investment item is initially annualized, then summed. Other operational costs of the system, on the other hand, include total fixed and variable operation and maintenance costs. This cost item is another annual cost and so not need to be annualized. In addition, environmental costs are designed to represent possible negative environmental impacts and additional costs are designed to represent other miscellaneous expenses of the system.

The cost items listed above are calculated in both discounted and undiscounted versions. Discounted costs are used in the objective function and affect the optimization process. Undiscounted costs, on the other hand, are used for reporting purposes and result analysis.

(i) *Total Annual Undiscounted Cost*: This aggregate cost item is constructed with the purpose of tracking the total annual undiscounted cost of period t . In this relation, annual supply, investment, other operational, environmental, and additional costs are summed in undiscounted forms.

$$\begin{aligned} undanncost(t) = & undannsupply(t) + undanninv(t) \\ & + undannother(t) + undannenv(t) + undannadd(t) \end{aligned} \quad (4.2)$$

where

- $undannadd(t)$: annual total of undiscounted additional costs at period t ,
- $undannenv(t)$: annual total of undiscounted environmental costs at period t ,
- $undanncost(t)$: total annual undiscounted cost of period t ,
- $undanninv(t)$: annual total of undiscounted investment costs at period t ,
- $undannother(t)$: annual total of undiscounted operational costs at period t ,
- $undannsupply(t)$: annual total of undiscounted supply costs at period t .

(ii) *Total Annual Discounted Cost*: Total annual discounted costs of each period are deployed in the objective function. The annual undiscounted costs discussed in the above section are properly discounted to the initial year or to a year predefined by the user. Discount process works in two steps: (i) costs are discounted within the period, (ii) and then the costs, which are already discounted to the beginning of the period, are rediscounted to an initial or user defined discount year. Details of the discount process are given in Section 4.1.7.3.

$$\begin{aligned} disanncost(t) = & disannsupply(t) + disanninv(t) \\ & + disannother(t) + disannenv(t) + disannadd(t) \end{aligned} \quad (4.3)$$

where

- $disannadd(t)$: annual total of discounted additional costs at period t ,
- $disannenv(t)$: annual total of discounted environmental costs at period t ,
- $disanncost(t)$: total annual discounted cost of period t ,
- $disanninv(t)$: annual total of discounted investment costs at period t ,

- $disannother(t)$: annual total of discounted operational costs at period t ,
- $disannsupply(t)$: annual total of discounted supply costs at period t .

4.1.7.3. Total Annual Supply Cost. This cost includes any cost item related with the energy source supply. In addition, transmission and distribution costs of electricity and LTH are considered as well. Energy supply expenses come from the Supply Submodule. Electricity/LTH distribution and transmission expenses, on the other hand, come from the Energy Conversion Submodule. However, the associated costs of investments on transmission or distribution facilities or due to the operation of these facilities are not considered in this cost item. Investment and operational costs of electricity/LTH transmission or distribution facilities are included in total investment cost and other operational costs of the system, respectively. Besides, LTH only has transmission related costs. In addition, supply costs of export technologies, which are exogenously defined by the user, are multiplied by a minus sign before placed into the model. This way, they act like a revenue and reduce the total system cost.

(i) *Total Annual Undiscounted Supply Cost:* Annual undiscounted supply cost of the system is a cost item constructed with the purpose of tracking the total undiscounted supply cost at period t . This cost is a function of energy supply, $r_{supply}(m, t)$, electricity/LTH distribution and electricity transmission technology activities, $r_{act}(m, t)$. The first item in the relationship sums supply costs of period t over the supply technology set. The second and third items are used to represent the total costs of distributing and transmitting electricity at period t , respectively. The last item represents the total cost of transmitting LTH at period t .

$$\begin{aligned}
undannsupply(t) = & \sum_{m \in s} scost(m, t) * r_supply(m, t) \\
& + \sum_{m \in ce} edistom(m, t) * outent(m, t) * r_act(m, t) \\
& + \sum_{m \in ce} etranom(m, t) * outent(m, t) * r_act(m, t) \\
& + \sum_{m \in ch} dtranom(m, t) * outent(m, t) * r_act(m, t)
\end{aligned} \tag{4.4}$$

where

- $dtranom(m, t)$: unit transmission cost of LTH from technology $m \in ch$ at period t ,
- $edistom(m, t)$: unit distribution cost of electricity from technology $m \in ce$ at period t ,
- $etranom(m, t)$: unit transmission cost of electricity from technology $m \in ce$ at period t ,
- $outent(m, t)$: level of output generation per unit activity of technology m at period t ,
- $scost(m, t)$: unit supply cost of technology $m \in s$ at period t .

(ii) *Total Annual Discounted Supply Cost*: Annual discounted supply cost is the properly discounted form of annual undiscounted supply costs of the system, discussed in above section. The only difference is the implementation of discount factor, $pri_df(t)$.

$$disannsupply(t) = pri_df(t) * undannsupply(t) \tag{4.5}$$

where

$$pri_df(t) = \sum_{y=1}^{nyrsper} (1 + discount)^{-(y-1)} \tag{4.6}$$

$$* (1 + discount)^{-(-startyrs + nyrsper * (t-1))}$$

Unit supply cost of technology m is an annual cost not a period cost. $(1 + discount)^{(1-y)}$ is used to calculate the discounted cost of each year (y) in the period. This formula is in the form of basic present value computation with respect to a specific discount rate applied to any cost realized in a specific time. The discounted cost of each year in the period, then, is summed to obtain the total discounted cost of the period.

The second part, $(1 + discount)^{-(-startyrs + nyrsper * (t-1))}$, discounts the total discounted period cost to the beginning of the planning horizon by reapplying the basic present value formula. This time, n is represented by $-startyrs + nyrsper * (t - 1)$. $startyrs$ is the shift from the first year of the model to the relative to which all discounted costs are to be calculated and $nyrsper$ gives the number of years in a period. Thus, $-startyrs + nyrsper * (t - 1)$ together gives the number of years to which all the discounted costs are to be calculated.

4.1.7.4. Total Annual Investment Cost. Investment cost represents the cost realized per unit new capacity addition of technology m at period t . This cost item is different from the other regular expenses of the model, which are paid on per capacity, activity, or supply. Investment cost is paid once at the period, in which the investment is realized. Thus, it needs to be annualized initially based on the lifetime of the technology.

The actual investment cost of period t (which includes the investment costs of electricity/LTH transmission and distribution systems as well, if applicable) is spread over the lifetime of the technology by applying the capital recovery factor. Capital recovery factor is obtained based on the annualization in Equivalent Annual Cost (EAC) formula.

$$EAC = AP * \frac{i}{1 - (1 + i)^{-n}} \quad (4.7)$$

where i is the discount rate, n is the number of years, and AP is the asset price at the beginning of the period. From this point of view, capital recovery factor is calculated as a

product of technology discount rate and lifetime. i is represented by $discount(m)$ and n is represented by $life(m)$. The factor formula is as follows.

$$crf(m) = \frac{discount(m)}{1 - (1 + discount(m))^{-life(m)}} \quad (4.8)$$

where

- $crf(m)$: capital recovery factor of technology m ,
- $discount(m)$: discount rate of technology m .
- $life(m)$: lifetime of technology m .

(i) *Total Annualized Undiscounted Investment Cost*: Annual undiscounted investment cost of period t is the totality of the costs associated with the new investment realized in this period and the investments realized in the previous periods but still available in the current period. Since the investment cost is annualized according to the lifetime of the technology, there should be no associated cost when its lifetime is over. After all the investments of technology m that are still available at period t are determined, those investments are summed to find the total capacity and the associated investment cost of that period.

Whether a technology investment is alive or not in a period depends on its lifetime and the period in which the investment is occurred.

$$(t - u_m), u_m = \max\{0, t - \text{lifetime of technology } (m)/\text{nyrsper}\} \quad (4.9)$$

gives the interval for available investments of technology m at period t (among all capacity additions of technology m realized up to period t). This way, the retired capacity additions of technology m at the previous periods are not included in the period t 's total capacity.

Once the total available capacity and the associated costs of each technology at period t are obtained, the total annual undiscounted investment cost is realized.

$$undanninv(t) = \sum_m \sum_{h=u_m}^t cost_inv(m, h) * r_inv(m, h) \quad (4.10)$$

where $cost_inv(m, h)$ is the annualized investment cost of technology m at period h (which includes the unit investment cost plus electricity/LTH transmission and distribution investment costs, if applicable). Annualization is done according to the capital recovery factor, which is discussed above. In addition, the last period is considered more carefully. If the technology lifetime is not a multiplier of the number of years in a period, investment is not available for all of the last period, but a fraction of it. Thus, the associated cost is applicable for a fraction of the last period. The fraction rate, $fraclife(m)$, is exogenously determined based on the lifetime of the technology and the number of years in a period. The rate is set to unity if lifetime of technology m is a multiplier of the number of years in a period (there is no fraction), otherwise $\frac{life(m)}{nyrsper} - t$ is used as the fraction rate.

$$cost_inv(m, t) = crf(m) * (inv_cost(m, t) + edistinv(m, t) + etraninv(m, t) + dtraninv(m, t)) * fraclife(m) \quad (4.11)$$

where

- $crf(m)$: capital recovery factor of technology m
- $dtraninv(m, t)$: unit investment cost for LTH transmission system 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 ,
- $fraclife(m)$: the last period fraction rate,
- $inv_cost(m, t)$: unit investment cost of technology m at period t .

(ii) *Total Annualized Discounted Investment Cost*: Annual discounted investment cost is the summation of annualized and discounted investment costs of the system technologies at period t . Therefore, the unit investment cost of each technology is initially

annualized and discounted. The actual investment cost includes the same cost items discussed above in the undiscounted investment cost section minus the salvage cost and plus the decommissioning cost. Salvage cost is defined as the remaining value of a technology at the time its useful life is over. Thus, it is usually a revenue to the system. However, we assume that some of the technologies like nuclear power plants do not end up with a valuable asset at the end of their lifetime, instead they may incur extra costs like decommissioning costs.

The annualization and discount of the actual investment cost is done with an aggregate annualization/discount parameter, $pri_disc(m, t)$. Annualization is done based on the capital recovery factor. Discount, on the other hand, is done based on the basic present value formula, discussed earlier in $pri_df(t)$ case.

$$pri_disc(m, t) = crf(m) * (1 + discount)^{-(-startyrs + nyrsper * (t-1))} \quad (4.12)$$

Then, the discounted actual investment cost, $pri_inv(k, t)$, is as follows.

$$pri_inv(m, t) = pri_disc(m, t) * (inv_cost(m, t) + edistinv(m, t) + etraninv(m, t) + dtraninv(m, t) - salvcost(m, t) + decomcost(m, t)) \quad (4.13)$$

where $salvcost(m, t)$ and $decomcost(m, t)$ are the unit salvage cost and unit decommissioning cost of technology m at period t , respectively. Decommissioning cost is considered as an exogenous cost parameter. On the other hand, there are two different treatments to implement the salvage cost: (i) as an exogenous unit cost parameter, (ii) as an endogenously calculated unit cost according to below formula.

$$salvcost(m, t) = \frac{1 - (1 + discount(m))^{-nyrsper * t + \frac{life(m)}{nyrsper} - npers - 1}}{(1 + discount(m))^{nyrsper * (npers + 1 - t)} - 1 - (1 + discount(m))^{-life(m)}} \quad (4.14)$$

$$* (inv_cost(m, t) + edistinv(m, t) + etraninv(m, t) + dtraninv(m, t))$$

where $npers$ is the total number of periods.

The total annual discounted investment cost of period t is, then, a summation of discounted actual investment costs of the system over the technology set m .

$$disanninv(t) = \sum_{m \in \mathcal{U}d} pri_inv(m, t) * r_inv(m, t) \quad (4.15)$$

4.1.7.5. Total Annual Other Operational Cost. This cost item is the aggregation of all fixed and variable costs. Fixed operational and maintenance costs are calculated over technology capacities. Thus, these expenses are realized if there is an available capacity on hand.

On the other hand, variable operational and maintenance costs are calculated over technology activities. Demand technologies do not have activity variables. Instead, capacity utilization factor, which is the fixed proportion of capacity dedicated to activate, is used to determine the active capacity of a demand technology.

(i) *Total Annual Undiscounted Other Operational Cost:* Annual undiscounted other operational cost of the system is a cost item which is constructed with the purpose of tracking the discounted other operational costs of period t . The first item in the relationship gives the total fixed operational cost aggregated over all technologies. The second and third items are for variable operational costs. The variable costs of energy conversion technologies are directly calculated over technology activities. For demand technologies, on the other hand, capacity is firstly multiplied by capacity utilization factor. Unit conversion factor is used as well if the capacity unit is different than the activity unit. Capacity unit of demand technologies is determined in accordance with the demand service unit.

$$\begin{aligned}
undannother(t) = & \sum_{m \in c \cup d} fixom(m, t) * r_cap(m, t) \\
& + \sum_{m \in c} varom(m, t) * r_act(m, t) \\
& + \sum_{m \in d} varom(m, t) * capunit(m) * cf(m, t) * r_cap(m, t)
\end{aligned} \tag{4.16}$$

where

- $capunit(m)$: unit conversion factor for technology m ,
- $cf(m, t)$: capacity utilization factor of technology m at period t ,
- $fixom(m, t)$: 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 .

(ii) *Total Annual Discounted Other Operational Cost*: Annual discounted other operational cost is the properly discounted form of annual undiscounted other operational costs of the system technologies. The cost structure remains similar to the undiscounted cost discussed in above section. The only difference is the implementation of discount factor, $pri_df(t)$. Discount factor is the same parameter that is used to discount annual supply costs.

$$disannother(t) = pri_df(t) * undannother(t) \tag{4.17}$$

4.1.7.6. Total Annual Environmental Cost. Environmental costs represents all environmental penalties, fees, and costs related with the various undesirable emissions and other negative impacts of energy generation, transmission, and consumption activities to the system. In a standard BUEM model, these costs are usually taken zero. However, they constitute an interesting research area in scenario applications.

(i) *Total Annual Undiscounted Environmental Costs:*

$$undannenv(t) = \sum_v env_cost(v, t) * r_em(v, t) \quad (4.18)$$

where $envcost(v, t)$ is the unit emission cost per emission item v at period t .

(ii) *Total Annual Discounted Environmental Costs:*

$$disannenv(t) = pri_df(t) * undannenv(t) \quad (4.19)$$

4.1.7.7. Total Annual Additional Cost. This cost item represents the costs that do not fit to any cost category listed above in the cost formulation section. They are mostly non-energy costs and not needed in the standard model, but in scenario analysis. For example, insulation cost of residential buildings or construction cost of railroads are such cost items that do not fit in a regular cost category and can be tracked as additional expenses.

4.1.8. Regular Performance Constraints

4.1.8.1. Balance Constraint. These constraints guarantee that total usage of any energy source cannot exceed its total supply. Thus, in the developed framework, each energy source is related with two sets; one for the technologies supplying and producing the energy source and one for the technologies exporting and consuming the energy source. The balance relationship is built between those two sets.

The technologies supplying and producing the energy source are represented at the left hand side of the constraint. The total supply/production of an energy source is the summation of total supply from supply technologies and total production from energy conversion technologies. It is assumed that one unit of output is generated per unit supply, thus, there is no output parameter, $outent(m, t)$, associated with supply technologies.

The technologies exporting and consuming the energy source, on the other hand, are represented at the right hand side of the constraint. Consuming technologies can be any type of system technology (e.g. supply, energy conversion, and demand technologies). However, how and how much they consume the energy source depends on the set the technology belongs to. For example, consumption level of a supply technology is a product of supply level and associated input requirement. Consumption level of an energy conversion technology is based on activity level. Consumption level of a demand technology, on the other hand, is based on capacity level. However, capacity utilization factor and efficiency rate is related with the capacity to determine the consumption level of demand technologies. The total export/consumption of an energy source, then, is the summation of exports and consumptions of supply, energy conversion, and demand technologies together.

- m_e : set of the technologies supplying and producing the energy source e ,
- k_e : set of the technologies exporting and consuming the energy source e .

$$\begin{aligned}
& \sum_{m \in m_e \cap s} r_supply(m, t) + \sum_{m \in m_e \cap c} outent(m, t) * r_act(m, t) \\
& \geq \sum_{k \in k_e \cap s} inpent(m, t) * r_supply(m, t) \\
& + \sum_{m \in k_e \cap c} inpent(m, t) * r_act(m, t) \\
& + \sum_{m \in k_e \cap d} inpent(m, t) * cf(m, t) * capunit(m) / eff(m, t) * r_cap(m, t)
\end{aligned} \tag{4.20}$$

where

- $eff(m, t)$: efficiency rate (of input usage) 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 .

4.1.8.2. Capacity Constraints. Capacity constraints are applied to manage the capacity of technologies per period. There are three different capacity constraints in the model.

- (i) Periodic capacity constraint
- (ii) Capacity decay/growth constraint
- (iii) Capacity bound constraint

The first two constraints are discussed in this subsection (while the third constraint is discussed in Section 4.1.8.6).

(i) *Periodic Capacity Constraint:* This relationship ensures that period capacity is equal to the residual capacity (which is installed before the start of the planning horizon, but still alive in the current period) plus the new capacity additions of previous periods (but still exists in the current period) and the current period. Residual capacities are exogenously determined and placed into the model at the beginning of the planning horizon. Thus, there is no associated investment cost.

On the other hand, new capacity additions of the previous periods are the capacities that become operational in the past periods and are still operational in the current period. Those capacities are linearly depreciated between periods. Linear depreciation is realized in a way that each year technology capacity is decreased by the inverse of its lifetime. For example, if the lifetime of a technology is “20” years, it loses “1/20” of its original capacity each year and “ $nyrsper * 1/20$ ” of original capacity each period. On the other hand, capacity depreciation factor is used to determine the percentage of the capacity that is to be depreciated (in some cases, certain percentage of the capacity may not be needed to depreciate). For example, if the factor indicates “1”, all the invested capacity is depreciated until the useful lifetime is over. If the factor is “0.5”, then half of the capacity is depreciated. However, if the factor is “0”, the capacity does not depreciate and preserves its existing level until the end of its lifetime.

In addition, earlier investments should be removed from the total capacity when the associated lifetimes are over. Whether an investment is alive or not in period t depends on the lifetime of the technology and the period in which the investment is occurred. From this point of view,

$$(t - u_m), u_m = \max\{0, t - \text{lifetime of technology } (m)/\text{nyrsper}\} \quad (4.21)$$

gives the interval for available investments of technology m at period t .

$$r_cap(m, t) = resid(m, t) \quad (4.22)$$

$$+ \sum_{h=u_m}^t (r_inv(m, h) - cdf(m) * r_inv(m, h) * (t - h) * \frac{\text{nyrsper}}{\text{life}(m)})$$

where

- $cdf(m)$: capacity depreciation factor for technology m ,
- $resid(m, t)$: level of residual capacity of technology m at period t .

(ii) *Capacity Decay/Growth Constraints*: Decay or growth of the capacity of any technology between consecutive periods is limited by decay and growth rate parameters. These relationships prevent capacity of any technology to decrease/increase below/above a certain percentage of the previous period's capacity.

$$r_cap(m, t + 1) \geq r_cap(m, t) * decay_c(m, t + 1)^{\text{nyrsper}}, m \in c \cup d \quad (4.23)$$

$$r_cap(m, t + 1) \leq r_cap(m, t) * growth_c(m, t + 1)^{\text{nyrsper}}, m \in c \cup d \quad (4.24)$$

where

- $decay_c(m, t)$: maximum annual decay rate of technology m 's capacity between period t and period $t + 1$,
- $growth_c(m, t)$: maximum annual growth rate of technology m 's capacity between period t and period $t + 1$.

4.1.8.3. Supply Decay and Growth Constraints. Decay or growth of possible supply level from a particular supply technology between consecutive periods is also limited by decay and growth rate parameters. These relationships prevent the supply of any supply technology to decrease/increase below/above of a certain percentage of the previous period's supply.

$$r_supply(m, t + 1) \geq r_supply(m, t) * decay_s(m, t + 1)^{nyrsper}, m \in s \quad (4.25)$$

$$r_supply(m, t + 1) \leq r_supply(m, t) * growth_s(m, t + 1)^{nyrsper}, m \in s \quad (4.26)$$

where

- $decay_s(m, t)$: maximum annual decay rate of technology m 's supply level between period t and period $t + 1$,
- $growth_s(m, t)$: maximum annual growth rate of technology m 's supply level between period t and period $t + 1$.

4.1.8.4. Demand Constraint. These constraints ensure that there is always sufficient capacity to meet the demand requirements. Total activities of technologies serving a specified demand should be greater than or equal to demand service itself.

- $d_{dm}(m)$: set of demand technologies serving the demand service dm .

$$\sum_{m \in d_{dm}} outent(dm)(m, t) * capunit(m) * cf(m, t) * r_cap(m, t) \geq demand(dm, t), m \in d \quad (4.27)$$

where

- $demand(dm, t)$: level of demand service dm at period t ,
- $outent(dm)(m, t)$: level of demand service dm satisfied per unit activity of technology $m \in d$ that services the particular demand dm at period t .

4.1.8.5. Activity - Capacity Relation Constraint. These relationships ensure that activity level of any energy conversion technology cannot exceed its available capacity. Available capacity is a product of annual availability factor of the capacity and capacity level itself. In addition, unit conversion factor is used for unit conversion between capacity and activity (if capacity and activity units are different). This factor is primarily applied to electricity/LTH generation technologies. Capacities of those technologies are typically displayed in GW while the activities are displayed in PJ.

$$r_{act}(m, t) \leq af(m, t) * capunit(m) * r_{cap}(m, t), m \in c \quad (4.28)$$

where

- $af(m, t)$: annual availability factor of technology $m \in c$ at period t ,
- $capunit(m)$: unit conversion factor for technology m .

4.1.8.6. Bound Constraints.

(i) *Periodic Limitations*: Periodic limitations are used to restrict activity, capacity, investment, or supply of a technology per period. In the representations below, $r_x(m, t)$ represents activity/capacity/investment/supply (the one that is applicable) of technology m at period t . x represents the set of technologies that activity, capacity, investment, or supply variables are applicable. For example, there is no activity variable for demand technologies and no investment/capacity/activity for supply technologies.

$$r_x(m, t) \leq bound_x_upper(m, t), m \in x \quad (4.29)$$

$$r_x(m, t) = bound_x_fix(m, t), m \in x \quad (4.30)$$

$$r_x(m, t) \geq bound_x_lower(m, t), m \in x \quad (4.31)$$

where

- $bound_x_fix(m, t)$: fixed bound on activity/capacity/investment/supply of technology m at period t ,

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

(ii) *Cumulative supply limit*: These constraints are used to apply cumulative supply limitations such as reserve capacity limitations on domestic resources or contract limitations on imported resources. They are only applicable to supply technologies.

$$\sum_t r_supply(m, t) * nyrsper \leq cum(m), m \in s \quad (4.32)$$

where $cum(m)$ is cumulative capacity limitations on supply technology $m, m \in s$.

(iii) *Activity limitation on a multiple output technology*: Some of the technologies such as refineries may produce more than one output (e.g. gasoline, diesel, lpg, heavy fuel oil, light fuel oil, jet fuel) in real system applications. This process is also reflected into the developed framework. Each technology in the system has the ability of multiple output production. However, if this is the case, this relationship limits the total production from those types of technologies to a fraction of the total technology activity. In other words, the limiting fraction reflects the efficiency of the multiple output process. The right hand side of the constraint details the total production profile of the technology. The left hand side of the constraint equates total production to the limiting fraction of the technologic activity.

$$limit(m, t) * r_act(m, t) = \sum_e outent(m, e, t) * r_act(m, t), m \in multiple\ output\ technologies \quad (4.33)$$

where

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

(iv) *Import Restriction*: These relationships are used to restrict the supply levels of import technologies. These constraints are not active in a standard BUEM model but are implemented in scenario or sensitivity analysis.

$$\sum_{m \in sim} r_{tsep}(m, t) \leq import_share(t) * \sum_{m \in S} r_{tsep}(m, t) \quad (4.34)$$

where $import_share(t)$ is the import fraction of total supply at period t .

4.1.8.7. Electricity Performance Equations.

(i) *Baseload Constraint for Electricity Production*: These constraints ensure that only a certain percentage of the night time demand is met by baseload power plants. Such plants (e.g. hydro, large coal-fired, nuclear) cannot be easily started, shutdown, or restarted, but instead tend to be run at full capacity almost all of the time. Thus, even when the night time demand is lower than the total generation capacity of baseload plants, they should still operate. These constraints ensure that a percentage of the total night time demand is met by non-baseload plants, so that if there is an unexpected decrease of night-time demand, non-baseload plants would be the ones to be shut down.

The left hand side of the constraint represents the limit for total night time electricity generation from baseload power plants. The limit is the product of total night time electricity generation and the highest percentage of baseload power plants in this total. The right hand side of the relationship, on the other hand, gives the night time production from baseload power plants.

$$\begin{aligned} & \sum_{m \in ce} outent(m, "electricity", t) * qhr_n(m, t) * r_act(m, t) * baseload(t) \quad (4.35) \\ & \geq \sum_{m \in ce \cap baseload \text{ plants}} outent(m, "electricity", t) * qhr_n(m, t) * r_act(m, t) \end{aligned}$$

where

- $baseload(t)$: the highest percentage of the baseload power plants in total electricity generation at period t ,
- $outent(m, e, t)$: level of electricity generation per unit activity of technology $m, m \in ce$, at period t ,
- $qhr_n(m, t)$: night time share of electricity generation from technology m at period t .

(ii) *Electricity Peaking Constraint*: These constraints are used to provide sufficient reserve capacity to be installed to meet the peak demand. Thus, the inequality ensures that total electricity generation capacity of any period is greater than or equal to the total electricity demand in that period (which is upwardly adjusted by a reserve fraction). The left hand side of the relationship represents the total electricity generation capacity which is applicable towards the peaking requirement at period t . The peaking contribution parameter is used to determine the fraction of this capacity reserved for peak time. Imported electricity is considered in this total as well. The right hand side of the relationship, on the other hand, represents the total electricity demand of period t (which is upwardly adjusted by the reserve fraction). Supply, energy conversion, and demand technologies can all use electricity; thus, they are all displayed on the right hand side.

$$\begin{aligned}
 & teent(e, t) * \left(\sum_{m \in s} peakcon(m, t) * qhr_y(m, t) * r_supply(m, t) \right) \quad (4.36) \\
 & + \sum_{m \in ce} peakcon(m, t) * capunit(m, t) * af(m, t) * qhr_y(m, t) \\
 & * r_cap(m, t)) \geq \left(\sum_{m \in s} inpent(m, e, t) * qhr_y(m, t) * r_supply(m, t) \right. \\
 & + \sum_{m \in c} inpent(m, e, t) * qhr_y(m, t) * r_act(m, t) + \sum_{m \in d} inpent(m, e, t) \\
 & \left. * cf(m, t) * qhr_y(m, t) * r_cap(m, t) / eff(m, t) \right) * (1 + ereserv(t))
 \end{aligned}$$

where

- $ereserv(t)$: peaking reserve factor for electricity generation at period t ,
- $inpent(m, e, t)$: level of electricity demand per unit activity of technology m at period t ,
- $outent(m, e, t)$: level of electricity generation per unit activity of technology $m, m \in ce$, at period t ,
- $peakcon(m, t)$: the fraction of the technology m 's capacity at period t that should be credited towards the peaking requirement at period t ,
- $teent(e, t)$: transmission efficiency of electricity at period t .

4.1.8.8. Emission Constraints. Functional relationships representing emission activities can be separated into two groups: (i) non-constraint equations that track the emission levels, (ii) constraint equations that are used for scenario applications like emission bounds. Emissions are organized according to submodule divisions in this section. However, sectoral division is also possible.

(i) *Emissions from Supply Technologies:* These non-constraint equations track the level of emissions emitted per unit supply of supply technology $m, m \in s$.

$$\sum_{m \in s} envsep(m, t) * r_supply(m, t) = r_em("emis_supply", t) \quad (4.37)$$

where $emisep(m, t)$ is the level of emissions emitted per unit supply of technology $m, m \in s$ at period t .

(ii) *Emissions from Energy Conversion Technologies:* These non-constraint equations track the level of emissions emitted per unit activity of energy conversion technology $m, m \in c$.

$$\sum_{m \in c} emisact(m, t) * r_act(m, t) = r_em("emis_conversion", t) \quad (4.38)$$

where $emisact(m, t)$ is the level of emissions emitted per unit activity of technology $m, m \in c$ at period t .

(iii) *Emissions from Demand Technologies*: These non-constraint equations track the level of emissions emitted per unit activity of demand technology $m, m \in d$. Activity of demand technologies is determined by the capacity utilization factor, $cf(m, t)$.

$$\sum_{m \in d} emisact(m, t) * capunit(m, t) * cf(m, t) * r_cap(m, t) \quad (4.39)$$

$$= r_em("emis_demand", t)$$

where $emisact(m, t)$ is the level of emissions emitted per unit activity of technology $m, m \in d$ at period t .

(iv) *Total Emissions*: These non-constraint equations track the level of total emissions per period.

$$totemis(t) = \sum_v r_em(v, t) \quad (4.40)$$

where $totemis(t)$ is the level of total emissions emitted at period t .

(v) *Emission Bounds*: These constraints are used to limit the related emissions below to a certain level. These constraints are not active in a standard BUEM model but are implemented in scenario or sensitivity analysis.

$$totemis(t) \leq emis_bound_upper(t) \quad (4.41)$$

where $emis_bound_upper(t)$ is the upper bound on total emission at period t .

4.1.8.9. Accounting Relationships. Most of the items in this group are non-constraint equations that are used to prepare developed model results for reporting (e.g. table or figure formats). For example, total supply of an energy source is calculated by summing the operating level of all technologies producing or supplying that energy source.

(i) *Energy Source Supply:* This relationship is used to determine the total supply level of any energy source.

$$\begin{aligned} energy_supply(e, t) = & \sum_{m \in \left(\begin{smallmatrix} \text{set of technologies} \\ \text{producing } e \end{smallmatrix} \right) \cap s} r_supply(m, t) \\ & + \sum_{m \in \left(\begin{smallmatrix} \text{set of technologies} \\ \text{producing } e \end{smallmatrix} \right) \cap c} outent(m, t) * r_act(m, t) \end{aligned} \quad (4.42)$$

where $energy_supply(e, t)$ is the total supply level of energy source e at period t .

(ii) *Installed Capacity:* This relationship is used to determine the total installed capacity that is credited towards to electricity generation from a particular energy source.

$$energy_elc_cap(e, t) = \sum_{m \in \left(\begin{smallmatrix} \text{set of electricity} \\ \text{generation} \\ \text{technologies processing } e \end{smallmatrix} \right) \cap c} r_cap(m, t) \quad (4.43)$$

where $energy_elc_cap(e, t)$ is the total installed capacity that is credited towards to electricity generation from energy source e at period t .

(iii) *Energy Consumption in Electricity Generation:* This relationship is used to calculate the level of an energy source processed to generate electricity (i.e. consumption of energy source e in electricity generation sector).

$$energy_elc_cons(e, t) = \sum_{\substack{m \in (\text{set of electricity} \\ \text{generation} \\ \text{technologies processing } e) \cap c}} inpent(m, t) * r_act(m, t) \quad (4.44)$$

where $energy_elc_cons(e, t)$ is the level of energy source e consumed for electricity generation at period t .

(iv) *Electricity Generation by Source*: This relationship is used to determine the overall level of electricity generated by technologies using energy source e .

$$energy_elc_gen(e, t) = \sum_{\substack{m \in (\text{set of electricity} \\ \text{generation} \\ \text{technologies processing } e) \cap c}} r_act(m, t) \quad (4.45)$$

where $energy_elc_gen(e, t)$ is the level of electricity generated by technologies using energy source e at period t .

(v) *Total Electricity Generation*: This relationship is used to determine the total electricity generation of period t .

$$elc_gen(t) = \sum_{m \in ce} r_act(m, t) \quad (4.46)$$

where $elc_gen(t)$ is the total electricity generation at period t .

(vi) *Energy Consumption by Sector*: This relationship is used to determine the level of energy source e consumed in sector f .

$$energy_f_cons(e, t) = \sum_{\substack{m \in (\text{set of technologies} \\ \text{in sector } f \text{ processing } e) \cap c}} inpent(m, t) * r_act(m, t) \quad (4.47)$$

where $energy_f_cons(e, t)$ is the level of energy source e used in sector f at period t .

(vii) *Import Dependence*: This relationship is used to determine the share of imported energy sources in the overall energy supply of period t .

$$import_dependence(t) = \sum_{(m \in sim)} r_supply(m, t) / \sum_{(m \in s)} r_supply(m, t) \quad (4.48)$$

where $import_dependence(t)$ is the share of imported energy sources at period t .

4.1.8.10. Scenario Constraints. The constraints in this category are developed with the purpose of possible scenario applications (e.g. limiting import dependence or coal consumption, forcing the consumption in the transport sector, etc.). They are not active in a standard BUEM model but are implemented in scenario or sensitivity analysis.

Most of these constraints are constructed on specific technology or energy source sets. Thus, according to scenario requirements, associated technology and energy source sets are formed as well. A few examples of possible scenario constraints are discussed in this subsection.

(i) *Restrictions on Total Imports of Energy Sources*: Such constraints can be used to restrict the total import of any energy source at period t .

$$\sum_{\substack{m \in (\text{set of technologies} \\ \text{importing } e)}} r_tsep(m, t) \quad (4.49)$$

$$\leq import_share(e, t) * \sum_{\substack{m \in (\text{set of technologies} \\ \text{supplying } e)}} r_tsep(m, t)$$

where $import_share(e, t)$ is the share of import in total supply of energy source e at period t .

(ii) *Support of a Particular Energy Source Usage in a Sector*: Such constraints can be used to force the consumption of energy source e at sector f (e.g. applying a lower bound to the total usage of electric vehicles in the transport sector).

$$\sum_{\substack{m \in (\text{set of sector } f \\ \text{technologies processing } e)}} \text{inpent}(m, e, t) * cf(m, t) * r_cap(m, t) \quad (4.50)$$

$$\geq \alpha(t) * \sum_{m \in (\text{set of sector } f \text{ technologies})} \text{inpent}(m, e, t) * cf(m, t) * r_cap(m, t)$$

where $\alpha(t)$ is the share of sector f technologies processing energy source e at period t .

4.1.9. Calibration of a Typical Energy Model

The model ought to be calibrated for an initial year, which is a past period, over which the system has no freedom, and for which the levels of variables are all fixed at their historical values. The main variables, which are calibrated to match the initial year data, can be energy consumptions, capacities, resource supply levels, and carbon emissions. Model outputs of the initial year should match the realized data within a tolerance limit. Lower, fixed, or upper bounds can be used to bring the output into tolerance limits. Cost parameters (such as operating and maintenance costs, investment costs,) and performance characteristics (such as annual availability factor/capacity utilization factor, input/output requirements, lifetime, efficiency, and emission factors) can also be adjusted to match the realized cost structures and fuel consumptions. The calibration procedure also affects the decisions for future periods. For example, existing capacities of some of the technologies at and after the initial period can be set at the beginning of the planning horizon.

4.1.10. Environmental Mechanisms of a Typical Energy Model

The mechanisms relating environmental impacts (especially GHGs emissions) with energy activities are fully integrated into the model. The objective function considers environmental costs as well. These costs can be applied either as a cost of each ton of

emission or as a penalty cost on each ton of excess emissions (emissions, which go beyond the determined emission levels, are considered as excess emissions). Policy measures dedicated to environmental impacts can affect the optimization process and change fuel and technology policies (e.g. more investment into renewable energy sources or Carbon Capture and Storage technologies (CCS)). On the other hand, global emissions are partitioned into sectoral levels and so the abatement measures can be all applied on sectoral scale as well. The possible policy instruments for the environment, as considered in the model, are:

- Sectoral reduction (in the form of a limitation constraint on emissions by sector);
- Global reduction (in the form of a limitation constraint on total emissions);
- Penalty measures on global emissions (in the form of a penalty cost application on total emissions);
- Penalty measures on sectoral emissions (in the form of a penalty cost application on emissions of a specific sector);
- Penalty measures on excess emissions ((in the form of a penalty cost application on excess emissions, in which case the permitted emission levels are exogenously given).

A macro model extension for environmental impacts is also considered. This time a non-linear penalty application is applied as a power of national consumption.

4.2. The Macro Model

4.2.1. General Structure of the Macro Model

BUEM Bottom-up modeling framework itself evaluates the energy sector in a very rich technological detail. However, this part does not address the interactions between energy sector and rest of the economy. There is not any relationship linking the energy demand and the energy prices. Instead, all demand services are treated as exogenous parameters to be inputted to the system by the user. However, in the real world, demand services are severely affected from price changes. It is expected that increase in prices

decreases the demand for energy services. Therefore, an extension of bottom-up module, namely macro module, is developed with the intension of generating demand services endogenously under the effects of energy prices.

Demands are produced in a single sector production function whose primary inputs are “Energy”, “Capital”, and “Labor”. This module has been designed as a non-linear optimization model based on consumption maximization.

The bottom-up/macro model solution algorithm involves two separate decision processes: (i) the least-cost choice of technologies and fuels in Bottom-up module, (ii) maximum consumer utility level in Macro module. The algorithm to solve the linked bottom-up/macro model is a straightforward iteration, beginning with a bottom-up solution for the initial year. Based on the solution of bottom-up model, energy system costs and aggregate energy supply levels are passed to the macro module. With this information, costs and supply quantities of macro model are calibrated. Calibration is done by defining a $\pm 5\%$ interval on each variable passed from bottom-up module. Bottom-up module, on the other hand, simultaneously uses the demands coming from the macro module. The two modules are calibrated in each period in a way that final energy demands and energy costs are consistent in two modules. The two models are solved iteratively, until the end of the planning horizon. A schematic overview of the algorithm is presented in Figure 4.5.

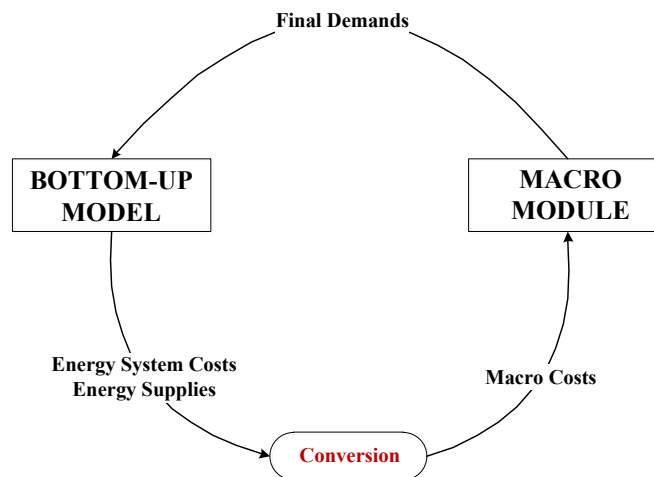


Figure 4.5. Schematic overview of bottom-up/macro model relations.

4.2.2. Functional Form of the Macro Model

The macro module links the general economic consideration with the energy sector considerations through the following non-linear optimization problem. Utility is maximized subject to a national production function and other economic considerations. National production is represented by a single sector general economy, which brings a constant elasticity of substitution among capital, labor and energy alternatives. The main variables of the macro module that are calibrated for initial year are consumption, national production, investment, and capital. The utility function is the discounted sum of the logarithms of total consumption over the planning horizon. Consumption, however, is divided into two parts: (i) Consumption on energy goods, (ii) Consumption on non-energy goods. Consumption on energy goods comes from the bottom-up module. This cost item represents the total expenses for operation and maintenance of final demand technologies in the bottom-up system.

$$\max U = \sum_t udf(t) * \ln(C_E(t) + C_{NE}(t)) \quad (4.51)$$

where

- $C_E(t)$: level of consumption on energy goods at period t ,
- $C_{NE}(t)$: level of consumption on non-energy goods at period t ,
- U : utility of overall planning horizon,
- $udf(t)$: utility discount factor at period t .

Decay and growth limitations on consumption on non-energy goods between the consecutive periods are exogenously placed into the module.

$$C_{NE}(t) * (1 - \beta_d(t)) \leq C_{NE}(t + 1) \leq C_{NE}(t) * (1 + \beta_g(t)) \quad (4.52)$$

where

- $\beta_{d/g}(t)$: maximum decay/growth rate of consumption on non-energy goods between the period t and $t + 1$.

Production is related with consumption, investment, net import (which is import minus export) and annual energy cost based on the Simple Keynesian Production Function.⁵ Energy cost is passed from bottom-up module. This cost item represents the total undiscounted annual energy cost of bottom-up system. However, to comprehend the function, it is represented as three separate parts of the production: (i) operation and maintenance costs of final demand technologies of the bottom-up system, which is defined as consumption on energy, (ii) total undiscounted and annualized investment cost of the bottom-up system, which is defined as investment on energy, (iii) total undiscounted annual energy cost of the bottom-up system excluding investment costs plus operation and maintenance costs of final demand technologies, which is defined as energy cost. This way, a possible double counting in the Keynesian function is eliminated.

$$Y(t) = C_E(t) + C_{NE}(t) + INV_E(t) + INV_{NE}(t) + \Delta IE(t) + EC(t) \quad (4.53)$$

where

- $EC(t)$: level of energy cost excluding energy investment costs plus operation and maintenance costs of final demand technologies at period t ,
- $INV_E(t)$: level of energy investment at period t . This cost item is the total undiscounted annualized investment cost of the bottom-up system.
- $INV_{NE}(t)$: level of non-energy investment at period t ,
- $\Delta IE(t)$: level of net import at period t ,
- $Y(t)$: level of production at period t .

The single sector production function is a CES function. The first term within the brackets is a value added aggregate, in which capital and labor may be substituted directly for each other in Cobb-Douglas fashion. The second term indicates that the energy supply services (e.g. electricity, coal, natural gas, etc.) at period t , defined and determined in the bottom-up module, may also substitute for one another. This substitution includes two decision mechanisms: (i) Energy supplies other than electricity may be substituted for each

⁵ The simple Keynesian consumption function: $C_t = c_0 + c_1 Y_{t-1}$, where C_t is total consumption, c_0 is autonomous consumption ($c_0 > 0$), c_1 is the marginal propensity to consume ($0 < c_1 < 1$), and Y_t is gross output.

other in CES fashion, (ii) Electricity and other energies (which include the energy supplies other than electricity) may be substituted directly for each other in a Cobb-Douglas fashion. Finally, the two aggregates (labor-capital on one hand, and energy supplies on the other) may substitute for each other, although with a different elasticity than the lower level substitutions of labor and capital or electricity and other energies. The exponents α_1 and α_2 are interpreted as the value share of capital and electricity in the value added aggregate, respectively. The exponent ρ_1 is directly related to the elasticity of substitution between the two aggregates (i.e. capital-labor and electricity-other energies pairs) via. In the same fashion, the exponent ρ_2 is directly related to the elasticity of substitution between the energy supplies other than the electricity. a , bel , and $be(e)$ are distribution parameters.

$$Y(t) = \left(a * (K(t)^{\alpha_1} * L(t)^{(1-\alpha_1)})^{\rho_1} + bel * (ELC(t)^{\alpha_2 \rho_1} * (\sum_e be(e) * E(e, t)^{\rho_2})^{(1-\alpha_2)\rho_1})^{\left(\frac{1}{\rho_1}\right)} \right) \quad (4.54)$$

where

- $E(e, t)$: production level of energy source e at period t ,
- $ELC(t)$: generation of electricity at period t ,
- $K(t)$: level of capital at period t ,
- $L(t)$: level of labor force at period t .

There is no endogenous dynamics for labor force in the macro module. Labor is exogenously specified to the model as an index with growth rate $growth_l(t)$.

$$L(0) = 1, L(t + 1) = (1 + growth_l(t))^{nyrsper} * L(t) \quad (4.55)$$

The underlying relationship between new investment and the existing capital stock, is given by the Capital Accumulation Function (Philippidis *et al.*, 2011). This relation ensures that current period's capital is equal to depreciated capital of the previous year plus the moderate of new investments of the current and previous periods.

$$K(t + 1) = K(t) * (1 - \partial)^{nysper} + \frac{nysper}{2} * (INV(t) + INV(t + 1)) \quad (4.56)$$

where

$$INV(t) = INV_E(t) + INV_{NE}(t) \quad (4.57)$$

Investment on energy comes from the bottom-up part. On the other hand, decay and growth limitations on non-energy investments between the consecutive periods are exogenously placed into the module.

$$INV_{NE}(t) * (1 - \theta_d(t)) \leq INV_{NE}(t + 1) \leq INV_{NE}(t) * (1 + \theta_g(t)) \quad (4.58)$$

where

- $\theta_{d/g}(t)$: maximum decay/growth rate of non-energy investment between the periods t and $t + 1$.

The links between the bottom-up and macro modules are set in several critical items such as demand and annual energy costs. Energy demands generated in the macro module provide the physical link from macro to the bottom-up module and energy costs produced in the bottom-up module provide the physical link from bottom-up to macro module.

5. COMPARISON OF THE BUEM FRAMEWORK WITH THE MARKAL FRAMEWORK

The basic philosophy behind the BUEM approach is mostly inspired by the MARKAL modeling framework. The MARKAL system is a large scale bottom-up energy modeling system, enabling the consideration of many aspects of the energy sector. However, its data requirements are immense. In most cases, the user has to compile extensive data sets that most likely will contain details that neither be needed in the policy analysis nor can be reliably assembled, but have to be provided in order to run the model. Such unused data and relations amplify the size of the model, which results in increasing memory requirements and computational challenges on model runs and increasing complexity and difficulty on result analysis. In addition, the modeling flexibility and functional forms provided in some of the relationships may lead to unnecessary mathematical complexity, misunderstandings, and misrepresentations. Enabled detail is mostly not necessary. From this perspective, in the BUEM framework, relations are represented in a simplified and straight forward fashion. Moreover, because of the pre-defined rigid structures or interfaces, implementation or representation of many other relations that may be required for a through policy analysis may be quite difficult (if not impossible) in the MARKAL framework. The BUEM framework, on the other hand, provides an open structure, in which the modifications of the relationships and implementations of the specific scenario requirements are possible. This way, policy analysis becomes more transparent, flexible, and simplified.

5.1. Comparison of the Structures

A major differentiation between the two approaches is in the representation of the electricity sector. The whole electricity sector is structured in a less detailed fashion in the BUEM framework. Like any other energy source, there is a set for the technologies producing electricity and another set for the technologies consuming electricity. The structure is similar for LTH. On the other hand, the set (of MARKAL) including those technologies generating both electricity and LTH is eliminated. In addition, seasonal time

division of electricity/LTH technologies is not used and only day/night division is maintained. This way, the number of sets, variables, and constraints are reduced.

Another difference is in the scope of “Conversion Technologies” in the two frameworks. In MARKAL, conversion terminology is used only for the technologies generating electricity and LTH. Process technologies, the other intermediate technologies that change the form of the energy source, are considered as a separate set. In other words, the Conversion Technology set of the MARKAL framework only includes electricity and LTH generation technologies. Compared to this, in the BUEM framework, all technologies transforming an energy form into another energy form are named as Energy Conversion Technologies. Electricity generation, LTH generation, and process technologies are all grouped under this category (This difference explains the changes in divisions and set names in Table 5.1 (e.g. *cp* replacing with *p*)). On the other hand, divisions of supply and demand technologies are similar in the two frameworks. For simplicity of comparison, similar set letters and variable abbreviations are used in the two frameworks (as can be seen from Table 5.1 and 5.2).

Table 5.1. Comparison of the technology sets in the MARKAL and the BUEM frameworks.

MARKAL FRAMEWORK		BUEM FRAMEWORK	
Supply Technologies:	<i>s</i>	Supply Technologies:	<i>s</i>
Import Technologies	<i>sim</i>	Import Technologies	<i>sim</i>
Mining/Extraction Technologies	<i>smn</i>	Mining/Extraction Technologies	<i>smn</i>
Renewable Technologies	<i>srn</i>	Renewable Technologies	<i>srn</i>
Export Technologies	<i>sex</i>	Export Technologies	<i>sex</i>
Conversion Technologies:	<i>c</i>	Energy Conversion Technologies:	<i>c</i>
Electricity Generation Tech.	<i>ce</i>	Electricity Generation Tech.	<i>ce</i>
LTH Generation Tech.	<i>ch</i>	LTH Generation Tech.	<i>ch</i>
Electricity/LTH Generation Tech.	<i>ceh</i>	(eliminated)	
Process Technologies:	<i>p</i>	Process Technologies	<i>cp</i>
Demand Technologies:	<i>d</i>	Demand Technologies:	<i>d</i>

Since the BUEM framework considers electricity and LTH in the group of standard energy sources, special variables (of MARKAL), associated with electricity and LTH generation (such as $r_{tezy}(ce, w, t)$, $r_{thz}(ch, w, t)$, $r_{tczyh}(ceh, w, t)$) are no longer necessary. Another specific variable (of MARKAL) associated with the production of multiple output technologies ($r_{lout}(p, t)$) is also not used. Thus, the BUEM framework almost halves the number of decision variables, compared to the MARKAL framework (as can be seen from Table 5.2).

Table 5.2. Comparison of the variable sets in the MARKAL and the BUEM frameworks.

MARKAL FRAMEWORK		
	Variable	Description
1	$r_{tsep}(s, t)^*$	Supply Level of Technology s
2	$r_{inv}(k, t)$	Investment Level of Technology $k, k \in c \cup p \cup d$
3	$r_{cap}(k, t)$	Capacity Level of Technology $k, k \in c \cup p \cup d$
4	$r_{act}(p, t)$	Activity Level of Process Technology p
5	$r_{lout}(p, t)$	Level of An Energy Carrier Produced by A Multiple Output Technology p
6	$r_{tezy}(ce, w, t)$	Activity Level of Electricity Generation Technology ce
7	$r_{thz}(ch, w, t)$	Activity Level of LTH Generation Technology ch
8	$r_{tczyh}(ceh, w, t)$	Activity Level of Electricity<H Generation Technology ceh
9	$r_{em}(v, t)$	Emission Level of Emitter v
BUEM FRAMEWORK		
	Variable	Description
1	$r_{supply}(m, t)^*$	Supply Level of Technology $m, m \in s$
2	$r_{inv}(m, t)$	Investment Level of Technology $m, m \in c \cup d$
3	$r_{cap}(m, t)$	Capacity Level of Technology $m, m \in c \cup d$
4	$r_{act}(m, t)$	Activity Level of Technology $m, m \in c$
	(eliminated)	
	(eliminated)	
	(eliminated)	
	(eliminated)	
5	$r_{em}(v, t)$	Emission Level of Emitter v

* r_{tsep} is represented by r_{supply} in the BUEM framework.

The described simplifications also reduce the number of constraints in the optimization structure (as can be seen from Table 5.3). The same general relations are

maintained with fewer constraints. The number of constraint sets comes down from 28 to 17. However, the size of the reduction is greater regarding the number of technologies and energy sources since constraints are constructed over technologies and energy sources (e.g. a constraint defined over energy source set is produced for each energy source in the set). Thus, reduction in number of constraints might be on the order of ten-thousands or more in an application. The elimination and simplification procedure of the relationships are discussed in detailed in the following subsections. The BUEM framework is also more suitable for the construction of “user-defined constraints” (which are usually inactive in the base modeling but can be very useful in scenario applications) and accounting/reporting relationships (which are not related with the optimization procedure but simplify and accelerate the reporting and analysis processes). The filtering mechanism which is used in combination with the user-defined constraint option allows building new sets and new constraints. The constraint structure is in a typical form. These mechanisms are discussed in the subsequent parts of this section.

Table 5.3. Comparison of the Relationships in the MARKAL and the BUEM frameworks.

MARKAL Framework		BUEM Framework	
1	Discounted Total System Cost	1	Discounted Total System Cost
2	Discounted and Annualized System Costs	2	Discounted and Annualized System Costs
3	Balance Constraints (for regular energy carriers)	3	Balance Constraints (for all energy sources)
4	Balance Constraints (for electricity)		(eliminated)
5	Balance Constraints (for LTH)		(eliminated)
6	Periodic Capacity Constraints (for process technologies)	4	Periodic Capacity Constraints (for all technologies)
7	Periodic Capacity Constraints (for conversion technologies)		(eliminated)
8	Periodic Capacity Constraints (for demand technologies)		(eliminated)
9	Capacity Decay/Growth Constraints	5	Capacity Decay/Growth Constraints
10	Supply Decay/Growth Constraints	6	Supply Decay/Growth Constraints
11	Demand Satisfaction Constraints	7	Demand Satisfaction Constraints
12	Activity-Capacity Relation Constraints (for standard energy carriers)	8	Activity- Capacity Relation Constraints (for all energy sources)
13	Activity-Capacity Relation Constraints (for electricity)		(eliminated)
14	Activity-Capacity Relation Constraints (for LTH)		(eliminated)

Table 5.4. Comparison of the relationships in the MARKAL and the BUEM frameworks
(cont.).

15	Lower, fixed, upper bounds on technology activity	9	Lower, fixed , upper bounds on technology activity
16	Lower, fixed, upper bounds on annual output from a conversion technology		(eliminated)
17	Lower, fixed, upper bounds on technology capacity	10	Lower, fixed , upper bounds on technology capacity
18	Lower, fixed, upper bounds on technology investment	11	Lower, fixed , upper bounds on technology investment
19	Lower, fixed, upper bounds on energy carrier supply	12	Lower, fixed , upper bounds on energy source supply
20	Cumulative supply limit	13	Cumulative supply limit
21	Activity limitation on a multiple output technology	14	Activity limitation on a multiple output technology
22	Efficiency of flexible output technologies		(eliminated)
23	Baseload Constraints for electricity production	15	Baseload Constraints for electricity production
24	Electricity Peak Reserve constraint	16	Electricity Peak Reserve Constraint
25	LTH Peak Reserve constraint		(eliminated)
26	Total Emissions	17	Total Emissions
27	Annual reservoir management for hydro plants		(eliminated)
28	Seasonal reservoir management for hydro plants		(eliminated)

As a consequence of those differentiations in the set, variable, and constraint structures, the parameter set changes as well. Some of the parameters are either eliminated (e.g. the ones specific to coupled electricity and LTH generation technologies) or embedded into other parameters (e.g. detailed cost parameters). This way, the data requirements of the BUEM framework is greatly reduced, compared to the MARKAL approach. These parameters are discussed in the following subsections in detail.

5.2. Comparison of the Functional Forms

The BUEM framework improves the modeling system and changes the structure based on the critical issues listed below:

- Rarely-used relations such as reservoir management in hydro plants are eliminated,

- Existing relations are simplified,
- New relations are added,
- Rarely-used parameters are either eliminated or embedded into other parameters; so a new parameter structure is created.

In the following subsections, relation/constraint formulations of the two frameworks are compared in detail.

5.2.1. Cost Relationships

5.2.1.1. Annual Supply Cost. The BUEM framework's annual supply cost function is much simpler than that of the MARKAL approach. Unit delivery costs of inputs to supply technologies (*delivent*) are eliminated and embedded into the unit supply cost parameter (*scost*). Sign parameter (*sign*) which is used to determine whether a technology is an export or import, is also not used. In the MARKAL framework, if the sign parameter is negative, then it is an export technology with a minus cost. If the sign parameter is positive, then it is an import technology with an additional cost to the objective function. On the other hand, in the BUEM framework instead of having an extra parameter, unit supply cost of export technologies are simply assigned negative values. This way, the associated summations in the cost function (of MARKAL) are eliminated.

In a similar manner, transform and distribution costs of imported electricity are also embedded into the unit supply cost in the BUEM framework (while these costs, namely *etranom* and *edistom*, are explicitly addressed in the annual supply cost function of MARKAL).

Moreover, effects of the simplification in the electricity sector, which is, briefly, the elimination of three related variables, are clearly visible on the annual supply cost formulation. In the MARKAL framework, three different cost items, associated with the three different generation types, are available. In addition, MARKAL considers that one unit of electricity is generated per unit activity of electricity generation plants. Thus, there is no parameter associated with the output generation (*outent*). This case is similar for the

plants whose single output is LTH. Compared to this, an output generation parameter is defined for each electricity or LTH generation technology in the BUEM framework.

All these changes are implemented on both undiscounted and discounted costs.

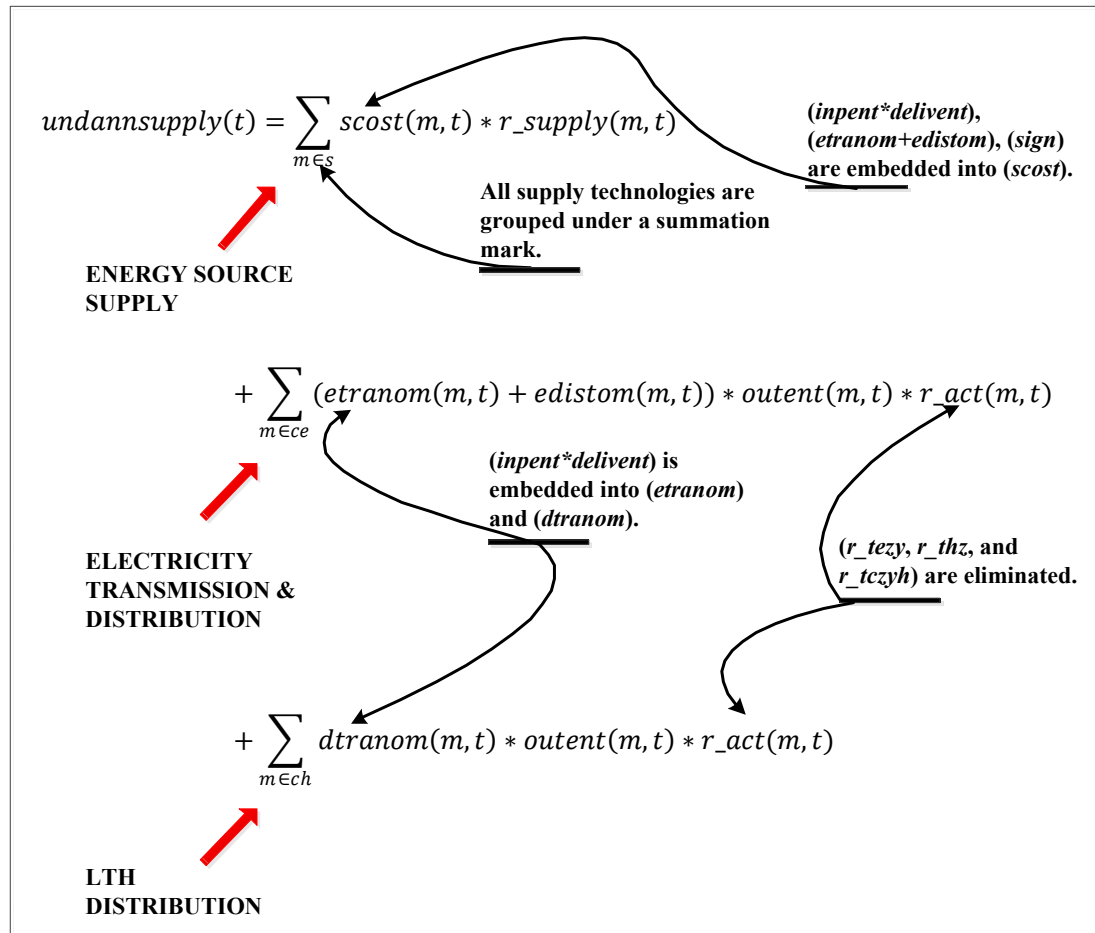


Figure 5.1. Representation of annual supply cost in the BUEM framework.

$$\begin{aligned}
undannsupply(t) = & \sum_{s,d} (scost(s,t) \\
& + \sum_e \underbrace{inpent(s_d,e,t) * delivent(s_d,e,t)) * r_tsep(s,t)}_{\text{embedded into } (scost) \text{ or } (etranom/dtranom)} \\
& + \sum_{s,nd} \underbrace{sign(s) * (scost(s,t) + (etranom(e,t) + edistom(e,t)))}_{\text{eliminated}} \\
& + \sum_e \underbrace{inpent(s,e,t) * delivent(s,e,t)) * r_tsep(s,t)}_{\text{eliminated}} \\
& + \sum_{ce,w} (etranom(e,t) + edistom(e,t)) \\
& + \sum_e \underbrace{inpent(ce,e,t) * delivent(ce,e,t)) * r_tczy(ce,w,t)}_{\text{eliminated}} \\
& + \sum_{ch,z} (dtranom(e,t)) \\
& + \sum_e \underbrace{inpent(ch,e,t) * delivent(ch,e,t)) * r_thz(ch,z,t)}_{\text{eliminated}} \\
& + \sum_{ceh,w} (etranom(e,t) + edistom(e,t) + dtranom(e,t)) \\
& + \sum_e \underbrace{inpent(ceh,e,t) * delivent(ceh,e,t)) * r_tczyh(ceh,w,t)}_{\text{eliminated}}
\end{aligned}$$

grouped under a summation mark
 embedded into *(scost)* or *(etranom/dtranom)*
 eliminated

Figure 5.2. Representation of annual supply cost in the MARKAL framework.

5.2.1.2. Investment Cost. Discounted investment cost item deployed in the MARKAL framework is set to cover salvage costs. Salvage cost is endogenously calculated in the MARKAL framework in a very specific fashion and there is no direct control over it.

The BUEM framework, on the other hand, allows using a similar structure. However, in addition to this, it is also possible for the user to define salvage cost of any technology as an exogenous parameter. Decommissioning cost is also considered through an exogenous parameter (while MARKAL does not include decommissioning cost). This contribution makes the cost structure more realistic.

BUEM Framework:

$$disanninv(t) = \sum_{m \in \cup d} pri_inv(m, t) * r_inv(m, t)$$

salvcost is disaggregated
from priinv.

$$-pridisc(m, t) * salvcost(m, t) * r_inv(m, t)$$

decomcost is added to
priinv.

$$+pridisc(m, t) * decomcost(m, t) * r_inv(m, t)$$

MARKAL Framework:

$$disanninv(t) = \sum_k pri_inv(k, t) * r_inv(k, t)$$

salvcost is
included in priinv.

Figure 5.3. Representation of discounted investment costs in the BUEM and MARKAL frameworks.

Undiscounted costs of the two frameworks are calculated in a similar fashion. The primary difference lies in the treatment and definition of the capital recovery factor (*crf*). The capital recovery factor is a product of technology discount rate, which is used to discount the annual costs of technologies to a user defined year, and lifetime. The MARKAL approach uses a global discount rate for all technologies, unless there is a specific discount rate defined for the technology. Thus, there are two different parameter sheets associated with a technology: (i) one for the global discount rate, (ii) one for the technology specific discount rate. In the BUEM framework, on the other hand, the linkage between the global discount rate and the technology is eliminated and a single technology specific discount rate is defined.

5.2.1.3. Other Operational Cost. In the BUEM framework, unit delivery costs of inputs to energy conversion technologies are eliminated. Such costs are embedded into the variable operational and maintenance costs. In addition, effects of the simplification in the electricity sector (i.e. elimination of the three related variables) are visible on other operational cost formulation as well.

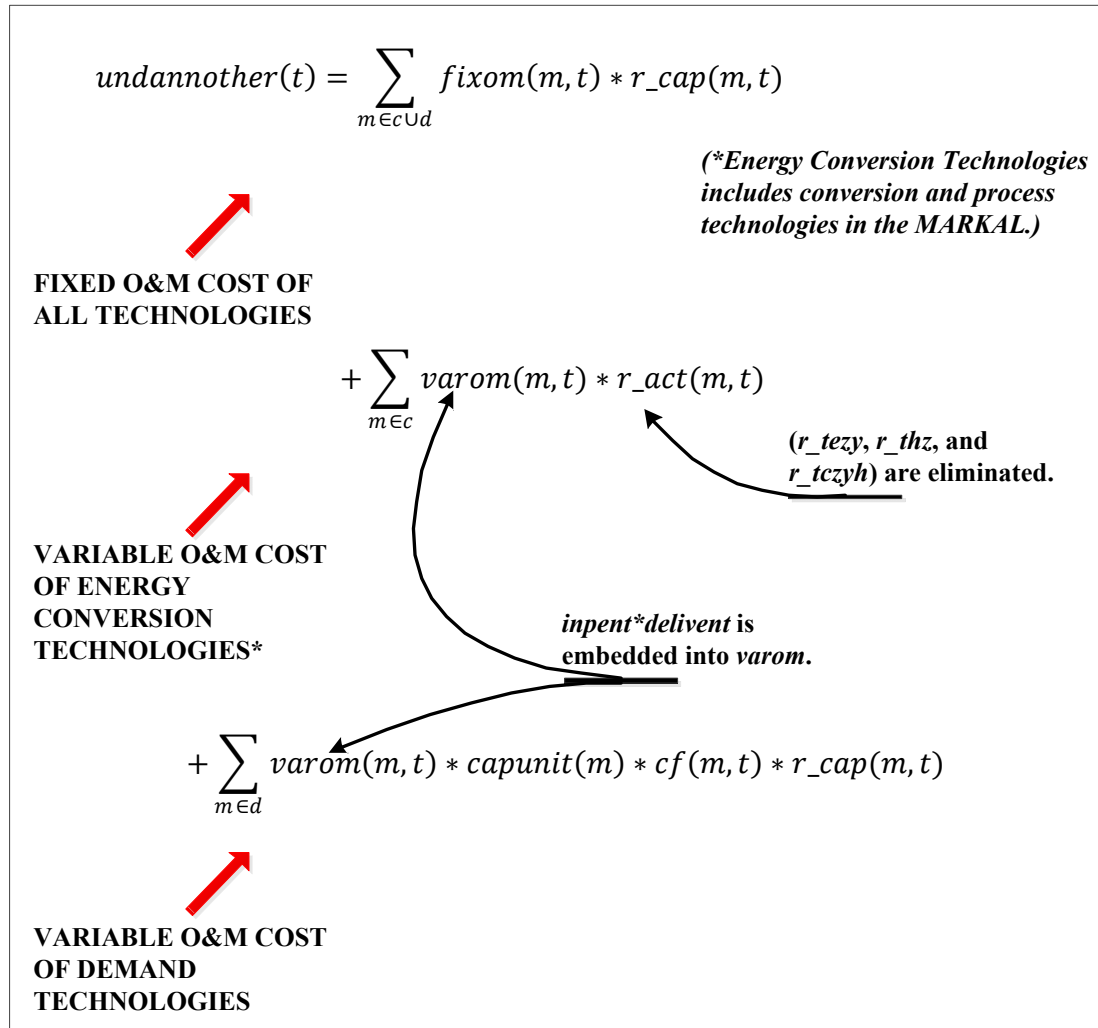


Figure 5.4. Representation of annual other operational cost in the BUEM framework.

$$\begin{aligned}
undannother(t) = & \sum_{p' = p \cup c \cup d} fixom(p', t) * r_cap(p', t) \\
& + \sum_p (varom(p, t) + \sum_e \underbrace{inpent(p, e, t) * delivent(p, e, t)}_{\text{embedded into } varom,} * r_act(p, t)) \\
& + \sum_{ce, w} (varom(ce, t) * r_tezy(ce, w, t)) \\
& + \sum_{ch, z} (varom(ch, t) * r_thz(ch, z, t)) \\
& + \sum_{ceh, w} (varom(ceh, t) * t_tczyh(ceh, w, t)) \\
& + \sum_d capunit(d) * cf(d, t) * (\sum_e \underbrace{maent(d, e, t) * delivent(d, e, t)}_{\text{embedded into } varom,}) \\
& + varom(d, t) * r_cap(d, t)
\end{aligned}$$

**FIXED O&M COST OF
PROCESS, CONVERSION,
AND DEMAND
TECHNOLOGIES**

**VARIABLE O&M COST OF
PROCESS AND
CONVERSION
TECHNOLOGIES**

— embedded into *varom*,

- - - eliminated.

**VARIABLE O&M COST OF
DEMAND TECHNOLOGIES**

Figure 5.5. Representation of annual other operational cost in the MARKAL framework.

5.2.2. Balance Constraints

Balance relations are also treated in a simplified fashion in the BUEM framework (compared to the MARKAL). As a result of the simplification in the electricity sector, the three electricity related variables are restructured under the activity variable. The multiple output technology variable, r_lout , is eliminated and embedded into the activity variable as well (this elimination is discussed later in this section). In addition, energy source production of demand technologies is considered insignificant and therefore removed from the relationship. In other words, the parameter representing any usable energy output produced by demand devices is eliminated. This is because of the fact that this kind of production is very rare, comparatively insignificant, and specific to special circumstances.

Moreover, while the MARKAL approach uses a different parameter representation for the input requirements of demand devices (*maent*), in the BUEM framework a single input parameter (*inpent*) is used for all system technologies. This way, another parameter sheet of the MARKAL is eliminated. The MARKAL framework also allows differentiation in efficiency rates of new investments and residual capacities (of demand technologies). However, since the newly invested capacity transforms into cumulative capacity after a period, this treatment ends up contributing to modeling complexity without providing significant representation power (nor precision in results). On the other hand, the BUEM framework does not consider different efficiency rates for new and residual capacity usages (instead, alternative technologies with new efficiency rates may be enabled in an application).

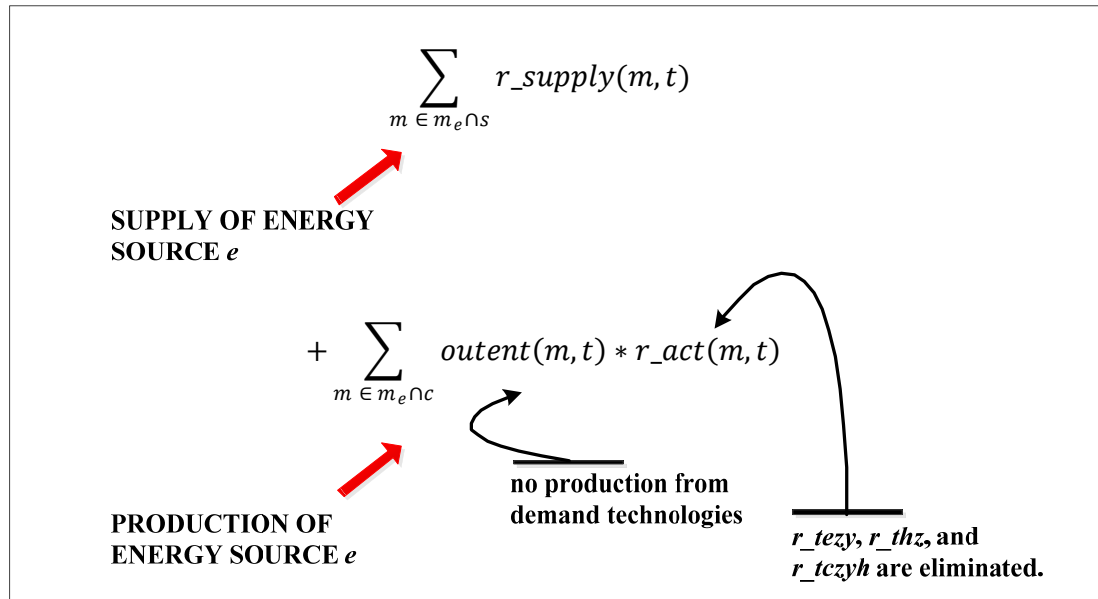


Figure 5.6. The balance constraint of the BUEM framework: the production side.

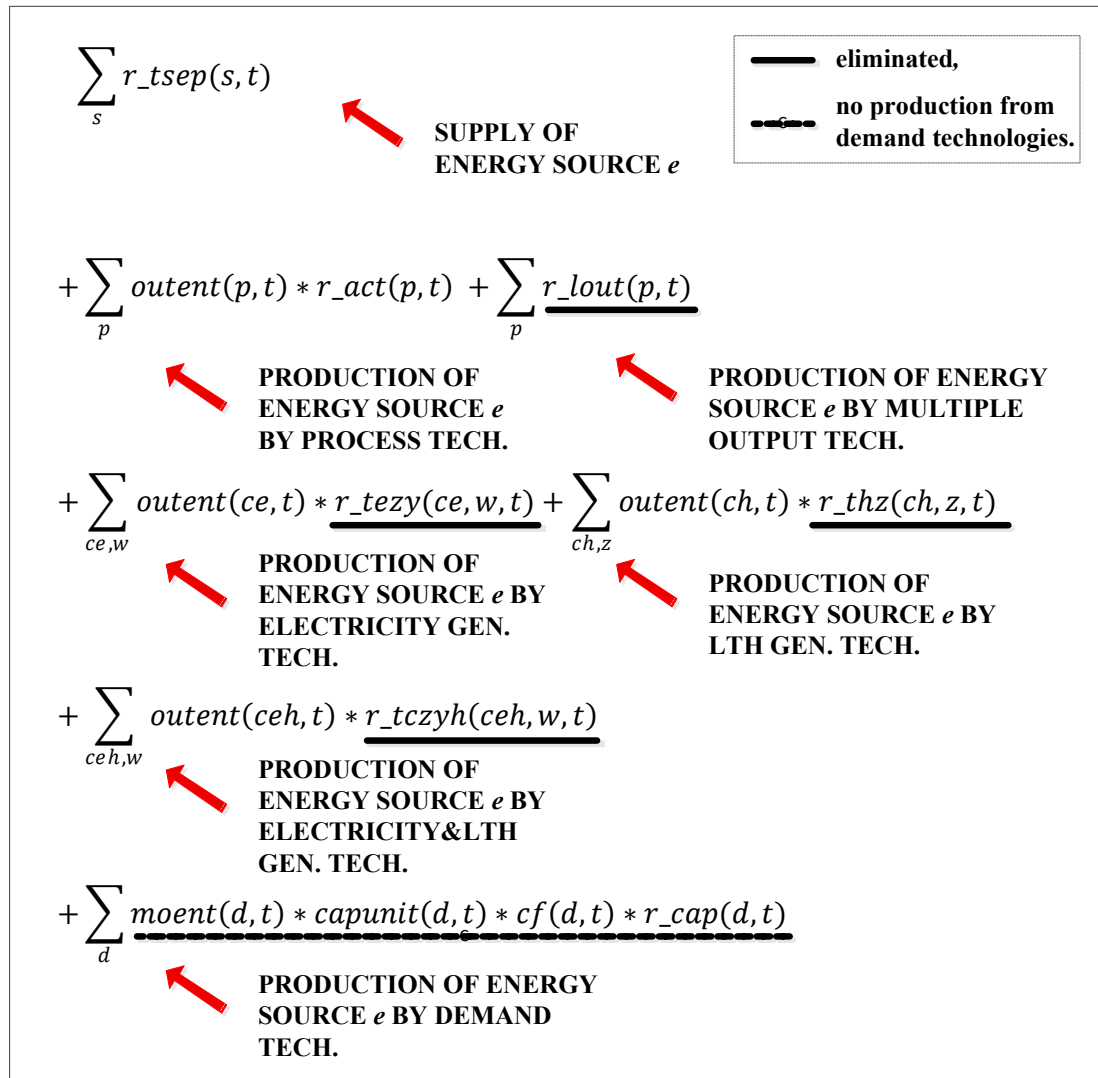


Figure 5.7. The balance constraint of the MARKAL framework: the production side.

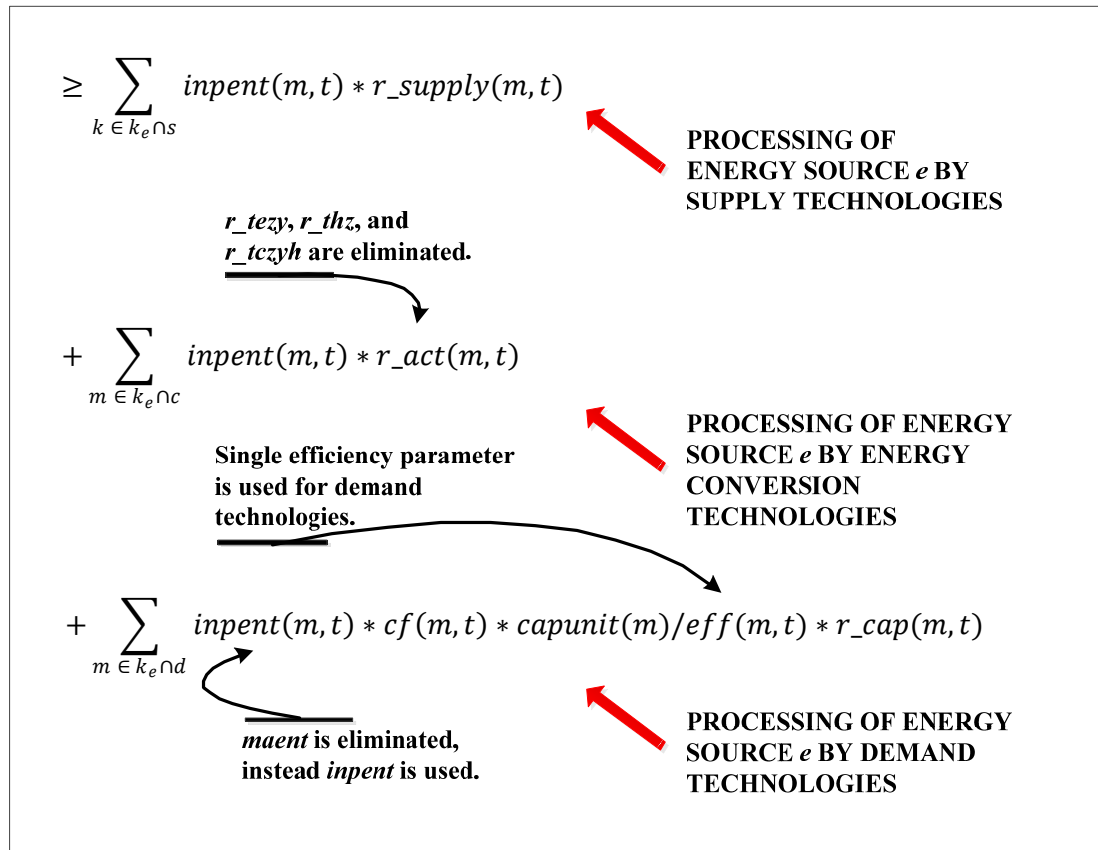


Figure 5.8. The balance constraint of the BUEM framework: the consumption side.

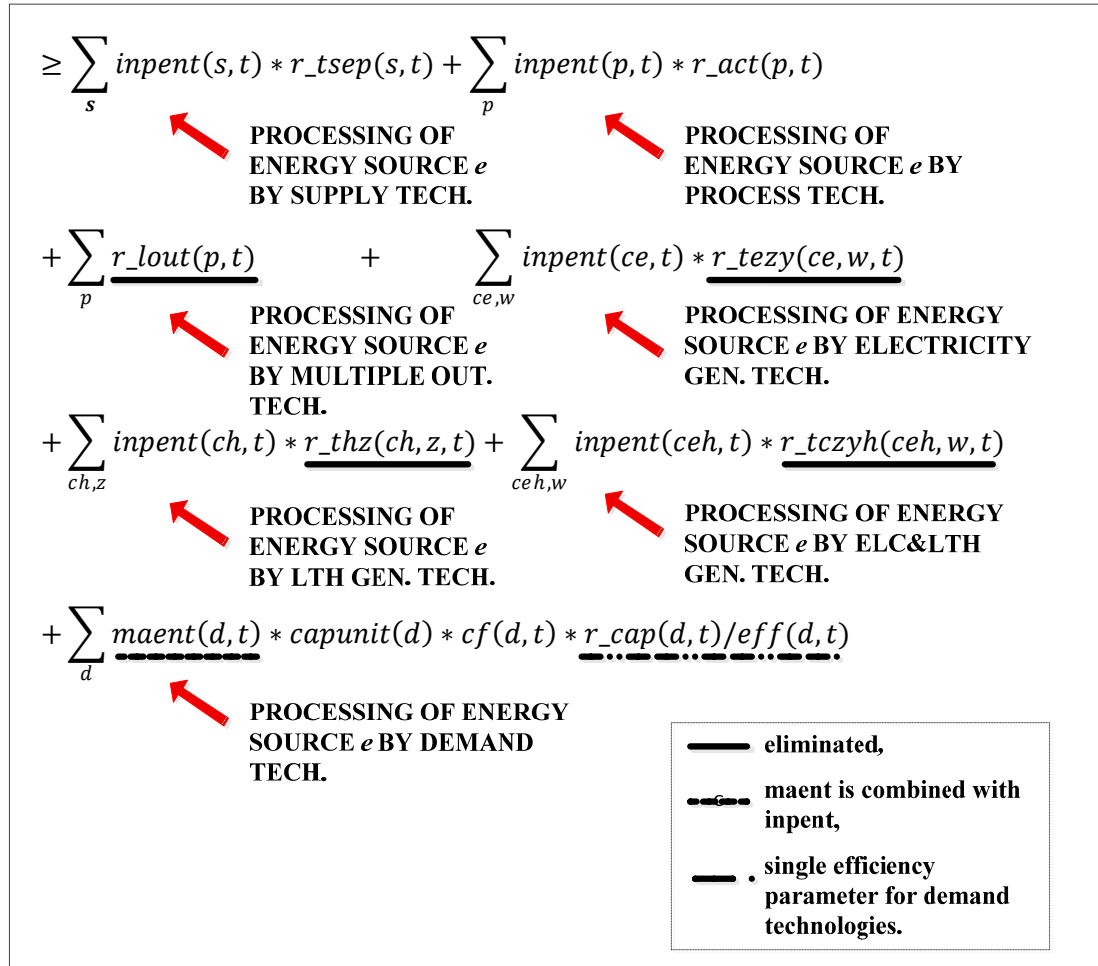


Figure 5.9. The balance constraint of the MARKAL framework: the consumption side.

5.2.3. The Treatment of Periodic Capacity

In both frameworks, what is meant by “Periodic Capacity” is the sum of residual capacity (which is what remains of the available capacity at the beginning of the planning horizon) plus new capacity (which is what remains of capacity additions of previous periods and capacity additions of the current period). The difference between the two approaches is in the availability of capacity depreciation in the BUEM framework. The MARKAL framework does not consider any capacity depreciation. Thus, all invested capacity stays enabled until its lifetime is over. For example, a 2 MB wind energy capacity investment in period one remains at that level for 25 years until its lifetime is over; then, it drops to zero (if there is no other investment up to that period). On the other hand,

depreciation (i.e. reduction of existing capacity due to wear and tear) is allowed in the BUEM framework with a capacity depreciation factor (*cdf*). This factor controls the share of capacity that is to be depreciated.

BUEM Framework:

$$r_cap(m, t) = resid(m, t) + \sum_{h=u_m}^t (r_inv(m, h) - cdf(m) * r_inv(m, h) * (t - h) * \frac{nyrsper}{life(m)})$$

cdf is added.

MARKAL Framework:

$$r_cap(k, t) = \sum_{h=t_k'}^t r_inv(k, h) + resid(k, t)$$

* no capacity depreciation; full capacity is used until the technology life is over.

Figure 5.10. Representation of periodic capacity in the BUEM and MARKAL frameworks.

5.2.4. The Treatment of Activity-Capacity Relations

Since the activity variables of the MARKAL framework's electricity sector technologies are embedded into a single activity variable in the BUEM framework, number of constraints structuring the activity-capacity relation decreases to one. In the MARKAL framework, four different structures, representing the same relation, are used depending on the technology type (i.e. process, electricity, LTH, and electricity/LTH generation technologies) as can be seen from Figure 5.11. In addition, the electricity/LTH generation variables are defined for individual time segments. This means that activity-capacity constraint set of an electricity generation technology (the constraint defined for the set *ce* in Figure 5.11) actually has six members, while the activity-capacity constraint set of a LTH generation technology (the constraint defined for the set *ch* in Figure 5.11) has three

members. On the other hand, the BUEM framework uses only one constraint for the same structural representation. This relationship ensures that activity level of any energy conversion technology in a period cannot exceed its available capacity in that period. In addition, since division of activity variables (according to time segments) are eliminated, number of constraints structuring the activity-capacity relation decreases to one.

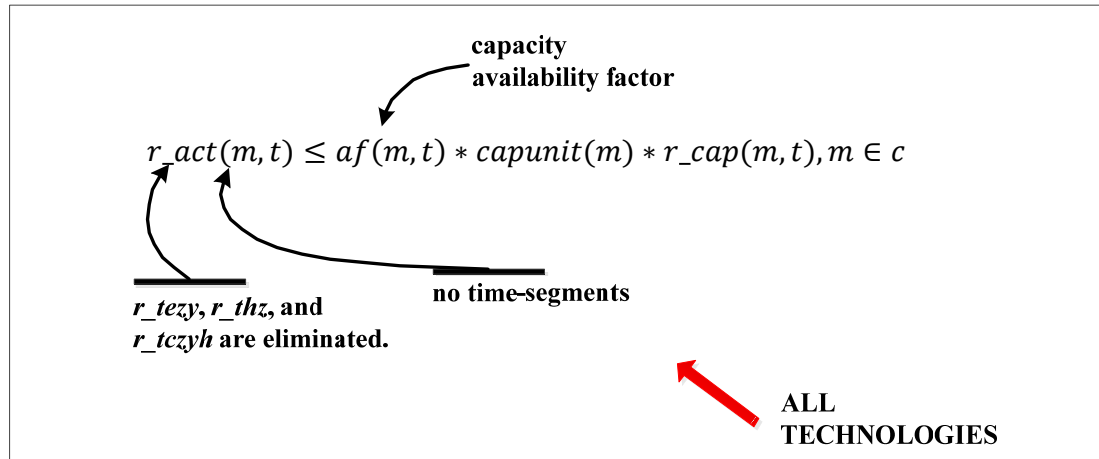


Figure 5.11. Representation of activity-capacity relations in the BUEM framework.

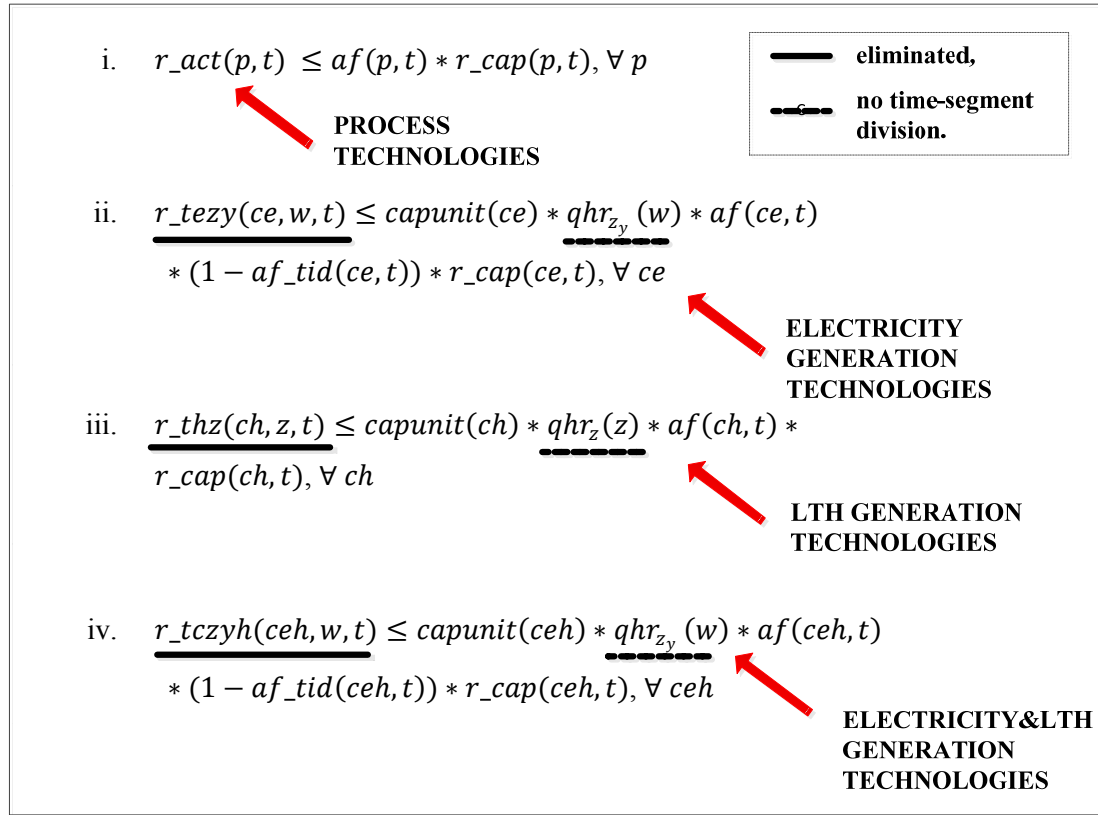


Figure 5.12. Representation of activity-capacity relations in the MARKAL framework.

5.2.5. The Treatment of Multiple Output Technologies

Operation of multiple output technologies are associated with two different decision variables in the MARKAL framework; (i) one representing the level of energy carrier produced by a specific multiple output technology ($r_{lout}(k, e, t)$) (ii) one representing the activity level of the multiple output technology ($r_{act}(k, t)$). Since the first variable is not used in the BUEM structure, a new functional form is created. Two functions of the MARKAL modeling framework are aggregated into a single function. The MARKAL framework, initially defines the production level of an energy carrier ($r_{lout}(k, e, t)$) as equal to the amount of the energy carrier that the technology is actually outputting ($outent(p, e, t) * r_{act}(p, t)$). Then, the total energy carrier production from the technology is bounded with a limiting factor of the activity. The BUEM framework, on the other hand, use the production level ($r_{lout}(k, e, t)$) definition of the first relationship of MARKAL (i.e. $outent(p, e, t) * r_{act}(p, t)$) in the second relation (as can be seen from

Figure 5.13). This way, the two constraints of MARKAL framework is combined into one constraint.

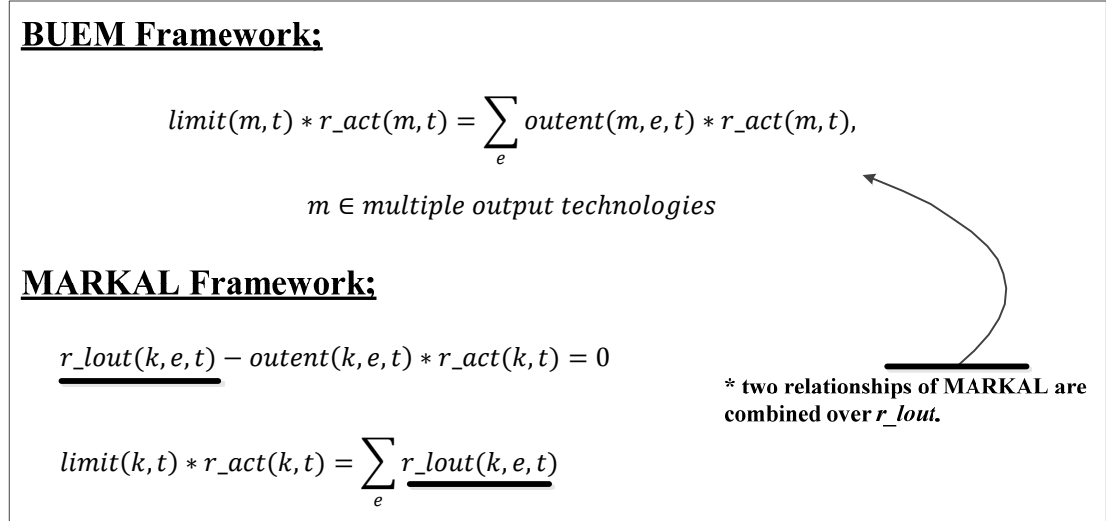


Figure 5.13. Treatment of multiple output technologies in the BUEM and MARKAL frameworks

5.2.6. Treatment of Baseload and Peaking Requirements in Electricity Production

The simplification in the BUEM framework has its greatest impact on electricity baseload and peaking requirements. Eliminations of the three electricity/LTH related variables, the associated parameters (lm, ce_h) and the time segment division of activity variables decrease the complexity of the functional forms and ease their interpretations. As can be seen from Figure 5.14 and 5.15, activity of baseload power plants are grouped under the general activity variable of the BUEM framework. The night time share parameter ($qhr_n(m, t)$) of electricity generation technologies is used to obtain the night time production level of those technologies (instead of night time activity variables ($r_{tezy}(ce, z, 'N', t)$ and $r_{tczyh}(ce_h, z, 'N', t)$, where N indice represents the “night”) of the MARKAL framework). On the other hand, seasonal share of the activity is not tracked and is not used in the BUEM framework.

In addition, since the activity variable multiplied by the output parameter ($outent(p, e, t) * r_{act}(p, t)$) gives the electricity generation level of a technology, there is no need to use the specific parameters of coupled electricity/LTH generation technologies of the MARKAL that define the electricity loss per unit of heat gained (i.e. elm, ceh). Moreover, the BUEM framework does not consider imported and exported electricity in this relationship (while the MARKAL does). In other words, the BUEM framework only features the electricity generated and consumed in the system, while constructing the baseload relation. As a result of all these differences, number of summation marks at both sides of the relationship decrease to one.

$$\sum_{m \in ce} outent(m, "electricity", t) * qhr_n(m, t) * r_{act}(m, t) * baseload(t)$$

$$\geq \sum_{m \in ce \cap baseload \text{ plants}} outent(m, "electricity", t) * qhr_n(m, t) * r_{act}(m, t)$$

$r_{tezy}, r_{thz},$ and r_{tczyh} are eliminated.

Figure 5.14. Representation of the baseload relation in the BUEM framework.

$$\begin{aligned}
& (1 - \text{baseload}(e, t)) * \text{teent}(e, t) * \text{qhr}_{z_y}(z', N') \\
& * \left(\sum_{s \cap \text{baseload}} r_{\text{tsep}}(s, t) + \sum_{ce \cap \text{baseload}} \underline{r_{\text{tezy}}(ce, z', D', t)} \right) \\
& + \sum_{ceh \cap \text{baseload}} \left(\text{ceh}_{z_y}(ceh, z', D', t) * \left(\frac{1}{\text{elm}(ceh)} - 1 \right) * \underline{r_{\text{tczyh}}(ce, z', D', t)} \right) \\
& \leq \text{teent}(e, t) * \text{baseload}(e, t) * \left(\sum_{s \cap \text{nonbaseload}} \underline{\text{qhr}_{z_y}(z', N')} * r_{\text{tsep}}(s, t) \right. \\
& + \sum_{ce \cap \text{nonbaseload}} \underline{r_{\text{tezy}}(ce, z', N', t)} \\
& + \sum_{ceh \cap \text{nonbaseload}} \left(\text{ceh}_{z_y}(ceh, z', N', t) * \left(\frac{1}{\text{elm}(ce)} - 1 \right) \right. \\
& \left. \left. * \underline{r_{\text{tczyh}}(ce, z', N', t)} \right) \right)
\end{aligned}$$

— eliminated,

~~—~~ eliminated,

— — eliminated.

Figure 5.15. Representation of the baseload relation in the MARKAL framework.

On the other hand, Figure 5.16 and 5.17 define the electricity peaking constraints. The primary difference between the two frameworks in this regard is again due to elimination of electricity/LTH generation variables. As can be seen from the formulations, all the technologies that consume electricity, except supply and demand technologies, are grouped under one summation sign (by realizing the single general activity variable) in the BUEM framework. Since the operating level of supply and demand technologies are represented in similar fashions in the two frameworks, their definitions in the peaking relationship are similar (operating levels of supply technologies are represented by supply levels and the activity of demand technologies are defined as a fixed proportion of the capacity).

$$\begin{aligned}
& teent(e, t) * \left(\sum_{m \in s} peakcon(m, t) * qhr_y(m, t) * r_supply(m, t) \right. \\
& + \sum_{m \in ce} peakcon(m, t) * capunit(m, t) * af(m, t) * qhr_y(m, t) \\
& \left. * r_cap(m, t) \right) \geq \left(\sum_{m \in s} inpent(m, e, t) * qhr_y(m, t) * r_supply(m, t) \right. \\
& + \sum_{m \in c} inpent(m, e, t) * qhr_y(m, t) * r_act(m, t) \\
& + \sum_{m \in d} inpent(m, e, t) * cf(m, t) * qhr_y(m, t) * r_cap(m, t) / eff(m, t) \\
& \left. * (1 + ereserv(t)) \right)
\end{aligned}$$

$\overline{r_tezy, r_thz, \text{ and } r_tczyh}$ are eliminated.

$\overline{maent}$ is eliminated, instead $inpent$ is used.

Single efficiency parameter is used for demand technologies.

Figure 5.16. Representation of the peaking relation in the BUEM framework.

$$\begin{aligned}
& \frac{teent(e,t)}{(1+ereserv(e,t))} * (\sum_s peakcon(s,t) * qhr_{zy}(w) * r_{tsep}(s,t) \\
& + \sum_c peakcon(c,t) * capunit(c) * qhr_{zy}(w) * af(c,t) * r_{cap}(c,t) \\
& \geq \sum_s inpent(s,t) * qhr_{zy}(w) * r_{tsep}(s,t) \\
& + \sum_p inpent(p,t) * qhr_{zy}(w) * r_{act}(p,t) \\
& + \sum_{ce} inpent(ce,t) * \underline{r_{tezy}(ce,w,t)} \\
& + \sum_{ch} inpent(ch,t) * (\frac{qhr_{zy}(w)}{qhrz(z)}) * \underline{r_{thz}(ch,z,t)} \\
& + \sum_d \underline{maent(d,t)} * capunit(d) * cf(d,t) * qhr_{zy}(w) * r_{cap}(d,t)) / \underline{eff(d,t)} .
\end{aligned}$$

~~————~~ eliminated,
~~-----~~ *maent* is combined with *inpent*,
~~— . —~~ single efficiency parameter for demand technologies.

Figure 5.17. Representation of the peaking relation in the MARKAL framework.

5.2.7. Treatment of Additional Constraints and Conditions

5.2.7.1. Environmental Considerations. The environmental considerations can be basically classified in two groups: (i) bound constraints, (ii) penalty cost applications. Bounds can be applied either sectorally or globally and penalties can be applied either on total emissions or excess emissions exceeding a defined level. The MARKAL framework allows sectoral and global bound and tax applications in its base structure. These applications are also practicable in the BUEM framework.

The BUEM framework uses the name “penalty” instead of “tax”. The basic reasoning for this practice is the confusing meaning of the word, tax. Tax is paid by producers or consumers to the government, thereby being a revenue (negative cost) for the government. While in the BUEM framework any taxes or other monetary instruments are

basically treated as tools to “discourage” emissions (i.e. entities that the optimization objective automatically tries to reduce). Accordingly, the term penalty is considered to be more convenient. The BUEM framework also allows penalty measures on excess emissions, which is not possible in the MARKAL framework.

So, the possible environmental policy instruments considered, are:

- Sectoral emission bound constraint (applicable both in the MARKAL and the BUEM frameworks) ;
- Global reduction (applicable both in the MARKAL and the BUEM frameworks);
- Penalty measures on global emissions (applicable both in the MARKAL (under the name of tax) and the BUEM frameworks);
- Penalty measures on sectoral emissions (applicable both in the MARKAL (under the name of tax) and the BUEM frameworks);
- Penalty measures on excess emissions (applicable in the BUEM frameworks).

5.2.7.2. Import Dependence Relationship. The issue and level of import dependence is especially critical for nations or regions that are highly dependent on imports.

Since this issue has a vital importance in the analysis of energy dynamics, it is especially considered the BUEM framework. It is possible to analyze import levels from MARKAL outputs. However, the key terms are not explicitly defined and the user has to calculate the total import level and its ratio to total energy supply outside the model. On the other hand, in the BUEM framework, import dependence level of the system is calculated as a percentage of total supply by an accounting equation. In addition, an import limitation constraint (Import Restriction) is defined as a standard formulation of the framework to restrict the supply from import technologies up to a share of total supply. This constraint is usually implemented in BUEM models for scenario or sensitivity analysis purposes.

5.3. Additional Features of the BUEM and MARKAL Frameworks

The MARKAL framework allows the user to define her/his own constraints in a pre-defined constraint structure (i.e. a typical type of constraint). Those constraints are called “user-defined constraints” and may be used as scenario analysis tools. The constraints are built in the form of limitations equations (lower, fix, or upper bounds) and applied on system technologies. They may be active on a single technology or a set of technologies (which are defined by the user according to technology characteristics). The user defined sets are created by applying filtering mechanisms of the MARKAL framework. In this mechanism, technologies can be filtered according to their names, definitions, or input/output energy carriers. Thus, names and definitions of technologies are important in filtering. For example, all renewable electricity generation technologies may have names starting with “ELCREN” abbreviation or may have definitions capturing the words “renewable” and “electricity”. Then, the user may filter the technologies according to these characteristics.

On the other hand, an example of user-defined constraints might be “at least 30% renewable electricity generation”. Two sets are created through the filtering mechanism; (i) a set of renewable electricity generation technologies (ii) a set of power generation technologies. Then, the user-defined constraint created over those sets is as follows.

$$\sum_{\substack{c \in \text{renewable power} \\ \text{generation plants}}} r_{act}(c, t) - \sum_{\substack{c \in \text{power} \\ \text{generation plants}}} r_{act}(c, t) * 0.3 \geq 0$$

The user-defined constraint option has full practice in the BUEM framework as well. In other words, limitation type of constraints can be applied on any technology or technology sets in the BUEM framework, too. On the other hand, the open structure of the BUEM framework also allows the user to define other types of relations or modify the existing relationships. For example, the user may want to analyze the effects of insulation at residential buildings. In the MARKAL framework, it is not possible to include the insulation cost into the total system cost since insulation cannot be defined as a technology that consume or produce an energy source. Similar difficulties arise for many other non-

energy costs, such as railroad constructions. The open structure of the BUEM framework, on the other hand, provides the flexibility of adding those types of non-energy costs (indirect investments of energy system) to the total system cost. There may also be some incentives from government that the user may want to represent in the model. For example, electricity generation from renewable energy technologies may be encouraged by the government by giving discounts or bonuses. These discounts are difficult to trace in the MARKAL framework. In the BUEM framework, however, they may be included as additional cost items within the total system cost (as discussed in Chapter 4).

6. THE BUEM MODEL APPLICATION FOR TURKEY

A Turkish Energy Sector model (TES-BUEM Model) has been developed on the BUEM framework as a case study analysis. The initial purpose of this model has been the validation of the BUEM framework. However, after the validation, it has been used as a policy analysis tool and run under various scenarios.

Energy sources, technologies, and demand sets of the TES-BUEM model are structured in a way of representing the Turkish energy sector. The associated parameters are organized according to the most updated statistics that are collected over various publicly available sources (such as Turkish Statistical Institute (TSI), various NGOs, industrial corporations, expert views, and so on).

Form this point of view, this section is organized as follows: Section 6.1 summarizes the current energy supply and demand profile of Turkey; Section 6.2 addresses the TES-BUEM model and its data structure in detail; Section 6.3 discusses the validation of the BUEM framework.

6.1. The Current Energy Supply and Demand Profile of Turkey

Turkey's total primary energy supply (TPES) was 4.2 exajoules (EJ) in 2009. From 2006 to 2009, TPES increased on average by 1.6% per year. Fossil fuels accounted for 91.5% of TPES in 2009, with a breakdown of 1.4 EJ coal, 1.3 EJ natural gas, and 1.2 EJ oil (see Figure 6.1). Currently, Turkey depends on imports for 73% of its TPES including for practically all her oil and natural gas needs, and most of her coal needs.

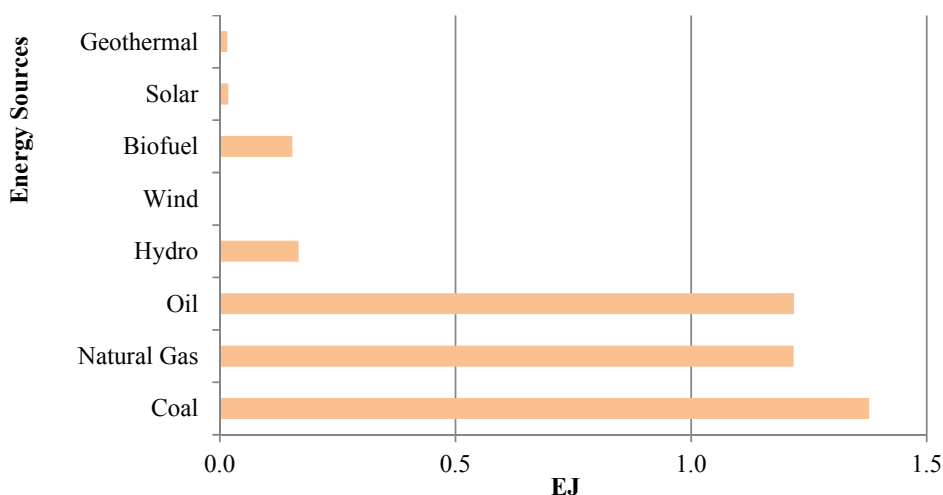


Figure 6.1. Total primary energy supply of Turkey by source.

As a developing country, Turkey's electricity demand has grown very rapidly in the last decade. Just from 2000 to 2009, electricity consumption increased by 51%, growing at an average of 5.4% per year. The drastic increase between 2002 and 2008 can be seen from Table 6.1. However, as a consequence of the global economic crisis, electricity consumption declined by 2% from 2008 to 2009, marking the first annual decline since 2001. Natural gas fired power generation has the largest share of total electricity production accounting for 50.1% in 2009. Coal is the second largest contributor with 37.2%, while hydropower, oil, and other sources provide 8.3%, 3.1%, and 1.3% respectively of electricity generation (as can be seen from Figure 6.2).

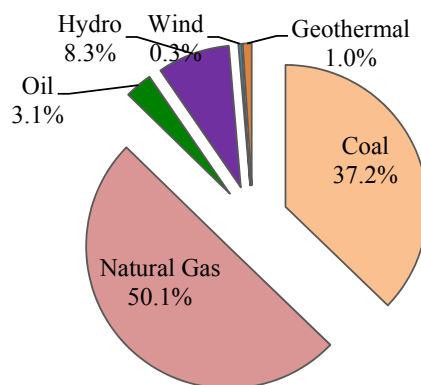


Figure 6.2. Shares of primary energy resources in Turkey.

Table 6.1. Electricity demand and growth profile of Turkey.

	Electricity Demand (TWh)	Growth Rate (%)
2000	128.3	8.3%
2001	126.9	-1.1%
2002	132.6	4.5%
2003	141.2	6.5%
2004	150.0	6.3%
2005	160.8	7.2%
2006	174.6	8.6%
2007	190.0	8.8%
2008	198.9	4.7%
2009	194.1	-2.4%
2010	209.4	7.9%
Average		5.4%

Data Source: Turkish Electricity Transmission Company, 2011.

In 2009, Turkey's total electricity supply reached 194 TWh, increasing on average by 7.5% annually from 2006 onwards. Hydropower capacity amounted to 14.6 GW and wind power to 0.8 GW. Coal, natural gas, and hydropower together account for 93% of total installed capacity, while oil account for 6.2% (as can be seen from Figure 6.3).

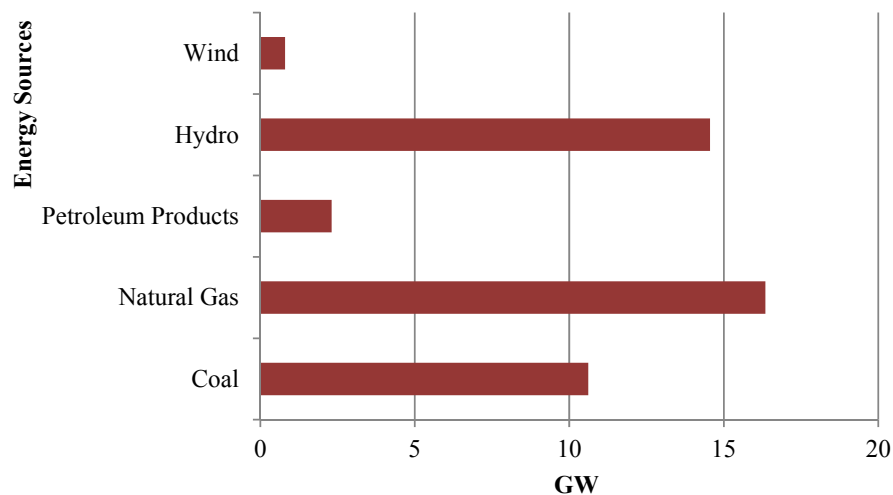


Figure 6.3. Installed electricity generation capacity in Turkey by source.

Industry sector is the largest consumer of the electricity. According to IEA, industry consumed 46.0% of electricity, while services accounted for 28%, households 24.0%, transport 1.0%, and agriculture/others 2.4% of electricity consumption in 2008 (as can be seen from Figure 6.4).

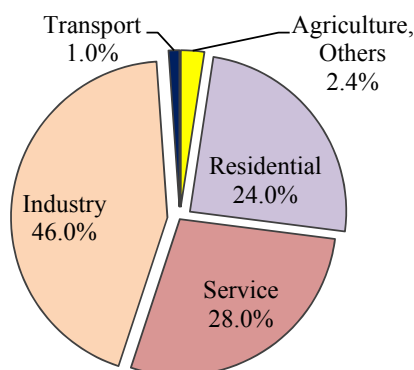


Figure 6.4. Electricity consumptions in Turkey by sector.

6.2. A BUEM Model Application for Turkey

A bottom-up, comprehensive model of the Turkish Energy Sector (TES) has been developed based on the BUEM framework. Since there have been no extraordinary political, economic or social events in 2006, and reliable data was available, 2006 has been chosen as the calibration year. The planning horizon is set in 5-year time intervals extending from 2006 to 2051. The TES application is also extended with the Macro module (TES-Macro Model) that is used in combination with the BUEM framework (as discussed in Section 4.2).

The TES-BUEM model has 128 power generation technologies, including current thermal power generation technologies, advanced thermal power generation technologies, new and renewable Electricity generation technologies, etc., which are listed in Appendix CD, “Electricity_Con_Tech_Set.xls” file. There are also around 50 energy conversion technologies (other than power generation technologies) including coal gasification, coke production, oil refinery, synthetic fuel production, and hydrogen production, etc., which are listed in Appendix CD, “Other_Con_Tech_Set.xls” file. The model considers five energy demand sectors; agriculture, industrial, commercial, residential, and transportation,

and these sectors are further divided into 73 subsectors (which are listed in Appendix CD, “Demand_Set.xls” file), with 773 demand technologies (which are listed in Appendix CD, “Demand_Tech_Set.xls” file) considered. The lists of all technologies are provided in the Appendix CD, “Tech_Set” folder.

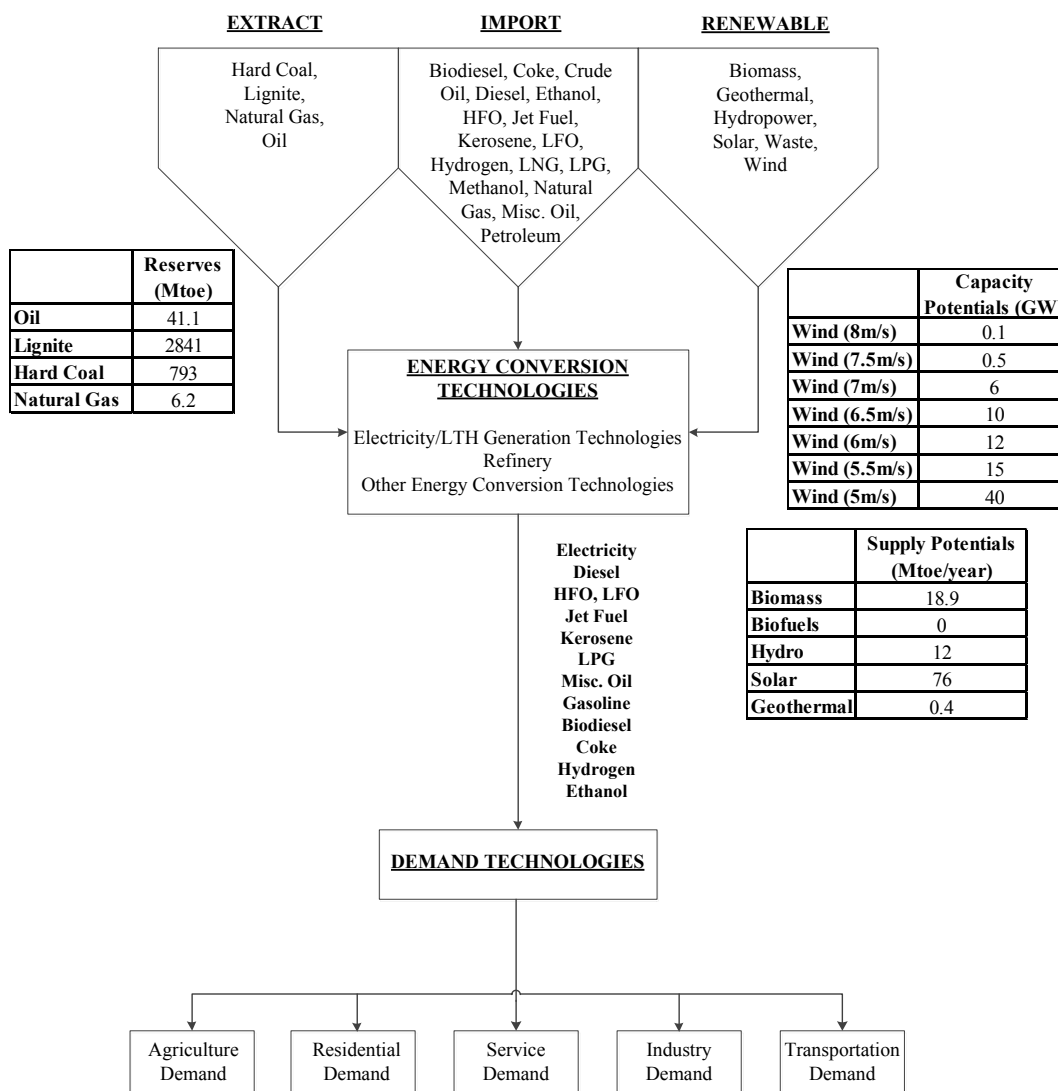


Figure 6.5. Energy flow diagram of the TES-BUEM model.

6.2.1. The Supply Submodule

The TES-BUEM model includes conventional fossil fuels (such as coal, oil, natural gas, etc.); renewable energy sources (such as hydro, wind, solar, biomass, geothermal);

nuclear energy, as well as some synthetic fuels (such as hydrogen, methanol) and so on. There are totally 36 different energy sources in the TES-BUEM model, which are listed in Appendix CD, “Energy Source_Set” folder.

The TES-BUEM model is initially run under the Base scenario, which defines a continuation of existing trends. Then, the Base scenario run results are compared with the results of three different scenario groups; (i) the first group of scenarios examining the energy system behavior under different emission targets, (ii) the second group examining the energy system behavior under different emission penalties, (iii) the third group examining the energy system behavior under an alternative policy scenario discussing restrictions on coal imports (The Base scenario and emission scenarios are also run under the TES-Macro extension).

A comprehensive modeling of the Base scenario requires a representation of geological and geographical characteristics and limitations on supply options. Therefore, the reserve capacities, annual supply potentials, and import restrictions are explicitly placed into the TES-BUEM model. Turkey’s recoverable proven fossil fuel reserves and supply potentials of renewable energy resources in 2006 are given in Table 6.2 and 6.3.

Table 6.2. Fossil fuel reserves considered in the base scenario (in Mtoe⁶).

	Reserves
Oil	41.1
Lignite	2841.0
Hard Coal	793.0
Natural Gas	6.2

Data Source: TSI

Nuclear power is not considered in the Base scenario, since currently there is no nuclear power generation in Turkey.

⁶ Mtoe: Million tonnes of oil equivalent

Table 6.3. Supply potentials and annul availabilities of renewable energy sources considered in the base scenario (in Mtoe/year and GW⁷).

	Supply Potentials (Mtoe/year)	Capacity Potentials (GW)	Annual Availabilities (Scale 0-1)
Biomass	18.9		1.00
Biofuels	0.0		1.00
Hydro	12.0		0.40
Solar	76.0		0.26
Geothermal	0.4		0.70
Wind (8m/s)		0.1	0.39
Wind (7.5m/s)		0.5	0.36
Wind (7m/s)		6	0.31
Wind (6.5m/s)		10	0.27
Wind (6m/s)		12	0.26
Wind (5.5m/s)		15	0.22
Wind (5m/s)		40	0.17

Data Source: TSI

Fuel supply prices are the other important parameters exogenously specified to the model. They are considered as one of the major determinants of the cost minimization objective. Coal is the cheapest fossil fuel (both imported and domestic) and renewable energy technologies have almost no supply cost (as can be seen from Table 6.4) However, the optimization process considers other costs of the technologies employed as well, such as technology investment and operational costs. Thus, the supply choice does not solely depend on the fuel prices.

The data sets of the remaining parameters (such as technology investment, operational and maintenance costs, technology availability factors and utilization rates, input requirements, output generation levels, annual capacity/activity/investment/supply limitations, supply and technology capacity decay/growth rates, efficiency rates, etc.) are given in Appendix CD, “Base_Data_Set” folder.

⁷ GW: Gigawatt - Unit of power, equal to 1 billion (10⁹) watts

Table 6.4. Fuel supply prices considered in the base scenario (Million TL/PJ).

Imported Fuels	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Biodiesel	47.9	47.9	47.9	47.9	47.9	47.9	47.9	47.9	47.9	47.9
Coal	8.6	6.7	8.6	9.6	10.1	10.1	10.1	10.1	10.1	10.1
Coking Coal	14.9	11.5	14.4	16.3	16.8	16.8	17.3	17.7	19.2	22.5
Crude Oil	28.8	32.1	39.8	44.6	47.9	50.3	53.7	58.5	66.6	78.6
Diesel	46.0	51.3	63.8	71.4	76.2	80.5	80.5	80.5	80.5	80.5
Ethanol	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8
Heavy Fuel Oil	26.8	30.2	37.4	42.2	45.1	47.5	47.5	47.5	47.5	47.5
Jet Fuel	47.0	52.3	65.2	73.4	78.1	82.5	82.5	82.5	82.5	82.5
Kerosene	54.7	60.9	75.7	85.3	91.1	96.4	96.4	96.4	96.4	96.4
Light Fuel Oil	46.0	51.3	63.8	71.4	76.7	80.5	80.5	80.5	80.5	80.5
Liquid Hydrogen	102.6	102.6	102.6	102.6	102.6	102.6	102.6	102.6	102.6	102.6
LNG from Russia	16.3	24.5	29.2	32.1	34.5	36.4	36.4	36.4	36.4	36.4
LNG from Algeria	23.0	34.5	41.7	46.0	48.9	52.3	52.3	52.3	52.3	52.3
LNG from Nigeria	25.4	38.4	46.0	50.8	54.2	57.5	57.5	57.5	57.5	57.5
LPG	32.1	36.0	44.6	49.9	53.7	56.6	56.6	56.6	56.6	56.6
Methanol	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3
Natural Gas from Iran	18.7	27.8	33.6	36.9	39.3	41.7	41.7	41.7	41.7	41.7
Natural Gas from Russia(1)	19.7	29.7	35.5	39.3	41.7	44.6	44.6	44.6	44.6	44.6
Natural Gas from Russia(2)	20.6	31.2	37.9	41.7	44.1	47.0	47.0	47.0	47.0	47.0
Natural Gas from Azerbaijan	22.1	33.1	39.8	43.6	46.5	49.9	49.9	49.9	49.9	49.9
Other Fuel Products	7.2	8.2	10.1	11.0	12.0	12.5	13.4	14.9	16.8	19.7
Petroleum	37.4	37.4	27.3	29.2	30.7	32.6	34.0	36.0	37.4	37.4
Nuclear(1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear(2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear(3)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Nuclear(4)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Nuclear(5)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Data Source: TSI and expert views

Table 6.4. Fuel supply prices considered in the base scenario (Million TL/PJ) (cont.).

Domestic Fuels	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Biomass(1)	23.0	17.7	22.5	24.9	25.9	26.4	26.4	27.8	30.2	35.0
Biomass(2)	36.0	27.8	35.5	39.3	40.8	41.2	41.7	43.1	47.0	54.7
Biomass(3)	57.5	44.6	56.6	62.8	65.2	65.7	66.6	69.0	75.3	87.3
Coal	4.8	4.8	6.2	5.3	5.3	4.8	4.8	5.3	5.3	5.8
Coking Coal	12.5	9.6	12.0	13.4	13.9	13.9	14.4	14.9	16.3	18.7
Geothermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydropower	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Petroleum	21.1	23.5	29.2	32.6	35.0	36.9	39.3	43.1	48.9	58.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (5.5m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (5m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (6.5m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (6m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (7.5m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (7m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind (8m/s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Data Source: TSI and expert views

The other technology costs such as investment cost, operational and maintenance costs are obtained from AEA Inc., which is an England based company that provides analysis, advice, and data on economically sustainable solutions for the most pressing global energy and environmental challenges.

6.2.2. The Demand Submodule

The energy demands of the five main demand sectors and the 73 demand sub-sectors for the years 2006 and 2011 are obtained through various publicly available sources such as TSI, various NGOs and industrial corporations. Then the sectoral and sub sectoral energy demands of future periods (from 2016 to 2051) are exogenously estimated by linking demand projections to GDP projections with the exception of the industry sector

demands. Industry sector demands are taken from Alemdar (2010). On the other hand, some of the demand services such as agriculture sector energy demand are specifically treated. For those services, GDP growth projections are distorted by a multiplier. The GDP projections for the planning horizon (which are obtained from TSI) and all the related sectoral and sub sectoral energy demand projections are displayed in Appendix CD, “demanddata.csv” file. From 2000 to 2010, GDP increased on average by 4.3% a year. Furthermore, per capita GDP went up to 10079 USD in 2010 from 7583 USD in 2006. Figure 6.6 provides an overview of sectoral demands.

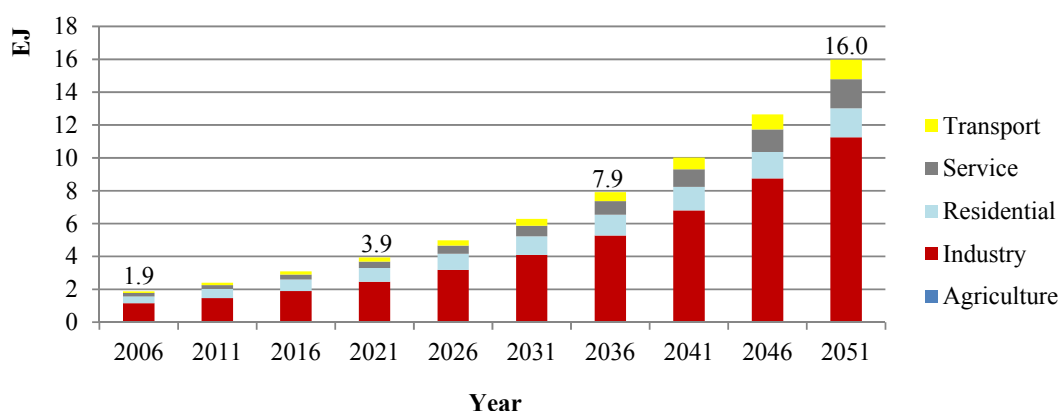


Figure 6.6. Demands of the TES-BUEM model by sector.⁸

Demands are categorized into; agriculture, residential, service, industry, and transportation sectors. The following subsections discuss the demand categories in detail.

The agricultural sector demand set is based on the energy type demanded by agricultural activities, the primary types being natural gas, coal, diesel, and electricity. No sub sectors are defined for this sector. The residential sector energy demand set is addressed in two categories of dwellings: (i) existing houses, (ii) new houses. At the level of the sub-sectors, dwellings are subdivided into various energy services, as displayed in “Table_Demands” in Appendix CD. The service sector energy demand is divided into six sub-sectors. Those sub-sectors are further divided into energy services, defined according to the pattern of technology. In total, six sub sectors and 36 end-use demands are defined, as displayed in “Table_Demands” in Appendix CD. The industry sector energy demand set

⁸ EJ: Exajoule - equal to 10^3 PJ

is divided into 11 industrial sub-sectors, namely cement, chemical, glass, iron and steel, non-ferrous metals, pulp and paper, automotive, food and beverage, textile, and other industries. Each demand sub-sector is further divided according to technology types deployed in that sub-sector (such as drying/separation, high temperature heat, low temperature heat, other heat, motor), as displayed in “Table_Demands” in Appendix CD. The transport sector energy demand set is addressed in terms of transportation modes (such as air, road, rail, and sea). Then, for each transportation mode, vehicle types serving or having the potential to serve are defined and classified. In addition, for each vehicle type several technologies based on available and future potential fuels are defined (e.g. hydrogen fueled car, electricity bus, etc.), as displayed in “Table_Demands” in Appendix CD.

6.3. Model Validation

The validation of the TES-BUEM model has been done in two different ways: (i) the TES-BUEM model results have been compared with the TES-MARKAL model (which is defined below) results, (ii) the TES-BUEM model results are compared with the realized statistics.

In the first validation process, the TES-BUEM model results are compared with the TES-MARKAL model results and similarities and differences are observed. The TES-MARKAL model is another, independent Turkish Energy Sector model, also developed and run under MARKAL modeling framework. This model has been developed at Boğaziçi University within the framework of a scientific research project financed by the Boğaziçi University Scientific Research Fund and several graduate studies (Alemdar, 2010; Cirit, 2011) to represent the national energy system and evaluate sectoral greenhouse gas reduction policies. In order to enable a more realistic comparison of the two models, the basic structure and most of the details of the TES-BUEM model are constructed similar to the TES-MARKAL model. In other words, the same data set and structure (used to develop the TES-MARKAL model) used in the TES-BUEM model (the structure, details, and data set used in these models are summarized in Appendix CD, “TES-BUEM_Calibration” folders).

On the other hand, both the data set and the model structure of the TES-BUEM model have been updated and expanded throughout this study. This expanded TES-BUEM model features better representation of the real system, has more predictive power, and offer a more powerful platform to support policy, scenario analysis, and decision making. However, there is no TES-MARKAL model result in line with the updated structure and data set, so a second validation practice has been developed. The second practice checks whether the 2009 realized statistics (which are the most updated and trustable energy data) are in the 2006 - 2011 estimation interval of the TES-BUEM model.

6.3.1. Comparison of the TES-BUEM and TES-MARKAL Models Results

Although the MARKAL modeling framework has been considerably simplified as discussed in Chapter 5, the TES-BUEM model run results turned out to be very close to the TES-MARKAL model results (as can be seen from Table 6.9 – 6.16). Primary energy supply levels slightly differ and the differences are below 5% in almost all aspects (see Table 6.9 and 6.10), while changes in total energy supply staying below 2% through the planning horizon (see Figure 6.7).

As discussed in Chapter 5, the electricity sector has experienced the most drastic simplifications and changes in the BUEM framework. Nevertheless, the TES-BUEM model results display very similar capacity and consumption patterns regarding installed capacity and energy consumption profile of power plants (as can be seen from Table 6.11 – 6.14). The variations in total generation capacity and resource usage between the two models do not exceed $\pm 7\%$.

Additionally, the observed deviations in the electricity sector are partly the results of changes in the variable and energy flow structure of the sector and partly the results of some adjustments/differentiations in original data set of the TES-MARKAL model. As discussed in Chapter 5, the variables and energy flow relationships in the MARKAL framework are constructed based on six combinations of season and time of day state, while the BUEM framework gives consideration to only two level time-of-day differentiation. Thus, some changes in total capacities and resource usage are expected.

The effects can be tracked overall results in general (as can be seen from Table 6.11 – 6.14). Moreover, in the BUEM framework there is no special treatment of the end periods, while in the MARKAL framework, some adjustments are automatically made in the last periods to cover for further continuation after the end of planning horizon. This may be the reason of the somewhat larger deviations between the two models.

Table 6.5. Energy supplies predicted by the TES-MARKAL model (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1214.7	1568.6	2963.4	4045.4	5577.2	8046.5	10893.5	14245.4	18869.9	24304.1
Natural Gas	1253.0	1323.7	789.6	925.0	887.6	529.3	491.6	599.0	714.0	915.0
Oil	1075.8	1335.1	1641.1	1938.1	2178.1	2541.6	2728.7	2992.3	3134.8	3636.6
Hydro	164.8	144.4	124.1	124.2	124.3	131.6	114.7	116.6	113.1	111.8
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	221.9	493.1	1196.6	1909.8
Wind	0.4	1.2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	4.0	2.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
TOTAL	3599.9	4094.6	5125.9	6570.2	8199.1	10662.5	13791.8	17726.4	23218.8	29909.4

Table 6.6. Energy supplies predicted by the TES-BUEM model (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1214.6	1639.4	3066.7	4181.1	5695.0	8053.5	11008.9	14410.7	18901.6	23778.6
Natural Gas	1253.0	1311.9	766.5	918.7	881.4	523.0	485.3	592.7	707.7	908.8
Oil	1075.8	1344.4	1547.2	1845.3	2129.2	2523.4	2438.2	2826.6	3081.7	3639.3
Hydro	164.8	144.4	124.1	124.2	124.3	134.9	114.6	117.9	113.0	113.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	367.4	583.2	1198.1	1844.6
Wind	0.4	1.2	1.2	6.9	6.9	6.9	6.9	6.9	1.2	1.2
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	3.9	2.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
TOTAL	3599.8	4163.0	5112.3	6612.6	8267.4	10655.3	13762.7	17818.1	23193.8	29317.6

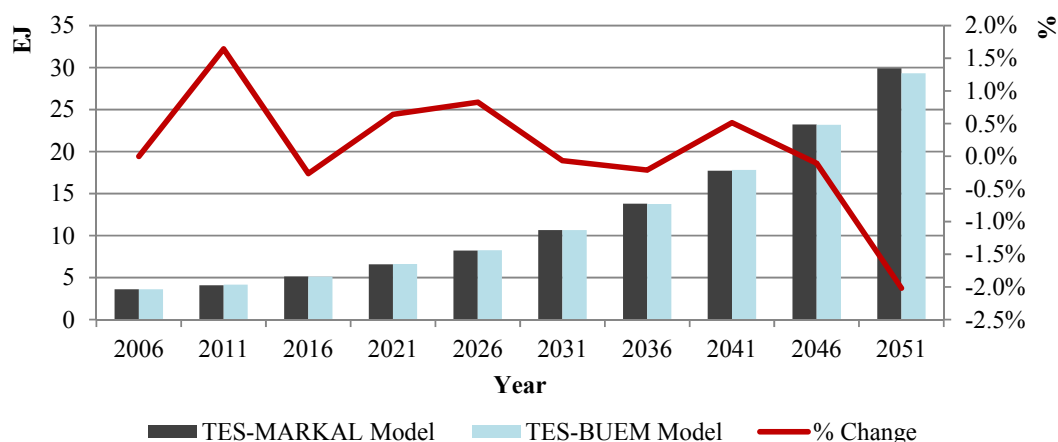


Figure 6.7. Total energy supply predicted by the TES-MARKAL and the TES-BUEM models.

Furthermore, the TES-MARKAL model features a deep in 2016 and a peak in 2021 in natural gas consumption (as can be seen from Table 6.13). To eliminate these irregular peak and deep points, a capacity decay parameter (which sets a lower bound for a period's capacity as a certain percentage of the previous period's capacity) is used for 2016 in the TES-BUEM. Thus, in the TES-BUEM model the natural gas consumption in the electricity sector has a smoother decrease (as can be seen from Table 6.14) and the model results are more realistic.

Table 6.7. Installed capacity predicted by the TES-MARKAL model (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	8.9	19.3	25.1	47.5	72.0	103.4	120.7	161.4	187.4
Natural Gas	10.0	17.0	25.1	25.2	26.3	25.2	31.1	39.7	49.1	53.9
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	11.5	9.8	9.9	9.9	10.7	9.9	9.9	9.7	9.7
Wind	0.1	0.1	0.1	0.6	0.6	0.5	0.5	0.5	0.0	0.0
TOTAL	35.8	39.9	56.7	63.2	86.6	110.8	144.9	170.8	220.2	251.0

Table 6.8. Installed capacity predicted by the TES-BUEM model (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	8.9	21.4	28.3	46.3	77.3	100.2	125.8	162.1	184.7
Natural Gas	10.0	17.5	19.4	21.1	21.0	20.1	29.1	36.6	48.4	55.0
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	11.4	9.8	9.8	9.9	10.7	9.1	9.3	9.0	9.0
Wind	0.1	0.1	0.1	0.6	0.6	0.6	0.6	0.6	0.1	0.1
TOTAL	35.8	40.4	53.2	62.2	80.1	111.1	139.0	172.4	219.5	248.7

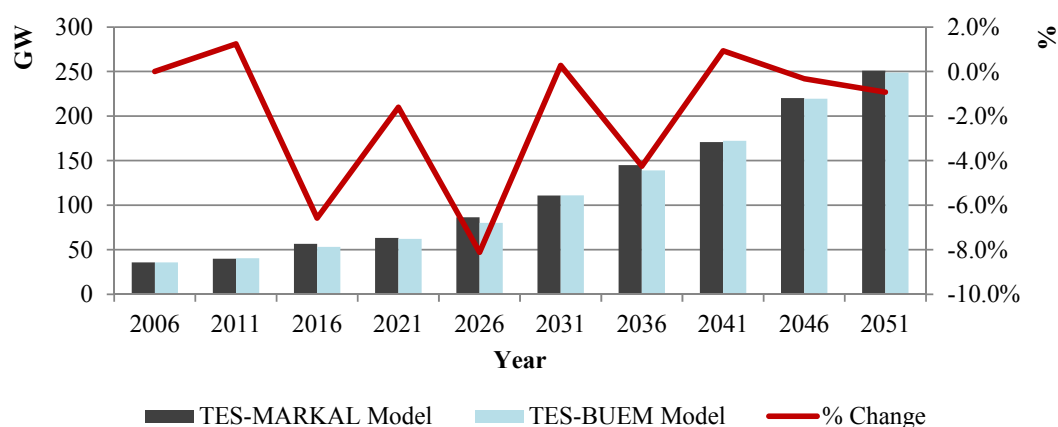


Figure 6.8. Total installed capacity predicted by the TES-BUEM and TES-MARKAL models.

Table 6.9. Energy resource usage for electricity generation predicted by the TES-MARKAL model (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	571.3	581.6	1264.0	1579.4	2323.0	3616.4	5015.3	6613.5	8087.5	9942.7
Natural Gas	562.5	732.9	502.0	662.9	620.4	485.0	434.0	390.6	351.5	316.4
Oil	43.0	47.8	18.3	11.3	10.7	7.0	1.3	0.6	0.0	0.0
Hydro	164.8	144.4	124.1	124.2	124.3	131.6	114.2	116.6	113.0	111.8
Wind	0.4	1.2	1.2	6.9	6.9	5.7	5.7	5.7	0.0	0.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	1342	1507.9	1909.6	2384.7	3085.3	4245.7	5570.5	7127	8552	10370.9

Table 6.10. Energy resource usage for electricity generation predicted by the TES-BUEM model (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	571.3	581.6	1264.0	1575.4	2319.1	3611.3	5009.7	6608.2	8087.5	9942.7
Natural Gas	562.5	732.9	661.5	595.4	535.8	482.2	434.0	390.6	351.5	316.4
Petroleum Products	43.0	47.8	18.3	11.3	10.7	7.0	1.3	0.6	0.0	0.0
Hydro	164.8	144.4	124.1	124.2	124.3	131.6	114.2	116.6	113.0	111.8
Wind	0.4	1.2	1.2	6.9	6.9	6.9	6.9	6.9	1.2	1.2
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	1342	1507.9	2069.1	2313.2	2996.8	4239	5566.1	7122.9	8553.2	10372.1

As discussed in Chapter 5, the BUEM framework's cost functions are not as detailed as the MARKAL approach (some cost items being aggregated). For example, input delivery costs and electricity transmission/distribution costs for imported electricity are embedded into the unit supply cost. In addition, electricity/LTH related activity variables are eliminated from the cost formulations. Nevertheless, cost realization in the TES-BUEM model differs than the results of the TES-MARKAL model by about 10%. Cost results of two models can be seen from Table 6.15 and 6.16, which validate our assumption that the aggregations and simplifications suggested in the BUEM framework do not lead to loss of precision in the results.

Table 6.11. System costs predicted by the TES-MARKAL model (in Billion TL).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Investment Cost	533.1	298.7	442.0	592.1	980.9	961.7	1394.2	1606.1	2364.0	2726.5
Fuel Expenses	79.6	97.8	129.0	161.1	181.7	238.8	271.4	322.7	373.0	451.1
Other Expenses	82.0	94.0	119.4	152.5	188.9	239.7	301.6	380.7	478.0	604.6
Salvage Cost	0.0	0.0	0.0	0.0	0.5	2.4	6.7	32.1	121.8	293.9
Total System Cost	695.2	490.5	690.4	905.6	1352.0	1442.6	1973.8	2342.0	3336.8	4076.1

Table 6.12. System costs predicted by the TES-BUEM model (in Billion TL).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Investment Cost	533.1	269.0	437.7	582.5	946.4	909.9	1406.1	1584.5	2288.3	2606.6
Fuel Expenses	77.7	83.9	115.5	145.7	163.5	215.3	255.1	308.3	369.2	459.8
Other Expenses	82.9	96.4	120.8	153.9	190.8	243.5	305.9	386.9	491.4	630.9
Salvage Cost	0.0	0.0	0.0	0.0	0.5	2.4	6.2	22.1	96.8	338.0
Total System Cost	693.7	449.2	674.1	819.8	1301.2	1371.2	1973.8	2301.7	3245.2	4035.8

6.3.2. Comparison of the TES-BUEM Model Results with Realized Statistics

The TES-BUEM model estimates and realized energy source supplies can be observed in Table 6.17, and Figures 6.9 and 6.10. An increasing or decreasing trend for each energy form except for oil is seen. The reason for this situation is considered to be the impact of the economic slowdown in 2008, which could not be foreseen by the model. According to the Turkish Petroleum Industry Association, diesel and gasoline use decreased by 2.7% and 3.9%, respectively, from 2008 to 2009. However, since this is a temporary situation, a growing trend for oil consumption is expected for the following periods.

Table 6.13. Energy supplies by source (in Mtoe).

	2006 TES-BUEM	2009 Realization	2011 TES-BUEM
Coal	29.0	32.9	37.4
Natural Gas	27.7	29.1	29.8
Oil	29.6	29.1	31.0
Hydropower	3.9	4.0	4.7
Hydrogen	0.0	0.0	0.0
Wind	0.0	0.1	0.3
Biofuels	4.3	3.7	2.7
Nuclear	0.0	0.0	0.0
Solar	0.6	0.4	0.4
Geothermal	0.0	0.4	0.4
Total	29.0	32.9	37.4

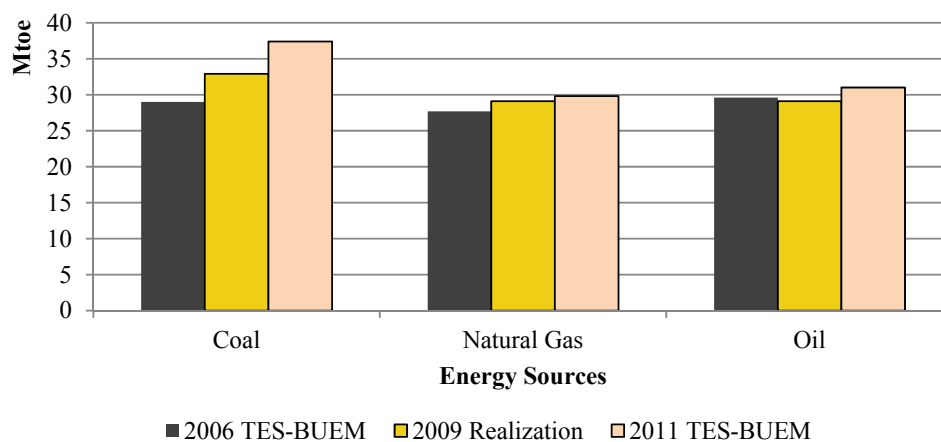


Figure 6.9. Fossil fuel supply.

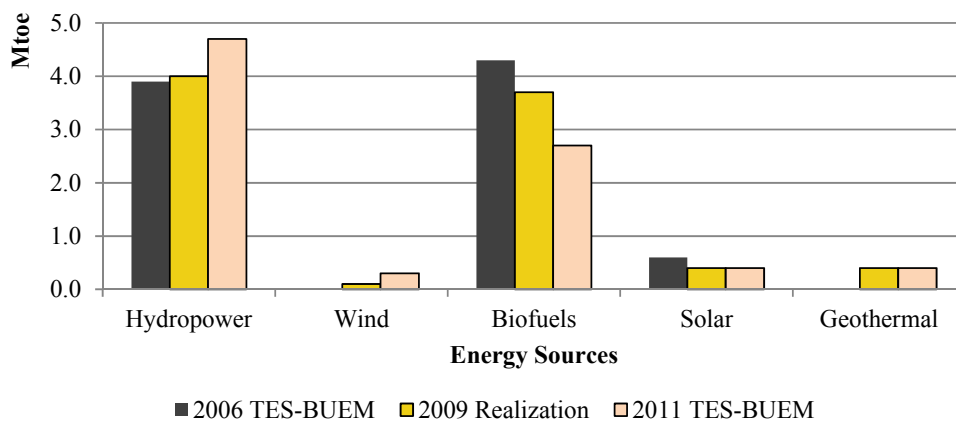


Figure 6.10. Renewable energy supply.

The comparison of the TES-BUEM model predictions for 2011 and the actual realization in 2009 lead to similar observations that the realized data display the behavior of the model predictions over electricity generations as well (as can be seen from Table 6.14 – 6.15 and Figure 6.11).

Table 6.14. Installed capacity by source (in GW).

	2006 TES-BUEM	2009 Realization	2011 TES-BUEM
Coal	10.2	10.6	12.3
Natural Gas	10.0	16.4	18.7
Oil	2.4	2.4	2.4
Hydropower	13.1	14.6	15.6
Wind	0.1	0.8	1.3
Nuclear	0.0	0.0	0.0
Solar	0.0	0.0	0.0
Geothermal	0.0	0.0	0.2
Waste	0.0	0.0	0.0
Total	35.8	44.8	50.5

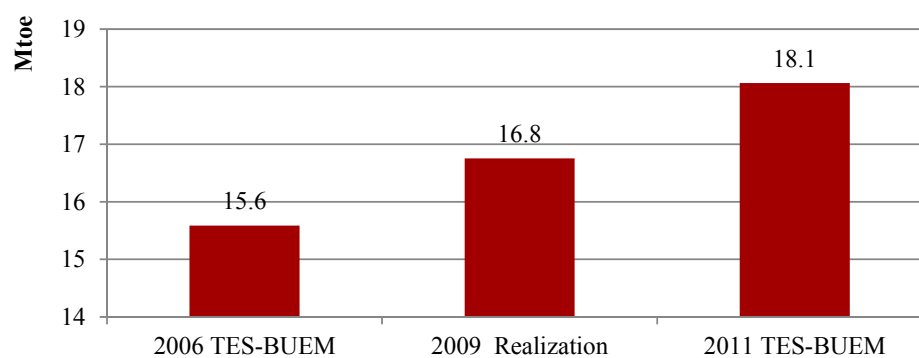


Figure 6.11. Electricity generation.

Table 6.15. Electricity consumption by sector.

	2006 TES-BUEM	2009 Realization	2011 TES-BUEM
Agriculture	2.4%	2.5%	2.3%
Industry	43.8%	35.6%	33.1%
Transport	1.1%	1.3%	1.4%
Residential + Service	52.7%	60.6%	63.2%

7. SCENARIO ANALYSIS

This section displays and discusses the TES-BUEM model results under a Base and several alternative scenarios. For each scenario, results are evaluated in regard to energy consumptions, zero carbon fuel and renewable energy shares, electricity generation levels, import dependence rates, energy intensities, CO₂ emissions, and energy costs.

Alternative scenarios can be divided into three different groups (as mentioned in section 6.2); (i) the one examining the energy system dynamics under emission targets, (ii) the one examining the energy system dynamics under emission penalties, (iii) the one examining the energy system dynamics under an alternative policy scenario discussing restrictions on coal imports. Base scenario and emission scenarios are also run under the Macro module integrated TES-BUEM model.

Form this point of view, each subsection is organized as discussing a scenario or scenario groups. The organization of the subsections is as follows: Section 7.1 discusses the Base Scenario; Section 7.2 discusses the Emission Restriction Scenarios; Section 7.3 discusses the Emission Penalty Scenarios; Section 7.4 discusses the Coal Import Scenario; Section 7.5 discusses the Base Macro Scenario (Base scenario that run under the Macro module integrated TES-BUEM model); Section 7.6 discusses the Emission Restriction Macro Scenarios (Emission restriction scenarios that run under the Macro module integrated TES-BUEM model); Section 7.7 discusses the Emission Penalty Macro Scenarios (Emission penalty scenarios that run under the Macro module integrated TES-BUEM model); Section 7.8 discusses the Emission Penalty on Consumer Utility Scenario (utility penalty scenario that run under the Macro module integrated TES-BUEM model).

7.1. The Base Scenario Results

7.1.1. Energy Supply

The Base scenario describes a continuation of the existing trends (of the Turkish energy system) in energy use, technology improvements, efficiency increases, resource availabilities, capacity utilization rates, etc. There is no additional energy or climate policy.

In this scenario, total energy supply grows on average by 25% per five-year period (as can be seen from Figure 7.1). The energy supply level increases from 3.9 EJ in 2006 to 11.4 EJ in 2031 and to 29 EJ in 2051.

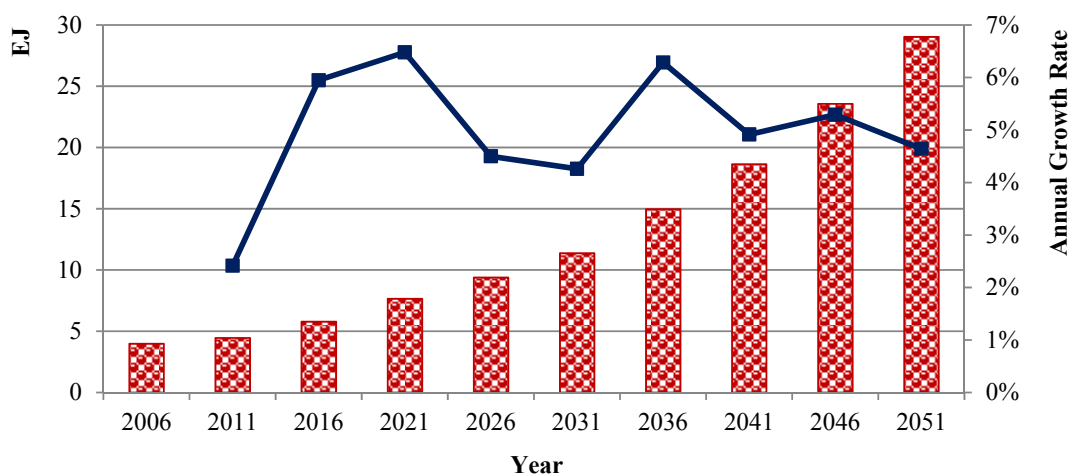


Figure 7.1. Total energy supply predicted in the Base scenario.

Fossil fuels including oil, coal, and natural gas account for 91% of total energy supply in the initial year (2006) while renewable energy sources provide the remaining 9%. However, after the initial two periods, the share of coal displays a rapid growth, replaces with other fuels (where it is possible), and dominates the fuel supply starting from 2016 (increasing from 30% in 2006 to 70% in 2026 and 80% in 2051). The increase in coal consumption can be attributed to the relatively cheap costs of coal supplies compared to other fuels. On the other hand, growth of electricity generation from wind energy between 2006-2011 has been calibrated according to the latest data. Due to this calibration, a large jump in wind energy consumption is realized between 2006 and 2011. However, since the

annual potentials of wind electricity generation technologies that have higher availability factors are limited (as can be seen from Table 6.3 in Chapter 6), a large part of the wind electricity generation capacity that are invested in these two periods comes from the technologies that have low availability factors. After five periods, when the useful lifetimes of the those technologies (that have lower availability factors) are over, the system abandons them and maintains the technologies that have high availability factors (but low generation potentials). This explains the sharp decreases of wind energy source in 2031. The electricity generation from wind energy technologies continues in later periods, but in lower levels.

The other energy sources remain either unchanged or have minimal changes with the exception of traditional biomass (mostly firewood) and solar energies. The unit supply price of wood increases with a fast growth rate compared to the supply prices of other sources (as can be seen from Table 6.4 in Chapter 6). As a result, the optimization process abandons biomass and invests on cheaper alternatives. The situation is similar in the case of solar energy. Since solar electricity generation technologies have higher investment costs (according to the AEA data set used in the TES-BUEM model), the optimization process prefers not to invest into solar electricity generation. In addition, the initial year calibration of water heating in buildings by solar energy decreases gradually and totally disappears by the end of the planning horizon (due to higher technology investment costs compared to other water heating technologies). These results show that, without significant incentive, subsidy or cost decline, investments into renewable energy technologies (with the exception of geothermal energy) is economically unattractive. Geothermal energy, on the other hand, has the cheapest supply and technology costs. Thus, related investments and generation capacities reach the stated limits as soon as the calibration period is over and remain there. However, forecasts regarding the future potential of geothermal energy may not be very reliable; the model is calibrated with the latest confirmed information (MNER, 2011).

Figure 7.2 provides a general overview summarizing the key observations with respect to fossil and zero carbon fuels (which are the sources with no carbon emissions such as renewable energy sources, nuclear energy, synthetics, etc.). The supply of fossil fuels increases gradually throughout the planning horizon (most of which belonging to

coal). The share of zero carbon fuels, on the other hand, decreases until 2031. From this year onwards, usage of hydrogen fueled vehicles, which are projected to be available after 2036, sharply increases. Thus, after an initial jump in 2036, share of zero carbons stabilize around 6-7%.

Table 7.1. Energy supplies predicted in the Base scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1565.4	3342.9	5061.2	6590.3	8359.7	11880.8	15001.2	19280.2	23504.3
Natural Gas	1157.5	1245.9	1003.7	958.7	895.5	914.1	948.0	1020.5	1127.8	1556.3
Oil	1237.8	1295.9	1154.9	1405.7	1681.3	1893.2	1288.3	1540.3	1745.5	2169.4
Hydro	164.8	196.8	176.5	156.1	156.2	166.8	146.5	149.9	145.0	111.9
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	667.7	900.5	1248.2	1677.4
Wind	0.4	13.6	13.6	13.6	13.6	13.6	1.2	1.2	1.2	1.2
Biofuel	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	3.9	2.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3978.8	4459.3	5785.5	7659.6	9382.7	11381.9	14959.9	18636.5	23568.0	29039.0

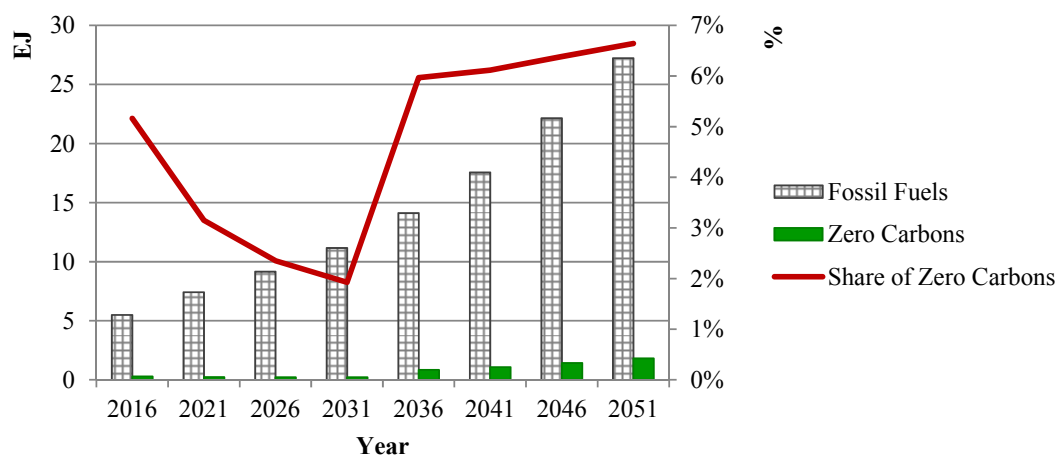


Figure 7.2. Fossil and zero carbon fuel supplies predicted in the Base scenario.

Energy intensity is a measure of the energy efficiency of a nation's economy. It primarily displays the energy requirements of the nation without affecting the economic and social development and calculated as energy consumption per unit of economic/social activity (measured and reflected in monetary units, i.e. GDP). However, there is an inverse relationship between energy intensity and energy efficiency. In this case, the lower the intensity (i.e. the lower the energy consumption), the better the efficiency is.

As can be seen from Figure 7.3, energy intensity declines, hence efficiency improves in most of the periods, except 2016, 2021 and 2036. In those periods, growth of total energy supply is greater than the growth of GDP. Consumption of hydro energy source decreases in those periods and hydropower is replaced with coal fueled electricity generation technologies (which have comparatively lower efficiency levels). This may be one of the reasons of the intensity trends in those periods.

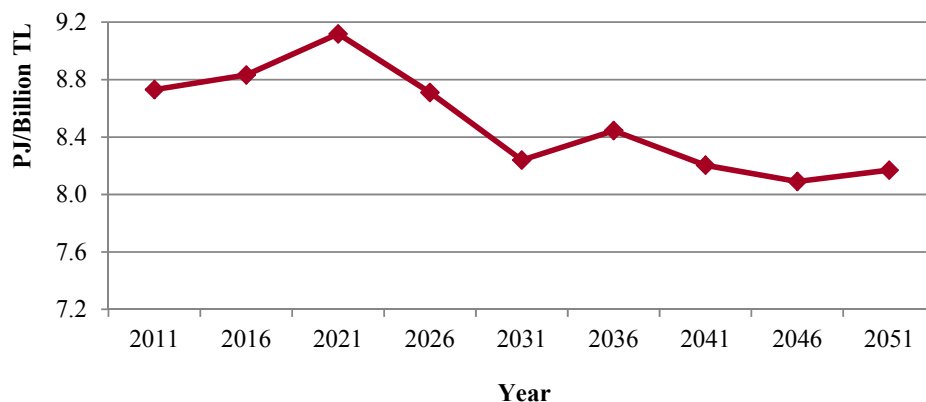


Figure 7.3. Energy intensities predicted in the Base scenario.

Turkey depends on energy imports, which accounted for 70% of total energy supply in 2006, including practically for all of the country's oil and natural gas needs and most of its coal needs. The calibration was done according to the import profile in 2006. However, the optimization process changes this profile in the later periods as displayed in Figure 7.4. Since domestic coal is the cheapest alternative, optimization tends to rely on this resource until the national reserves are exhausted in 2026. Accordingly, the dependence on imports rapidly decreases until 2026. Then, since there is no more domestic coal, imported coal is used in large amounts as the second cheapest alternative. This explains the sharp increase

between 2026 and 2036. Then, the share of imported coal stabilizes around 80%, while import dependence gradually rises to around 95%.

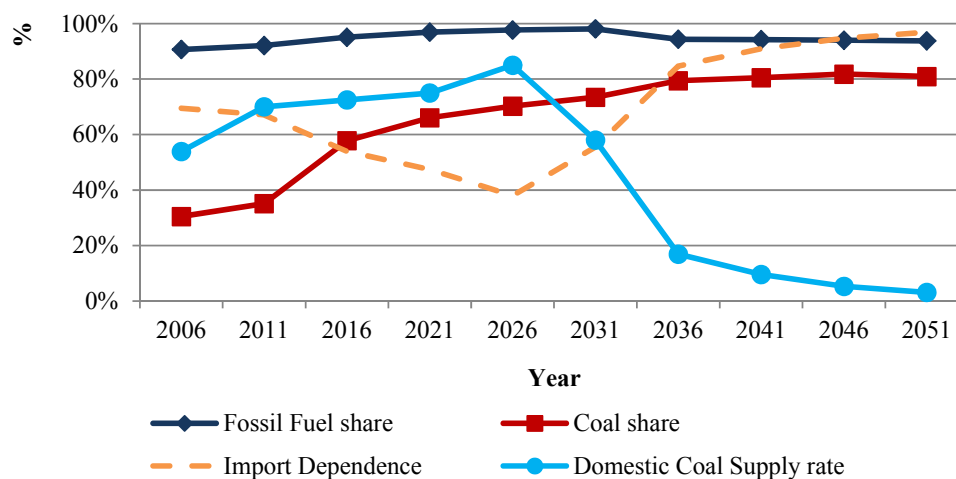


Figure 7.4. Import dependence and fossil fuel shares predicted in the Base scenario.

7.1.2. Electricity Generation

On the other hand, as displayed in Figure 7.5, total electricity supply in Turkey reaches 2.35 EJ (653.5 TWh) in 2031 (almost 4 times the level in 2006) and 5.35 EJ (1486.9 TWh) in 2051. In 2006, natural gas fueled 43.4% of total electricity generation, while coal, hydropower, oil and other sources accounted 41.5%, 11.9%, 3.1%, and 0.1%, respectively. However, as displayed in Figure 7.6, starting in 2011, this composition sharply changes: coal becoming the dominant fuel choice of electricity generation. This fast-growing trend is a result of the cheap supply price of coal as expected. Hydroelectricity generation, on the other hand, peaks in 2011 and then steadily declines. This is due to the higher technology costs and lower availability factors of hydroelectricity generation technologies compared to the coal electricity generation technologies. Other renewable energy sources, except geothermal, all decreases until the end of the planning horizon as well. Geothermal energy remains at its maximum potential.

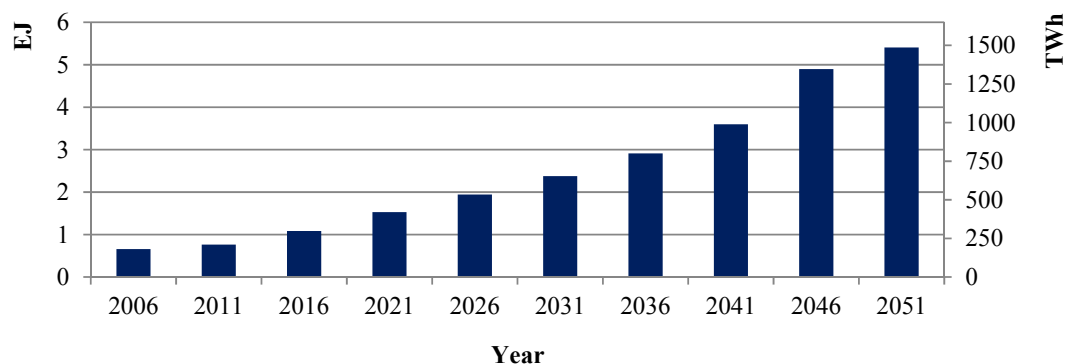


Figure 7.5. Electricity generations predicted in the Base scenario.

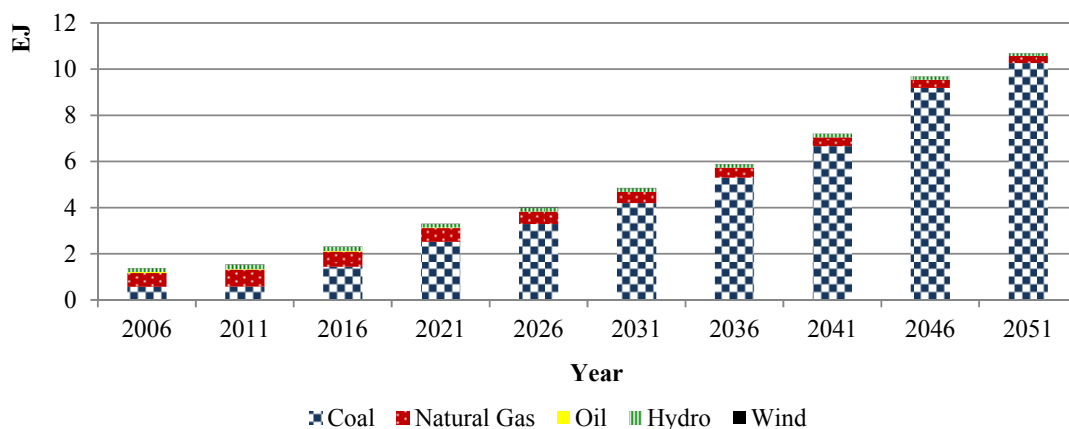


Figure 7.6. Energy usage for electricity generation predicted in the Base scenario.

One of the natural gas fueled electricity generation technologies (which is represented as “E_NGA_GT” in the technology set of the TES-BUEM model) has relatively cheaper investment cost among all generation alternatives. Thus, the optimization process invests on this technology to build a reserve capacity. That capacity does not generate any electricity but is kept as reserve. This result can be observed by comparing the natural gas fueled electricity generation levels (in Figure 7.6) with the installed capacity levels of natural gas technologies (in Table 7.2). Even though the total installed capacity of natural gas fueled electricity generation technologies increases and has 25% of the total capacity in 2051, the generation levels (by natural gas) decreases to 3% in 2051.

Table 7.2. Installed capacities predicted in the Base scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	22.0	40.1	58.4	72.4	91.3	114.9	159.8	179.5
Natural Gas	10.0	18.7	19.3	23.6	27.8	28.9	37.1	44.3	57.8	62.3
Petroleum Products	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydropower	13.1	15.6	14.0	12.4	12.4	13.2	11.6	11.9	11.5	8.9
Wind	0.1	1.3	1.3	1.3	1.3	1.3	0.1	0.1	0.1	0.1
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	35.8	50.5	59.2	79.9	102.5	118.4	140.4	171.4	229.4	250.9

7.1.3. Renewable Energy Sources

In 2006, renewable energy sources provided 370.9 PJ (or 9.3%) of total energy supply. That share declines to zero throughout the planning horizon (as can be seen from Figure 7.7). This is mainly because of the limited potentials and higher investment costs of renewable energy technologies. These results again indicate that, without significant incentive, subsidy or cost declines, investments into renewable energy technologies are economically not attractive for investors.

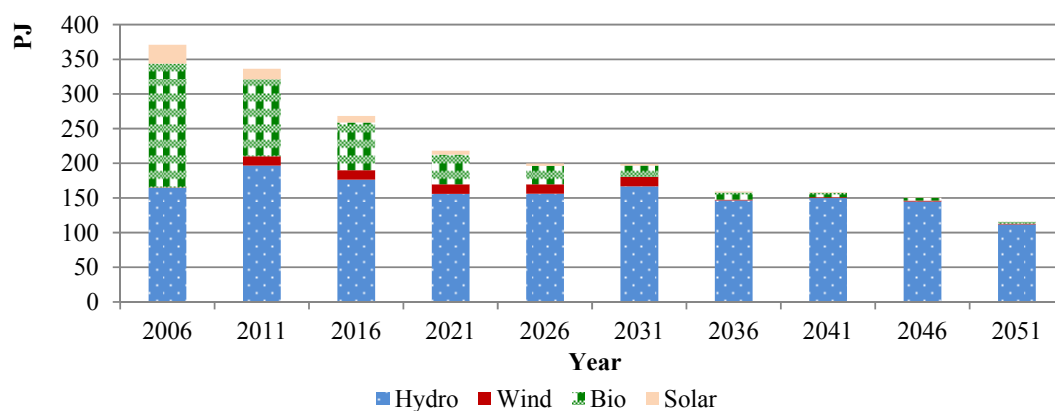


Figure 7.7. Renewable energy supplies predicted in the Base scenario.

7.1.4. Emissions

Total CO₂ emissions triple by 2026 compared to 2006 levels (as can be seen from Figure 7.8). The increase rate is even more dramatic in the second half of the planning horizon. The major reason here is the excessive consumption of coal in the later periods (coal having the highest emission factor among fossil fuels).

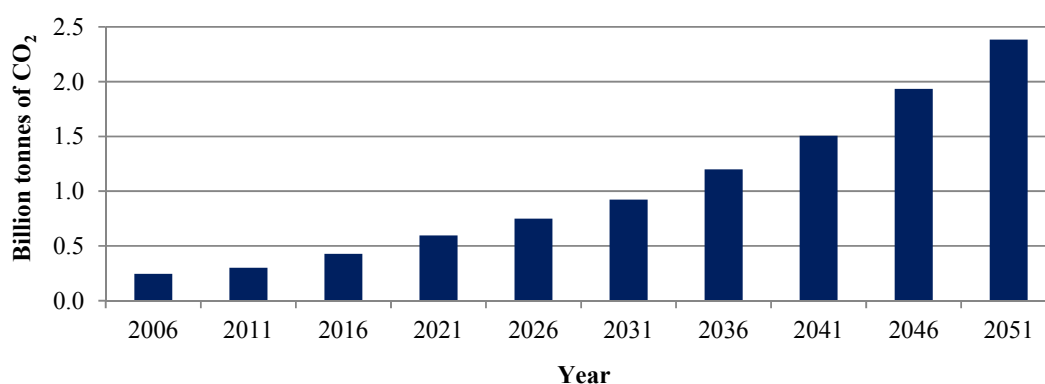


Figure 7.8. CO₂ emissions predicted in the Base scenario.

Electricity generation sector and industry sector are the largest emitters of energy-related emissions in 2006, accounting for 36.5% and 32.6% of the total, respectively. Residents account for 11.7% of all emissions, while transport and service sectors have 16.7%, and 2.1% shares, respectively. After 2011, on the other hand, share of power generation and industry together jumps to the 75-80% interval and stabilizes there. Coal is the primary fuel consumed in those sectors.

Table 7.3. Sectoral CO₂ emissions predicted in the Base scenario.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Power Generation	36.5%	31.9%	39.9%	44.5%	44.3%	44.6%	42.6%	42.0%	44.6%	40.2%
Industry	32.6%	36.5%	35.8%	33.3%	34.2%	36.0%	35.7%	36.7%	34.8%	38.5%
Residential	11.7%	9.8%	7.8%	7.4%	7.2%	6.2%	5.0%	4.1%	3.2%	2.6%
Service	2.1%	2.0%	1.8%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.8%
Transport	16.7%	19.8%	14.6%	13.1%	12.7%	11.4%	4.5%	4.2%	3.5%	3.6%
Others	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	10.6%	11.3%	12.2%	13.3%

7.1.5. Costs

As can be seen from Figure 7.9, investment costs account for more than 50% of the total system costs (which includes the fuel supply costs, investment costs, other operational costs, environmental costs, and additional costs) throughout the planning horizon. Accordingly, the periods, in which large investments occur, feature the peak points. For example, in 2011, the system invests more on new capacities compared to 2006. This is because; most of the technology capacities in 2006 belong to residual capacities (which are the capacities determined before the planning horizon and so not associated with investment costs but other operational costs). On the other hand, most of the technologies defined in the TES-BUEM model have useful lifetimes that last 20 or 25 years. Accordingly, the system needs to invest on new capacities after 20-25 years from the beginning of the planning horizon (which is around 2036). This explains the investment peak in 2036 (those peaks in 2011 and 2036 are realized in all scenario applications as displayed in the following subsections). In addition, needs for technology capacities and operations increase throughout the planning horizon (correspond to the increase in energy demand services). Thus, the system invests on technologies throughout the planning horizon when it becomes necessary.

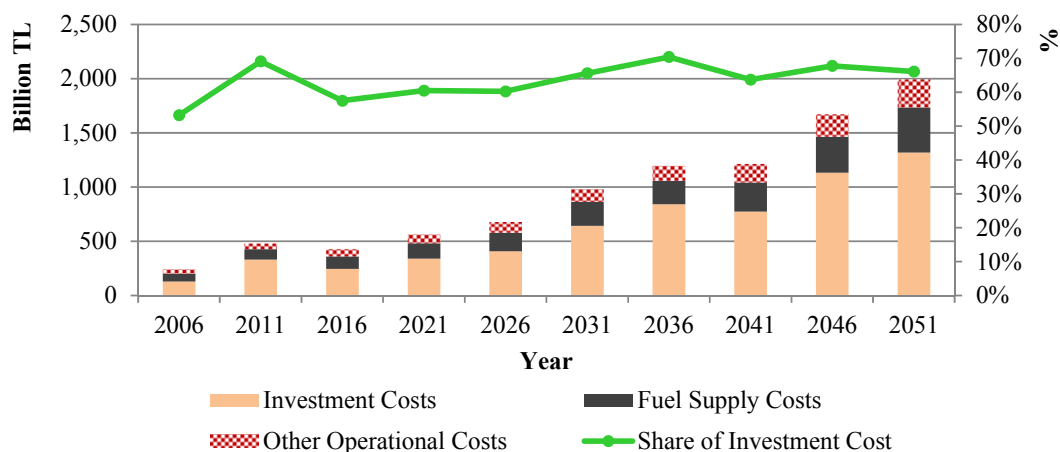


Figure 7.9. Undiscounted system costs predicted in the Base scenario.

7.2. Results of the Emission Restrictions Scenarios

In this subsection, the results of the two different CO₂ emissions restriction scenarios are discussed. The European Union's 20-20-20 objective states achieving at least 20% reduction in greenhouse gas emissions⁹, 20% share of renewable energies in overall energy consumption, and 20% improvement in energy efficiency by 2020 (EC, 2008). Inspired by these objectives, in the emission restriction scenarios an overall 30% reduction target is applied and results are analyzed by focusing on the share of renewable energies and improvements in efficiency. Currently, there is neither nuclear power plant nor any CCS plant in Turkey. However, the opportunity to show the effect of emission restrictions under the availability of investment options regarding nuclear power and CCS plants, may help policy makers to better assess and evaluate their future options (especially with respect to potential nuclear and CCS plant investments). Accordingly, the following two emission restriction scenarios are defined (to be compared against the Base scenario).

- (i) EM1 Scenario: Emissions are restricted 30% below of those in the Base scenario (restrictions to become active after 2016),
- (ii) EM2 Scenario: Emissions are restricted 30% below of those in the Base scenario; additionally, investment into nuclear and CCS technologies are allowed up to a limit (restrictions to become active after 2016).

In the EM2 scenario, investment into nuclear electricity generation is allowed up to a certain percentage of the total generation as displayed in Table 7.4. In the national strategic planning documents for the 2010-2014 period, the Ministry of Energy and National Resources targets to produce at least 5% of the national electricity supply from nuclear power by 2023 (MENR, 2010). This target has been adapted together with a CCS plant capacity bounded up to a reasonable limit as shown in Table 7.4.

⁹ rising to 30% if there is an international agreement committing other developed countries to comparable emission reductions and economically more advanced developing countries to contributing adequately according to their responsibilities and respective capabilities.

Table 7.4. Nuclear and CCS plant limits allowed in the EM2 scenario.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Nuclear Power Share (%)	0%	0%	0%	5%	10%	15%	20%	25%	30%	40%
CCS Plant Capacity (PJ)	0	0	100	200	300	450	600	800	1000	1200

7.2.1. Energy Supply

Both of the emission scenarios reduce total energy supply levels compared to the Base scenario results (as can be seen from Figure 7.10 and Table 7.5). Since the same final energy demand volume is satisfied by less total energy supply, it can be said that the efficiency of the system increases as well. For example, the EM1 and the EM2 scenarios lead to 19.2% and 18.4% reductions respectively on total energy supply levels in 2016. The reductions in the total energy supply needs of the two emission restrictions scenarios decrease after 2036. In 2041, the EM1 scenario reduces total energy supply 18.2%, while the EM2 scenario reduces 14%. This is primarily because of the annual potentials of low (or no) emission energy sources (e.g. renewable energy sources). Since the maximum annual potentials of those resources are approached after 2036, the improvements in efficiency levels slow down.

On the other hand, the difference in the total energy supplies between the two emission restriction scenarios primarily comes from the impact of the CCS technologies. Coal is the largest contributor of the emissions, so the system prefers to shift away from coal and invest in alternative sources when there are severe restrictions on emissions. However, the CCS technologies enable the consumption of coal while reducing emissions.

Table 7.5. Total energy supply reductions (compared to the Base scenario) predicted in the EM1 and EM2 scenarios.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
EM1	0.0%	0.4%	19.2%	22.0%	21.8%	21.0%	19.3%	18.2%	18.3%	18.3%
EM2	0.0%	0.4%	18.4%	20.7%	19.0%	17.7%	15.4%	14.0%	13.6%	12.1%

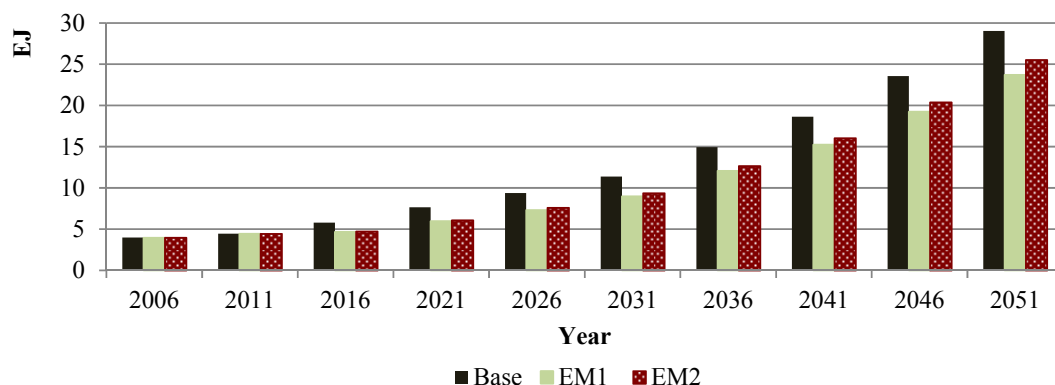


Figure 7.10. Total energy supplies predicted in the Base, EM1 and EM2 scenarios.

Since coal is the greatest contributor of the emissions, the most significant impact of emission restriction scenarios is observed on coal supply levels. Coal share increases under the emission restriction scenarios as well, but at lower levels (compared to the Base scenario). Between the two emission restriction scenarios, coal is used more in the EM2 scenario (as can be seen in Figure 7.11). In 2016 and 2021, (i.e. the periods in which the CCS plant capacity is severely restricted), the coal needs of the two emission restriction scenarios are similar. However, the increase in the CCS capacities in the mid-terms, leads to a much larger share of coal in the EM2 scenario (CCS Plants are used in more capacities in this case). On the other hand, reliance on nuclear power is increased in the last periods of the planning horizon as well, thereby replacing coal especially in electricity generation in the EM2 scenario. Thus, the coal consumption levels in the two scenarios get closer again, being still somewhat higher in the EM2 scenario.

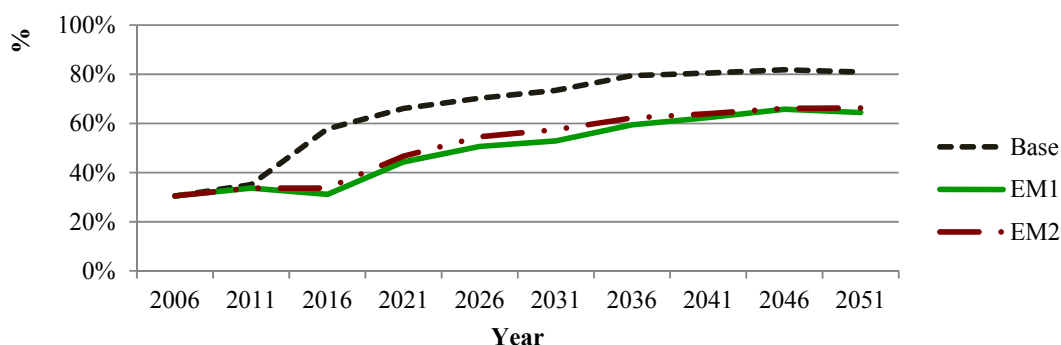


Figure 7.11. Coal shares in total energy supplies predicted in the Base, EM1, and EM2 scenarios.

Unable to deploy neither nuclear power nor the CCS technologies, the EM1 scenario naturally relies more on efficient technology usage. However, both scenarios support the diffusion of low and zero emission energy sources under emission restrictions (as can be seen from Table 7.6 and Table 7.7). In addition, the use of natural gas, a lower emission fuel compared to coal and oil, grows. The optimization process normally moves away from natural gas, since there are cheaper alternatives. However, when renewable energy sources, nuclear, and CCS capabilities are not available (or limited), natural gas becomes unavoidable. On the other hand, alternative fuel usage (e.g. ethanol and methanol) in the transportation sector is higher in the EM1 scenario, especially in later periods (even though they are used in considerable amounts in the EM2 scenario as well). These fuels are primarily replaced by oil source.

Table 7.6. Energy supplies predicted in the EM1 scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1497.1	1455.7	2648.9	3717.0	4752.7	7177.6	9509.9	12657.7	15286.5
Natural Gas	1157.5	1295.4	1479.1	1312.1	1336.0	1643.3	2297.2	2892.0	3434.3	4868.5
Oil	1235.1	1295.9	1050.3	1279.4	1453.4	1618.2	936.2	843.4	785.5	889.6
Hydro	164.8	196.8	315.5	390.7	460.2	504.0	504.0	504.0	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	699.6	985.8	1306.2	1611.8
Wind	0.4	13.6	249.1	249.1	249.1	353.2	353.2	394.3	417.3	417.3
Bio	178.7	111.0	100.0	73.9	97.7	98.3	89.2	100.0	122.2	120.7
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.5
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.1	4440.5	4674.8	5975.5	7332.8	8987.6	12074.1	15246.0	19243.3	23714.6

Table 7.7. Energy supplies predicted in the EM2 scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1496.0	1592.9	2837.4	4148.7	5381.0	7877.3	10251.3	13476.6	16912.7
Natural Gas	1157.5	1296.2	1379.3	1212.2	1125.8	1114.7	1622.6	2197.3	2795.3	3587.6
Oil	1235.0	1295.9	1071.0	1277.9	1474.2	1738.9	1139.3	1151.3	1139.5	1131.4
Hydro	164.8	196.8	304.9	358.9	371.6	504.0	504.0	504.0	502.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	699.6	932.4	1289.1	1668.4
Wind	0.4	13.6	249.1	249.1	249.1	305.6	353.2	353.2	353.2	353.2
Bio	178.7	111.0	100.0	73.9	97.7	87.6	89.2	100.0	66.5	100.0
Nuclear	0.0	0.0	0.0	46.3	114.0	212.9	350.3	525.9	732.9	1252.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.5
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.1	4440.1	4722.3	6077.2	7600.4	9362.6	12652.5	16031.9	20371.4	25525.5

Figure 7.12 and 7.13 underline the changes in the share of zero carbon fuels in each scenario implementation. The emission restriction scenarios realize peaks by 2016 and 2036. The peaks and the deep valleys are the results of the availability of zero-carbon fuels in the related periods. For example, in the EM1 scenario, under the drastic emission restriction, renewable energy technologies are relied upon immediately in 2016 and the share realizes its peak of 17.3%. However, even though the hydro and wind energy resources approach their maximum potentials, they cannot maintain the high shares in total energy supply, which exhibits a drastic growth parallel to the increase in total energy demand. On the other hand, the sharp peak in 2036 is the result of a new zero carbon entry, hydrogen (as realized in the Base scenario). The same peaks are presented in the EM2 scenario as well. The share of zero carbon fuels in the EM2 scenario surpasses 17% in 2036 and remains above that level till the end of the planning horizon (in the EM1 scenario it never goes up to 17.3% after 2016). This is the result of the significant nuclear power generation capability after 2036.

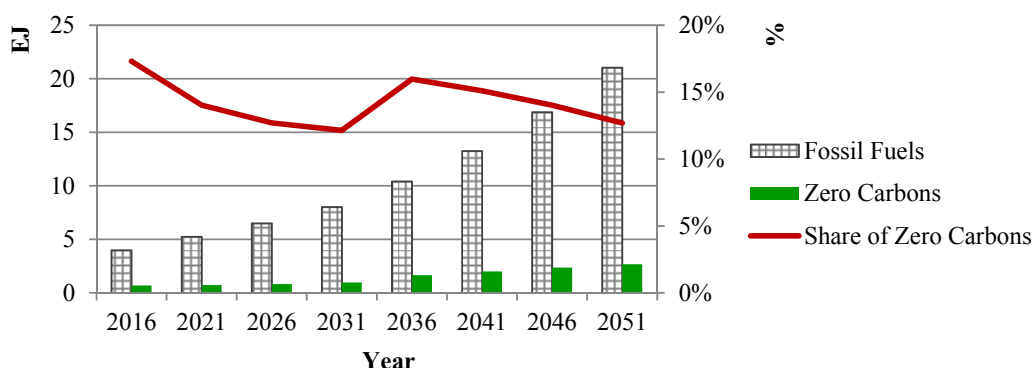


Figure 7.12. Fossil and zero carbon fuel supplies predicted in the EM1 scenario.

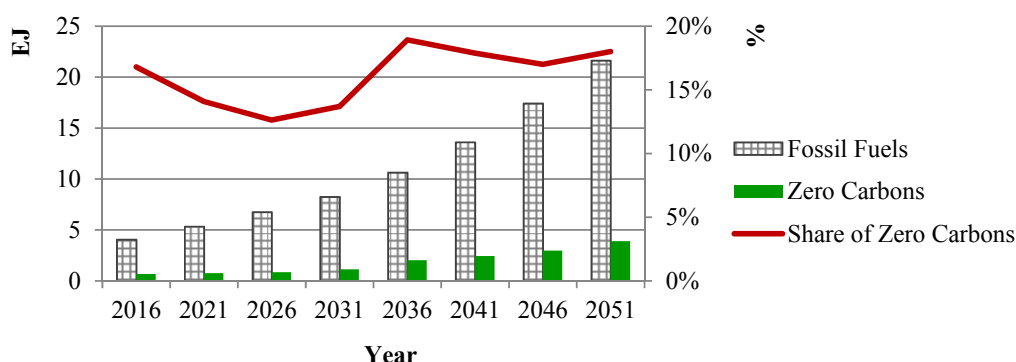


Figure 7.13. Fossil and zero carbon fuel supplies predicted in the EM2 scenario.

As can be seen from Figure 7.14, both emission restriction scenarios have better efficiency performances (as compared to the Base scenario). However, the EM1 scenario is more efficient; since the EM2 scenario allows clean coal usage, accordingly, there is less need to use efficient technologies. On the other hand, both scenarios achieve 20% improvement on energy efficiency in 2021: 22% improvement in the EM1 scenario; 21% improvement in the EM2 scenario.

In addition, emission restrictions scenarios delay the depletion of coal reserves, thereby significantly affecting import levels. Since low and zero carbon fuels are better deployed in the emission restrictions scenarios, national reserves remain available longer; coal reserves are exhausted by 2031 instead of 2026. However, in the first half of the planning horizon, the import dependence rates remain above the Base scenario levels (as can be seen from Figure 7.15). The basic reasoning of this is the heavier usage of imported natural gas in the first half. The potential of zero carbon fuels is not sufficient to satisfy

demand requirements in those periods. Thus, the optimization process finds natural gas as another low emission source, leading to a higher dependence on imports. However, after 2031, with the contribution of increased potentials of renewable energy sources and also nuclear energy (in the EM2 scenario), import dependence goes lower than its level in the Base scenario.

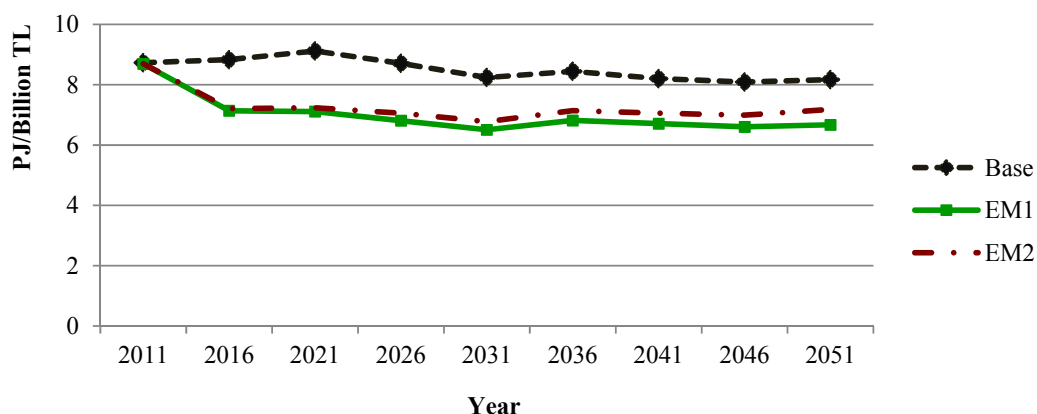


Figure 7.14. Energy intensities predicted in the Base, EM1, and EM2 scenarios.

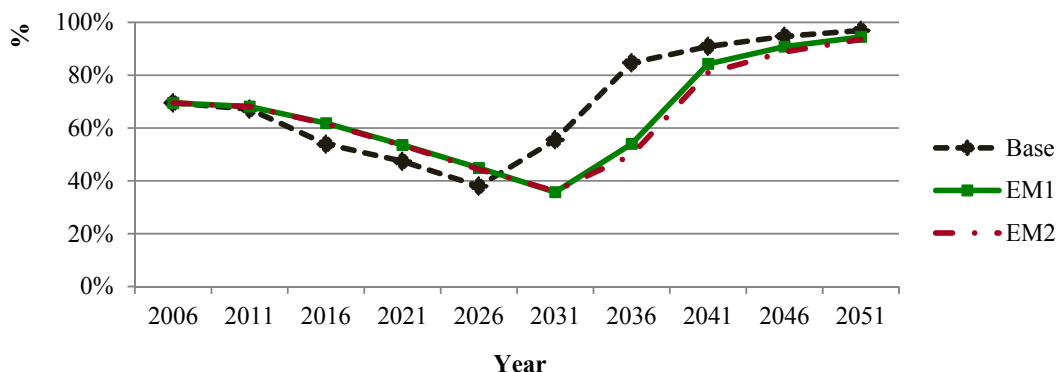


Figure 7.15. Import dependence rates predicted in the Base, EM1, and EM2 scenarios.

7.2.2. Electricity Generation

Emission restriction scenarios also feature less electricity generation compared to the Base scenario (as can be seen from Figure 7.16).

These declines are mainly due to the substitution of electricity with natural gas in the residential sector. The reduction levels, on the other hand, are very similar in the two emission restriction scenarios, especially in the first half of the planning horizon. Natural gas usage in residential sector instead of electricity is more in EM2 scenario with a small extend in later periods. This makes electricity generation slightly lower in the EM2 scenario.

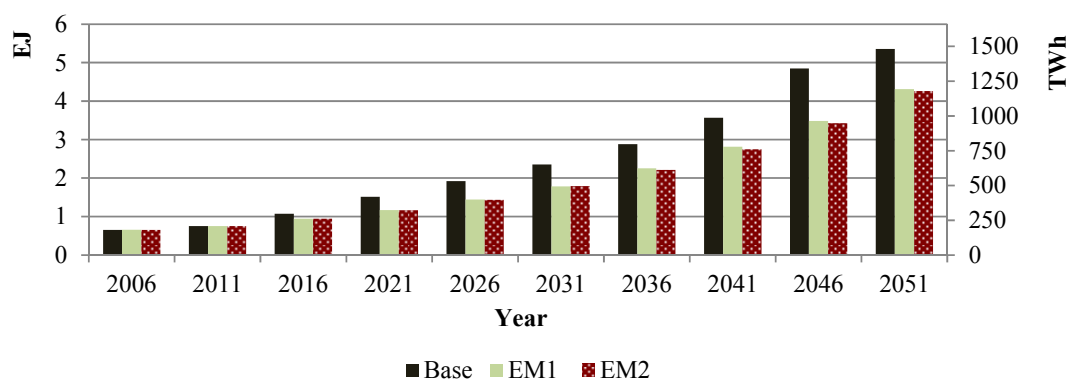


Figure 7 .16. Electricity generation levels predicted in the Base, EM1, and EM2 scenarios.

In 2016, coal fueled electricity generation is 95.5% less in the EM1 scenario and 93% less in the EM2 scenario compared to the Base scenario (as can be seen from Figure 7.17). Then, throughout the planning horizon these differences shrink. The renewable energy supplies approach their maximum potentials, coal, which is the cheapest alternative, becomes economic again. Coal is consumed more extensively in the EM2 scenario to generate electricity until 2031. From this year onwards reliance on nuclear power is increased, thereby replacing coal with nuclear energy.

Electricity generation capacities from coal electricity generation technologies are replaced to a large extend by hydro, wind, and nuclear technologies in both emissions restriction scenarios (as can be seen from Table 7.8 and 7.9). Since annual availability factors of hydro and wind electricity generation technologies are less than 50%, total installed capacities become higher than the Base scenario levels under emission restriction scenarios. Clearly, to generate the same amount of electricity, renewable electricity generation technologies are needed in higher capacities. The only exceptions are the last two periods of the EM2 scenario. In these periods, nuclear plants (which have the highest

load factors among all electricity generation technologies) are replaced with other electricity generation technologies, especially at wind energy resources.

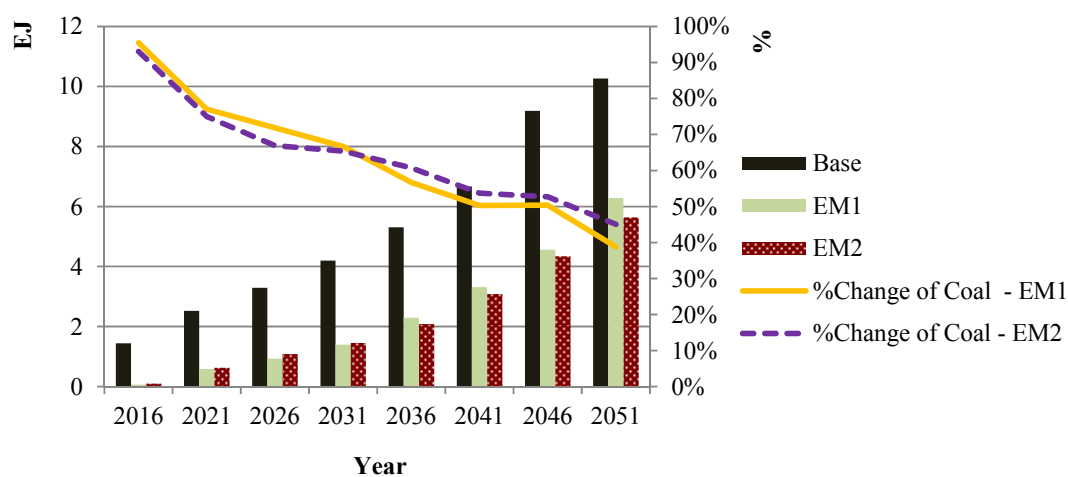


Figure 7.17. Coal supplies to electricity generation predicted in the Base, EM1, and EM2 scenarios.

Table 7.8. Installed capacity predicted in the EM1 scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	11.0	9.8	22.5	27.0	42.1	68.2	98.3	112.5
Natural Gas	10.3	18.7	29.0	28.9	28.4	29.8	38.2	37.2	37.2	60.0
Petroleum Products	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	25.0	31.0	36.5	40.0	40.0	40.0	40.0	40.0
Wind	0.1	1.3	28.6	28.6	28.6	43.6	43.6	51.3	55.6	55.6
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	36.1	50.5	96.2	100.8	118.6	142.8	164.1	196.8	231.2	268.2

Table 7.9. Installed capacity predicted in the EM2 scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	12.2	11.0	24.3	26.6	38.1	54.7	74.4	94.2
Natural Gas	10.3	18.7	29.0	28.9	28.4	28.9	36.7	42.3	50.7	57.1
Petroleum Products	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	24.2	28.5	29.5	40.0	40.0	40.0	39.8	40.0
Wind	0.1	1.3	28.6	28.6	28.6	36.7	43.6	43.6	43.6	43.6
Nuclear	0.0	0.0	0.0	0.5	1.3	2.4	3.9	6.2	8.9	15.7
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	36.1	50.5	96.6	100.0	114.6	137.2	162.4	186.9	217.6	250.7

7.2.3. Renewable Energy Sources

As can be seen from Figure 7.18, in the EM1 scenario, renewable energy share jumps to 14.4% in 2016 (from 7.6% in 2011). Then, throughout the planning horizon, even though the renewable energy supply levels are still high, they cannot maintain the high shares in total energy supplies, which exhibits a drastic growth parallel to the increase in total energy demand. Additionally, some of the renewable energy sources are replaced by nuclear energy and CCS technologies allow clean coal consumption that decrease the efficiency of the system (i.e. increase the total energy supply). Thus, the renewable energy source share is lower in the EM2 scenario.

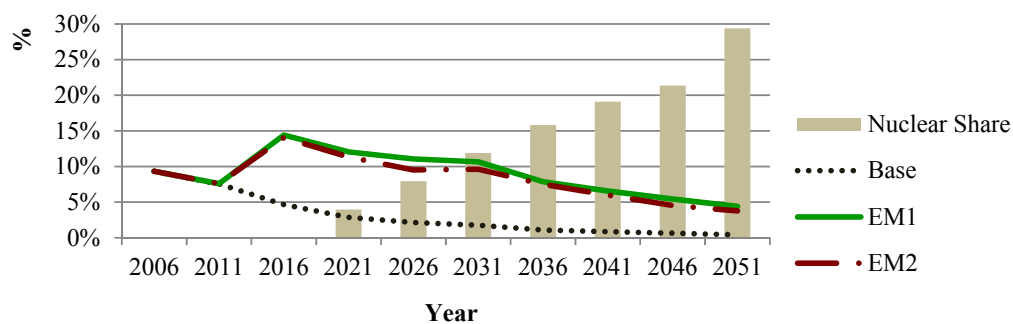


Figure 7.18. Renewable and nuclear energy shares predicted in the Base, EM1, and EM2 scenarios.

7.2.4. Costs

The cost structures are very similar in both emission restriction scenarios (as can be seen from Figure 7.19 and 7.20). Investment costs are the mostly affected ones. They increased in both scenarios compared to the Base scenario. The highest difference of investment costs from the Base scenario levels is observed in 2016. In this year, emission restriction scenarios become active and large investments on low and zero emission and efficient technologies are realized immediately. On the other hand, the large investments in 2036 (in which most of the technologies reach end of their lives and need to be invested again) are realized in those scenarios as well. The share of investment costs in the total energy cost is highest in 2036 in all three scenarios; the Base, EM1, and EM2 scenarios (as can be seen from Table 7.10).

Table 7.10. Share of investment costs predicted in the Base, EM1, and EM2 scenarios.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base	53.2%	69.1%	57.5%	60.5%	60.2%	65.6%	70.4%	63.7%	67.8%	66.1%
EM1	53.3%	69.0%	71.1%	61.9%	64.8%	71.1%	75.5%	73.6%	72.2%	72.5%
EM2	53.3%	69.0%	71.4%	62.1%	65.0%	72.4%	75.9%	71.6%	70.4%	74.3%

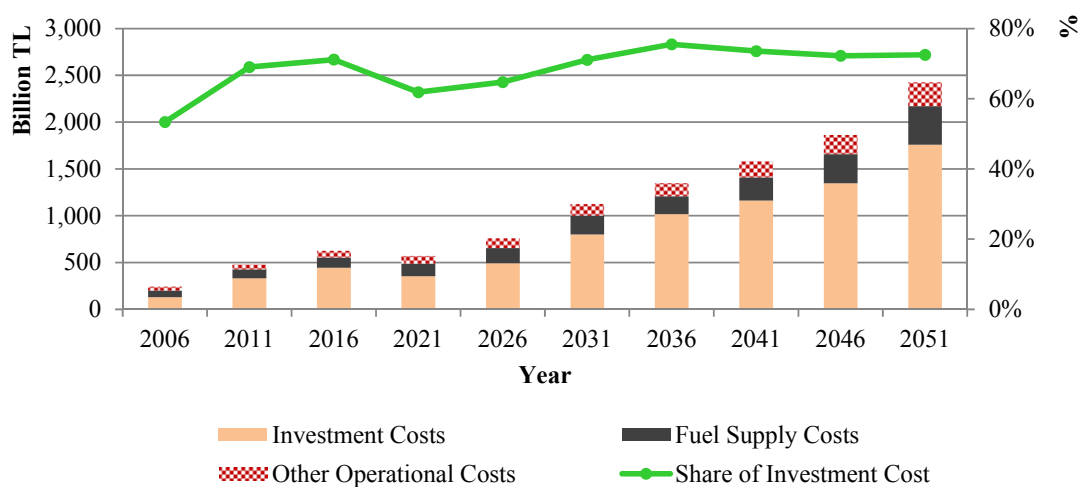


Figure 7.19. Undiscounted system costs predicted in the EM1 scenario.

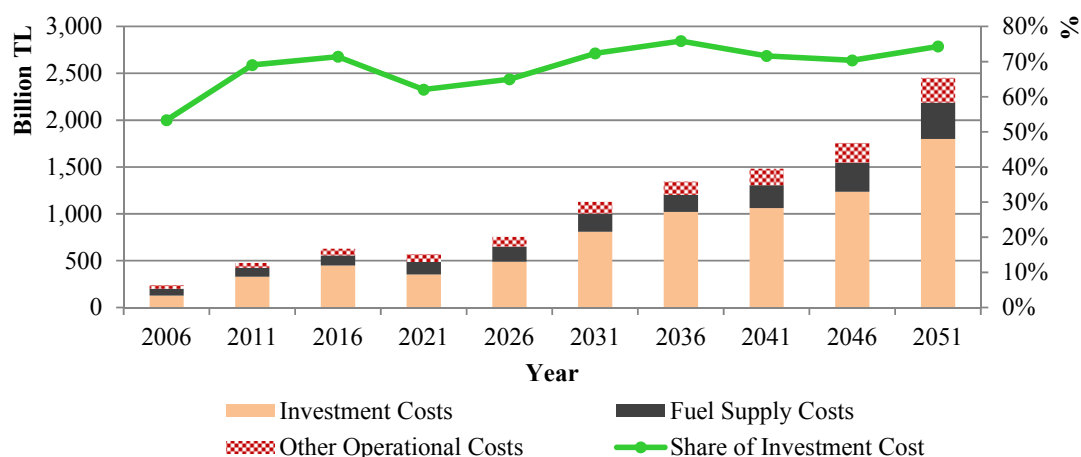


Figure 7.20. Undiscounted system costs predicted in the EM2 scenario.

Emission abatement cost estimates differ in emission restriction scenarios. Both of those scenarios necessitate huge investment expenditures in 2016 in order to be able to comply with the emissions bounds (as can be seen from Figure 7.21). The investments continue throughout the planning horizon. On the other hand, between the two emission restriction scenarios, the EM1 scenario results in higher emission reduction costs; 304.2 TL/tCO₂ in 2026, 388.5 TL/tCO₂ in 2036, and 309.3 TL/tCO₂ in 2046. This result is expected; since the CCS technologies are cheaper to procure than other low and zero emission technologies, the need for high cost investments is lower in the EM2 scenario.

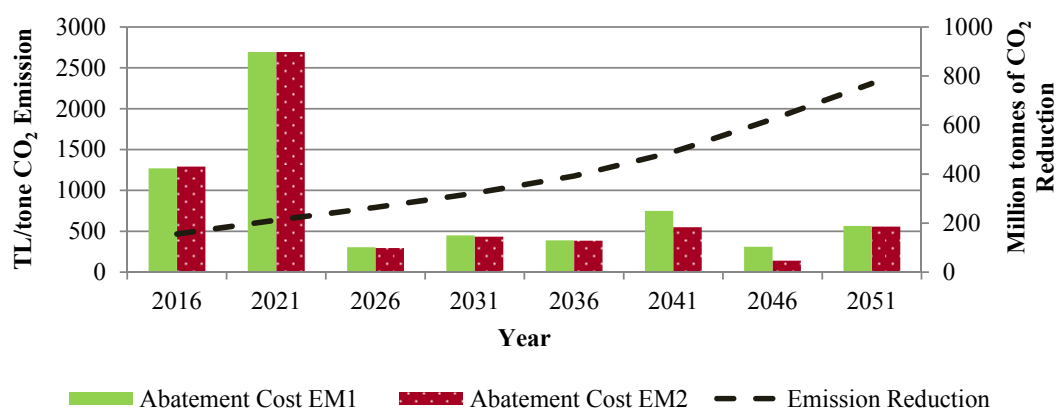


Figure 7.21. Cost of CO₂ emissions predicted in the EM1 and EM2 scenarios¹⁰.

¹⁰ Abatement cost is the cost of per tonne CO₂ emission reduction; cost increase (or decrease) compared to the Base scenario is divided by emission decrease (or increase) compared to the Base scenario.

7.3. Results of the Emission Penalty Scenarios

In this section, the other emission conscious scenario group that implements a penalty (fine) on emissions is discussed. In this scenario group, instead of bounding, a penalty fine has been applied on emissions that exceeds the available permits. In 2003, EC announces its intention to apply excess emission penalties on each tonne of CO₂ as a climate change action. However, this decision has not been realized yet. Inspired by this objective, in the context of emission penalty scenarios, fines are applied on excess emissions and the results are analyzed by focusing on the share of renewable energy sources and on improvements in efficiency as well. The opportunity to show the effect of emission penalties may help policy makers to evaluate the impacts of projected penalty fines on emissions. Availability of nuclear and CCS technologies under scenario circumstances are also evaluated as a second penalty scenario. The bounds applied on nuclear energy and CCS technologies in emission restriction scenarios are also used in this scenario group. The maximum available permit for emissions are defined as 30% below of the total emissions that are realized in the Base scenario. This way, it becomes possible to compare the results with the emission restriction scenarios. 100 Euro (235 TL) per tonne of CO₂, the penalty fine discussed by EC, is determined as the penalty level of the scenario. Accordingly, the following two scenarios are defined (to be compared against the Base scenario).

- (i) PE1 Scenario: 235 TL is applied on per tonne of CO₂ emissions exceeding available permits, which is 30% below of those in the Base scenario (the restrictions to become active after 2016).
- (ii) PE2 Scenario: 235 TL is applied on per tonne of CO₂ emissions exceeding available permits, which is 30% below of those in the Base scenario; additionally, investment into nuclear and CCS technologies are allowed up to a limit displayed in the Table 7.11 (the restrictions to become active after 2016).

Table 7.11. Levels of emission penalties and upper bounds on investments into nuclear/CCS technologies.

	2016	2021	2026	2031	2036	2041	2046	2051
Penalty Fine (TL/ton CO₂ emission)	235	235	235	235	235	235	235	235
Nuclear Power Share (%)	0%	5%	10%	15%	20%	25%	30%	40%
CCS Technology Capacity (PJ)	100	200	300	450	600	800	1000	1200

7.3.1. Energy Supply

Both of the emission penalty scenarios reduce the total energy supply levels, compared to the Base scenario (as can be seen from Figure 7.22). On the other hand, the energy supply levels of two penalty scenarios are very similar to each other. However, in the long run, the PE1 scenario provides lower energy supplies (invests more on efficient technologies). The increasing availabilities of nuclear power and CCS plant capacities in the PE2 scenario show its effects in the later periods. However, compared to emission restriction scenarios, efficiency improvements in penalty scenarios in early periods seem unremarkable (as can be seen from Figure 7.23). Clearly, the emission restriction scenarios are more effective than the penalty scenarios. Therefore, it can be said that restricting emissions up to a level are more effective than applying a penalty on excess emissions from the same restriction levels. In other words, the optimization process prefers to use more efficient technologies when emissions are forced below a certain level. However, in later periods, the gap between total energy supply levels of two scenario groups seems like declining. The EM2 and the PE1 scenarios provide almost the same supplies in the last two periods. This means that a similar total energy supply profile can be achieved in the long run by applying a penalty on excess emissions instead of bounding emissions with the existence of nuclear energy source and CCS technologies (see Appendix CD for higher penalty fines).

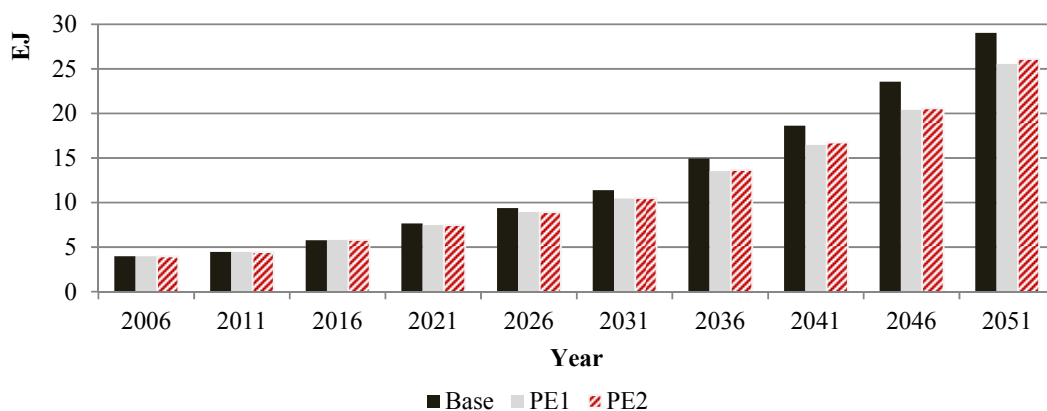


Figure 7.22. Total energy supplies predicted in the Base, PE1, and PE2 scenarios.

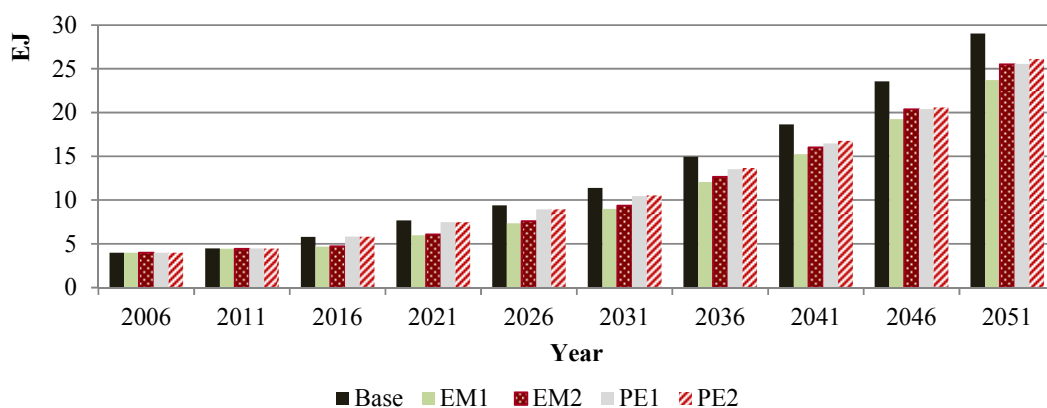


Figure 7.23. Total energy supplies predicted in the Base, EM1, EM2, PE1, and PE2 scenarios.

Efficiency improvements in penalty scenarios seem unremarkable in the first half of the planning horizon (Penalty scenarios provide almost the same supplies with the Base scenario until 2026). The PE1 scenario provides better results compared to PE2 scenario (lower energy source supplies and higher efficiencies) in the long run. Under the absence of nuclear and CCS technologies, the PE1 scenario invests more on efficient technologies. Since CCS technologies enable the consumption of coal while containing emissions, the optimization process prefers to invest less on efficient technologies compared to the PE1 scenario.

Table 7.12. Total energy supply reductions (compared to the base scenario) predicted in the PE1 and PE2 scenarios.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
PE1	0.0%	0.0%	0.6%	2.3%	4.8%	8.1%	9.5%	11.6%	13.4%	12.0%
PE2	0.0%	0.0%	0.6%	2.3%	4.8%	7.5%	8.7%	10.1%	12.6%	10.0%

Table 7.13. Energy supplies predicted in the PE1 scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1565.4	3332.9	4874.1	6202.9	7327.5	10241.2	12094.6	14387.6	19067.7
Natural Gas	1157.5	1245.9	1014.3	959.1	922.4	966.3	1065.7	1486.1	2685.85	2769.9
Oil	1237.8	1295.9	1188.5	1391.9	1590.5	1865.1	1236.3	1485.1	1184.8	1178.0
Hydro	164.8	196.8	176.5	176.5	156.2	196.8	196.6	196.6	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	699.4	932.3	1272.6	1669.3
Wind	0.4	13.6	13.6	16.4	16.4	65.6	65.6	249.1	249.1	249.1
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	100.0	100.0
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3978.9	4459.3	5819.7	7482.3	8934.3	10455.6	13532.1	16466.8	20400.2	25554.0

Table 7.14. Energy supplies predicted in the PE2 scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1565.4	3332.9	4874.1	6202.9	7169.1	10004.6	11843.9	14000.8	18394.3
Natural Gas	1157.5	1245.9	1014.3	959.1	922.4	966.3	1065.7	1486.1	2488.9	2760.2
Oil	1237.8	1295.9	1188.5	1391.9	1590.5	1865.1	1236.3	1485.1	1184.8	1178.0
Hydro	164.8	196.8	176.5	176.5	156.2	196.8	196.6	196.6	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	699.4	932.3	1272.6	1669.3
Wind	0.4	13.6	13.6	16.4	16.4	65.6	65.6	249.1	249.1	249.1
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	100.0	100.0
Nuclear	0.0	0.0	0.0	0.0	0.0	235.5	369.9	541.9	781.6	1263.7
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3978.8	4459.3	5819.7	7482.3	8934.3	10532.6	13665.4	16758.0	20597.9	26134.6

Since the emissions are lower in the early periods, the optimization process prefers paying some penalties rather than moving sharply into low or zero emission technologies. However, in the later periods, penalties get larger (due to the increase in demand and so emissions) and the optimization process prefers to invest on low and zero carbon fuels. That explains the increase in zero carbon fuel shares especially after 2031 (as can be seen from Figure 7.24 and 7.25). In addition, zero carbon fuel shares in the PE2 scenario is almost 50% higher than that of the PE1 scenario after 2031 (due to the opportunity of nuclear investments). However, share of zero carbon fuels in emission restriction scenarios is still much higher than those in emission penalty scenarios for each period. This shows that under the current penalty cost profile the system prefers to pay penalty cost for excess emissions instead of investing on zero and low emission technologies.

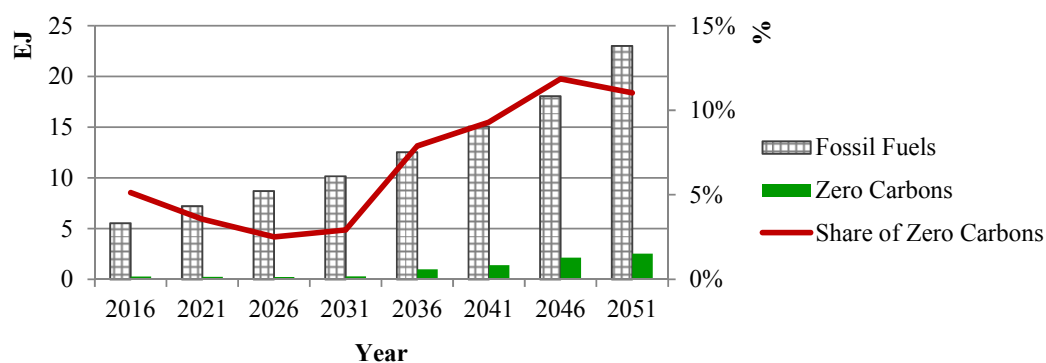


Figure 7.24. Fossil and zero carbon fuel supplies predicted in the PE1 scenario.

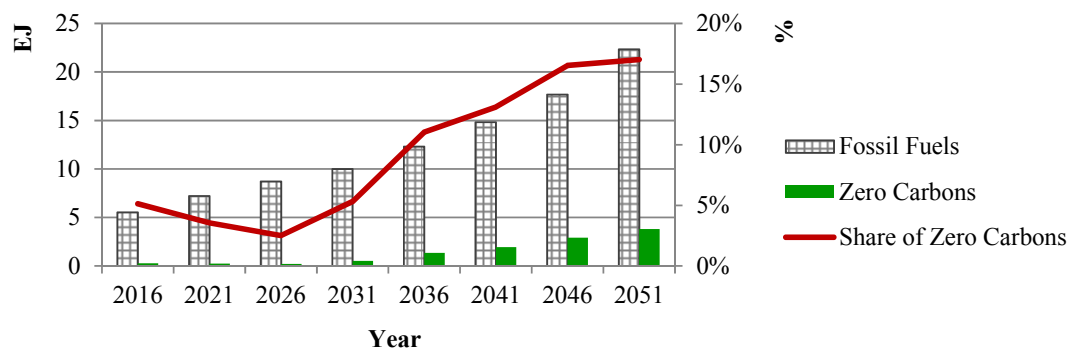


Figure 7.25. Fossil and zero carbon fuel supplies predicted in the PE2 scenario.

As can be seen from Figure 7.26, both scenarios improve the efficiency at the same levels. Since they produce almost the same total energy supply levels, except slight difference in the last periods, this result is expected. The highest improvement is 13% in 2046.

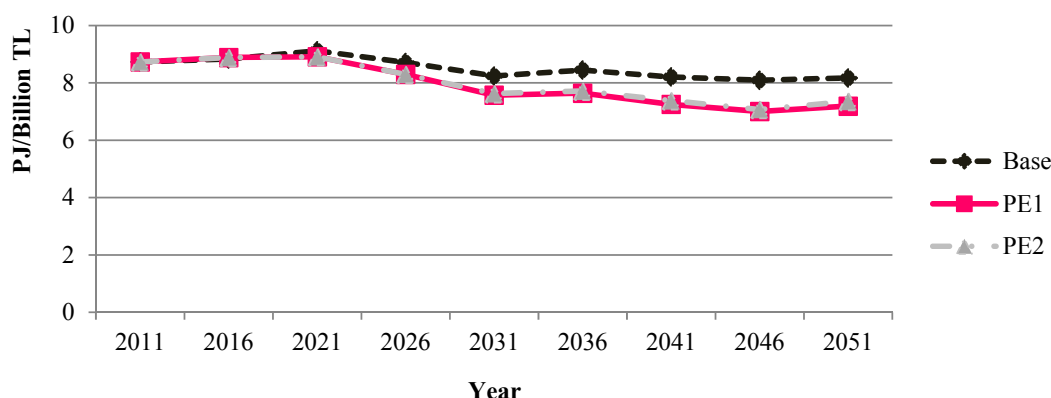


Figure 7.26. Energy intensities predicted in the Base, PE1, and PE2 scenarios.

Emission penalty scenarios have the same energy supply trends with the Base scenario for almost 5 periods. Since the optimization process prefers to pay penalties in both scenarios (instead of investing into low and zero emission technologies), coal supply levels stay almost unchanged. As a result, national reserves are exhausted at the same period with the Base scenario. On the other hand, large CCS technology availabilities in the last two periods brings the import rate slightly up in the PE2 scenario. In addition, when the last three periods are checked, it is observed that import levels of emission restriction scenarios are similar to the levels observed in the penalty scenarios.

On the other hand, it is interesting to note that in the last three periods of the planning horizon, the import dependence rates of the penalty scenarios resemble the emission restrictions and the Base scenario results. This means that once the national reserves are exhausted, all scenarios feature the same import dependence rates. This observation illustrates that Turkey will be extremely dependent on imported fuels in the mid-future, if the current energy profile and dynamics do not change. The country needs to establish new and alternative energy sources.

7.3.2. Electricity Generation

Electricity generation volumes decrease to very similar levels in both emission penalty scenarios (as can be seen from Figure 7.28). However, compared to the emission restriction scenarios, the emission penalty scenarios provide higher generation levels until 2036. After this period, on the other hand, generation volumes approach each other.

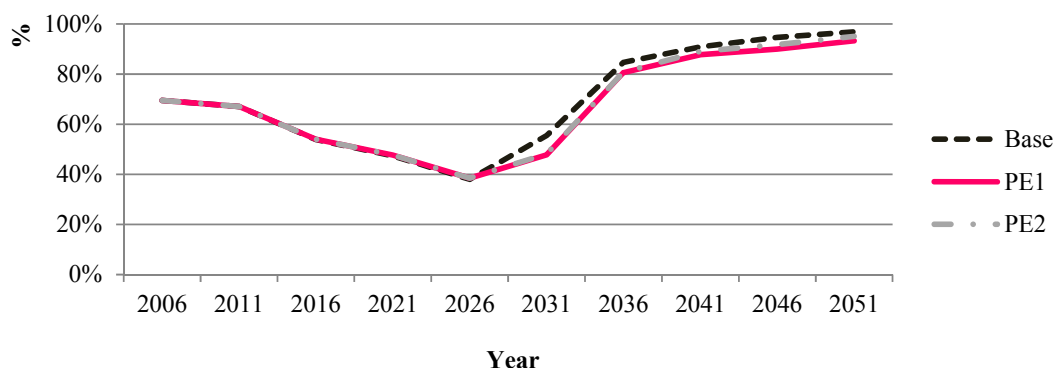


Figure 7.27. Import dependence rates predicted in the Base, PE1, and PE2 Scenarios.

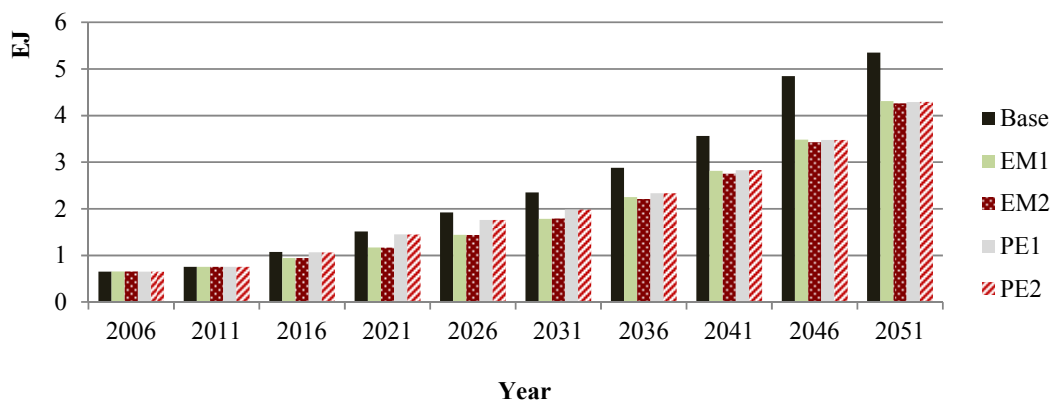


Figure 7.28. Electricity generation levels predicted in the Base, EM1, EM2, PE1, and PE2 scenarios.

Emission penalty scenarios, like emission restriction scenarios, lead reductions in coal electricity generation volumes (as can be seen from Figure 7.29). However, the change of coal supply levels in 2016 (which is the first penalty application year) compared to the Base scenario levels is less than 1%, in contrast to more than 90% decrease in emission restriction scenarios.

The emission penalty scenarios start to act against coal (use coal in lower amounts) in 2021. However, the reduction level in coal fueled electricity generation approaches the emission restriction scenario levels in 2046. On the other hand, between the two emission penalty scenarios, the PE2 scenario needs less coal because of the nuclear power availability. In 2036, coal supply volume is 29.6% less in the PE1 scenario and 34% less in the PE2 Scenario compared to the Base scenario levels. In contrast to the emission restriction scenarios, through the periods reduction rates grow.

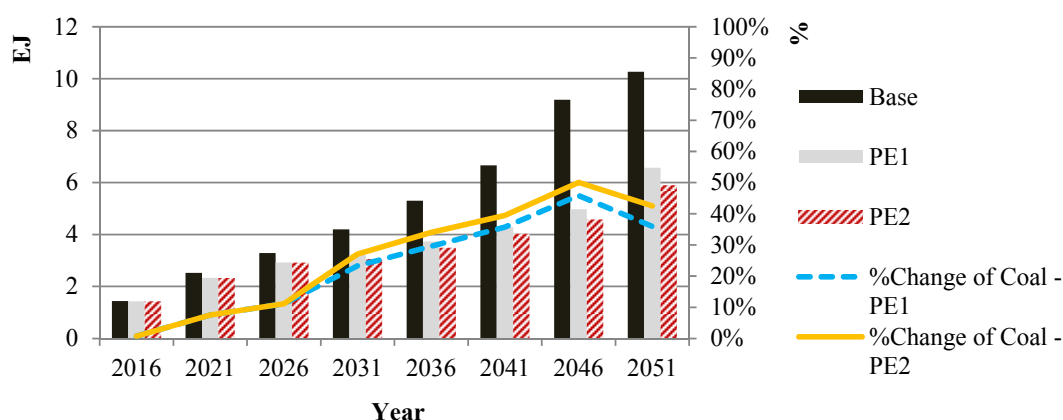


Figure 7.29. Coal supplies to electricity generation predicted in the Base, PE1, and PE2 scenarios.

Nuclear and renewable energy resources become attractive in the later periods (as demands and the emissions grow and penalty becomes higher). At some point investing on renewable energy sources (mostly on wind and hydro energy sources) becomes more preferable than paying penalties to the system (which is around 2041 and 2046). However, this planning horizon is not long enough to see the penalty and low or zero emission technology interactions clearly. Nevertheless, it again shows that in the long run penalty costs may force renewable technology usage (or as mentioned earlier higher penalty costs are needed to use renewable energy sources in earlier periods).

Table 7.15. Installed capacities predicted in the PE1 scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.20	12.30	21.81	37.01	52.38	56.29	84.95	104.20	115.57	144.85
Natural Gas	10.04	18.72	19.26	22.94	27.87	26.23	16.25	16.71	23.93	31.56
Oil	2.42	2.42	2.41	2.41	2.39	2.38	0.00	0.00	0.00	0.00
Hydro	13.06	15.60	13.99	14.00	12.38	15.60	15.59	15.59	39.95	39.95
Wind	0.10	1.32	1.32	1.57	1.57	6.60	6.60	28.60	28.60	28.60
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	35.83	50.53	58.97	78.10	96.76	107.28	123.56	165.27	208.23	245.14

Table 7.16. Installed capacities predicted in the PE2 scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.20	12.30	21.81	37.01	52.38	53.67	80.92	98.03	106.45	130.02
Natural Gas	10.04	18.72	19.26	22.94	27.87	26.23	16.25	16.74	23.95	31.65
Oil	2.42	2.42	2.41	2.41	2.39	2.38	0.00	0.00	0.00	0.00
Hydro	13.06	15.60	13.99	14.00	12.38	15.60	15.59	15.59	39.95	39.95
Wind	0.10	1.32	1.32	1.57	1.57	6.60	6.60	28.60	28.60	28.60
Nuclear	0.00	0.00	0.00	0.00	0.00	2.62	4.12	6.36	9.49	15.79
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	35.83	50.53	58.97	78.10	96.76	107.28	123.65	165.49	208.62	246.19

7.3.3. Renewable Energy Sources

Even though the renewable energy sources become attractive in the later periods under emission penalty scenarios, the share never goes more than 5% (as can be seen from Figure 7.30). Higher penalty costs are needed to force renewable energy source usage in earlier periods.

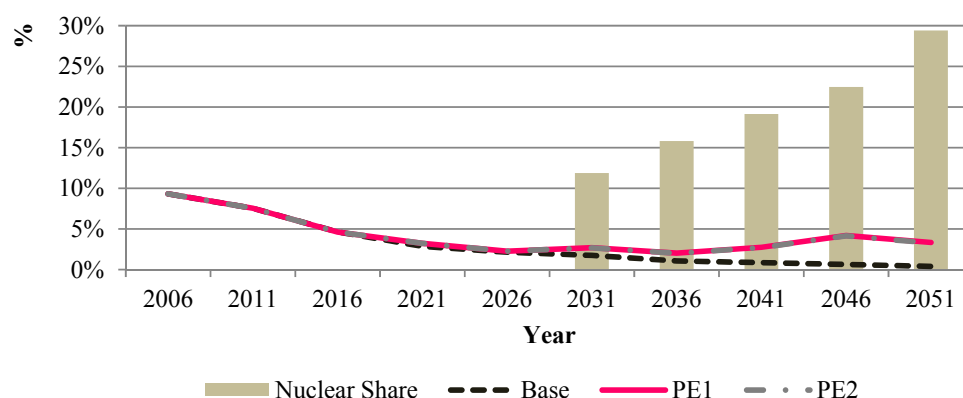


Figure 7.30. Renewable and nuclear energy shares predicted in the Base, PE1, and PE2 scenarios.

7.3.4. Emissions

It is clear that in the penalty scenarios, CO₂ emissions are reduced; the reduction levels are greater in later periods (as can be seen from Figure 7.31). Due to helping hand of the nuclear energy, emission levels turn out to be lower in the PE2 scenario especially in later periods. The PE1 Scenario reduces emissions by 5.4% in 2026, 12.1% in 2036, and 21.3% in 2046. On the other hand, the PE2 Scenario results in reductions of 11.7% in 2031, 22% in 2041, and 24.7% in 2051. As a result, the PE1 scenario reaches EC 2020 targets of emission reduction in 2046 while the PE2 scenario reaches in 2041.

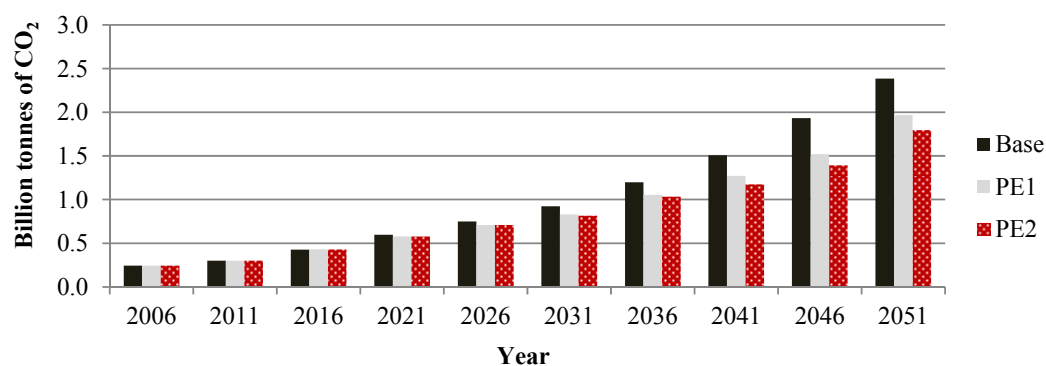


Figure 7.31. CO₂ emissions predicted in the Base, PE1, and PE2 scenario.

7.3.5. Costs

Similar to the results of the emission restriction and Base scenarios, investment cost levels obtained in the emission restriction scenarios have the highest shares in the undiscounted total system costs. The system costs are almost the same; they slightly differ from each other. The largest gap, 4%, is observed in 2031, in which a large nuclear investment is realized.

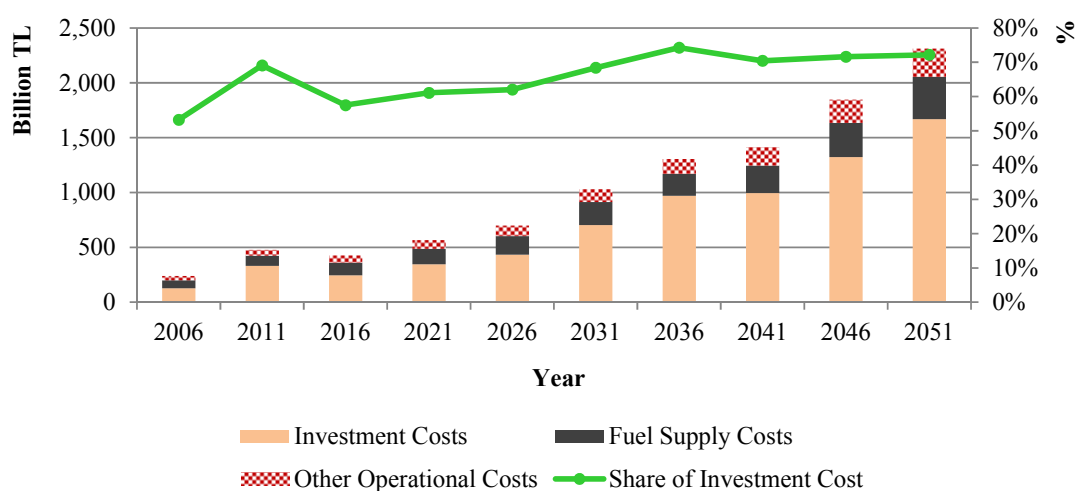


Figure 7.32. Undiscounted system costs predicted in the PE1 scenario.

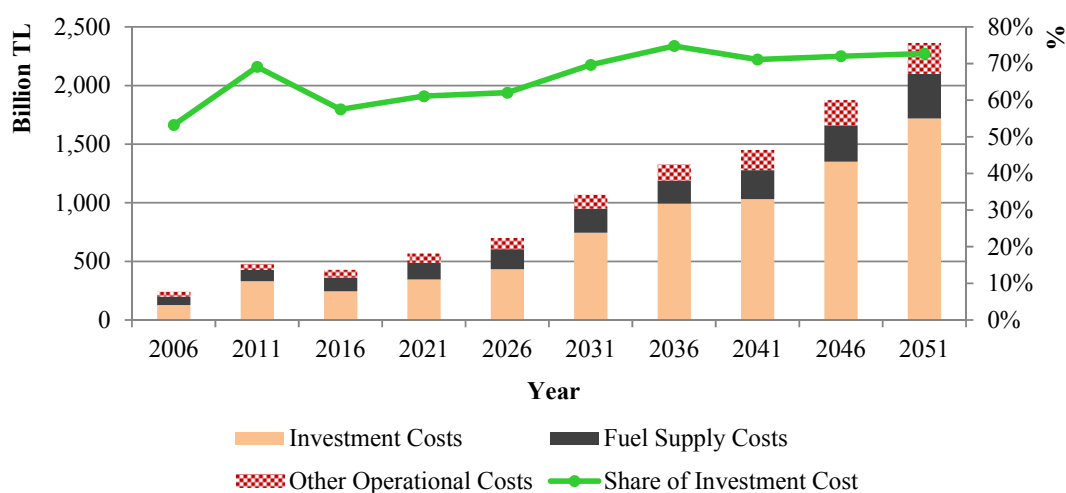


Figure 7.33. Undiscounted system costs predicted in the PE2 scenario.

The emission penalty scenarios lead to similar emission reduction levels and so similar abatement costs until 2026 (as can be seen from Figure 7.34). In contrast to the emission restriction scenarios, the emission penalty scenarios bring high investments on low and zero emission technologies after the first half of the planning horizon. The emission restriction scenarios, on the other hand, require a significant amount of investment in 2016 as soon as the emission bounds become active. On the other hand, between the two emission restriction scenarios, the PE2 scenario has a higher abatement cost in 2031. This difference is the result of expensive nuclear power investments in this year. In addition, emission reduction levels of the two scenarios are very similar in this period (so, they do not significantly affect the result). However, from this point onward the difference between the emission reduction levels grow and the PE2 scenario results less emission volumes (higher emission reduction levels). Therefore, even though the total system costs of the PE2 scenario are higher than the total system costs of the PE1 scenario, the cost of per tonne of CO₂ reduction becomes lower.

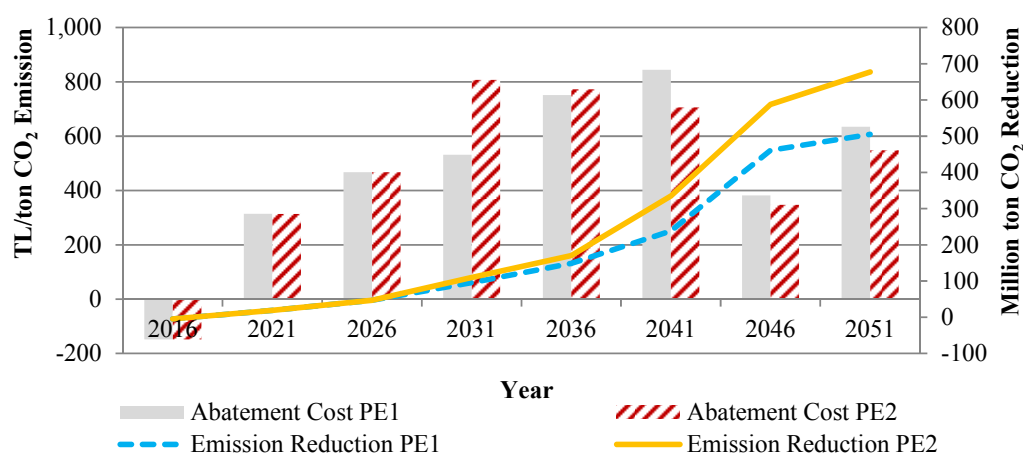


Figure 7.34. Cost of CO₂ emissions predicted in the PE1 and PE2 scenarios.

7.4. Results of the Coal Import Scenarios

According to the Base scenario, consumption of imported coal in the Turkish energy sector is projected to grow at a much faster rate during the later stages of the planning horizon (because of the relatively cheaper prices of imported coal, once national reserves are depleted). The share of imported coal in total energy supply reaches 81.8% in 2046,

which illustrates the country's high dependence on imports in the long run. A consequence of this dependence is the significant increase in CO₂ emissions (due to high usage of coal) and also risks associated with security of energy supply. Accordingly, the following scenario is defined (to be compared against the Base scenario).

- (i) IMP Scenario: Upper bounds imposed on coal imports, as displayed in Table 7.17 (the restrictions to become active after 2016). The bounds are kept higher in the early two periods to be more realistic. There may be long term contracts (which realized in 2006 or 2011) on coal imports that may cover those two periods and so it may not be realistic to have sudden decrease on coal imports.

Table 7.17. Coal import restrictions (in PJ).

	2016	2021	2026	2031	2036	2041	2046	2051
Upper Limit on Coal Import (PJ)	100	50	25	25	25	25	25	25

7.4.1. Energy Supply

Figure 7.35 displays total energy supply projections under the IMP scenario. The change in energy source supply levels rises throughout the planning horizon, has a peak in 2046 (at 31.2%) and then decreases in 2051. By comparison with the emissions restriction and penalty scenarios, the decreases in total energy supply levels are quite significant in the second half of the planning horizon.

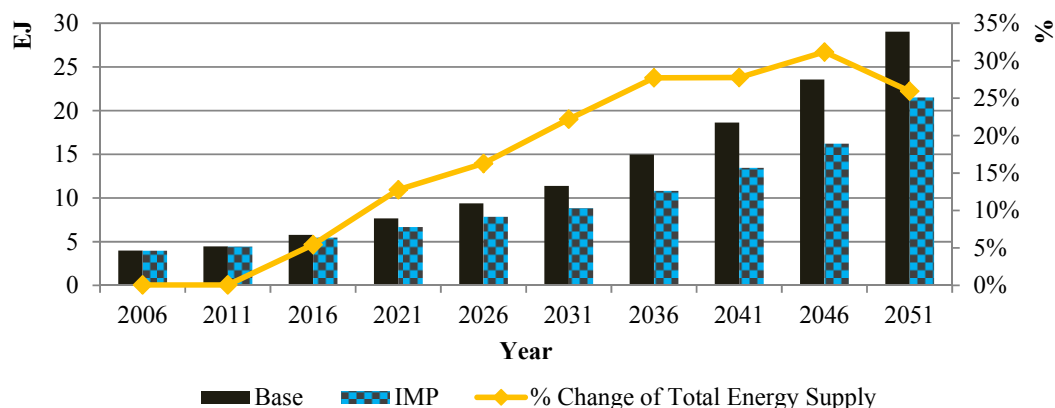


Figure 7.35. Total energy supplies predicted in the Base and IMP scenarios.

In this scenario, the optimization process somewhat levels domestic coal consumption over the planning horizon. However, coal is still the dominant fuel until 2031 (as can be seen from Table 7.18). It is, then, replaced by natural gas. The increase in natural gas supply after 2031 can be seen from Figure 7.36. Oil usage also increases in the later periods (doubles in 2046 and triples in 2051 compared to the Base scenario levels). Hydropower and wind energy sources reach their full potentials. Natural gas, which is a lower emission fuel compared to coal, and wind energy source, which is a zero emission fuel, feature levels greater than those in the emission scenarios.

Table 7.18. Energy supplies predicted in the IMP scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1193.2	1548.3	2968.4	3690.1	4222.7	4252.9	3073.2	1991.2	1122.1	807.1
Natural Gas	1174.7	1260.1	1058.5	1247.6	1495.1	1818.6	4576.4	7699.3	9536.1	12086.1
Oil	1237.8	1295.9	1157.2	1417.1	1692.7	1891.4	1309.2	1721.9	3268.9	6002.4
Hydro	164.8	196.8	176.5	196.6	196.7	504.0	504.0	504.0	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	665.9	862.3	1109.2	1427.2
Wind	0.4	13.6	16.4	65.6	202.4	353.2	567.6	567.6	567.6	567.6
Bio	178.7	111.0	68.9	42.8	26.6	16.5	100.0	100.0	100.0	100.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.5
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.5	4456.4	5470.9	6681.3	7855.6	8854.6	10813.4	13462.9	16224.2	21510.6

The share of zero carbon fuels in the IMP scenario increases to 20.7% in 2036 and to 16.5% in 2046, compared to 6% and 6.4% in the Base scenario. Since this scenario leads to greater usage of efficient technologies and renewable energy sources (especially hydro, wind and bio energy sources) compared to the Base scenario, this result is expected. The share surpasses 20%, in 2036, which is a level never achieved in the emission restriction and penalty scenarios.

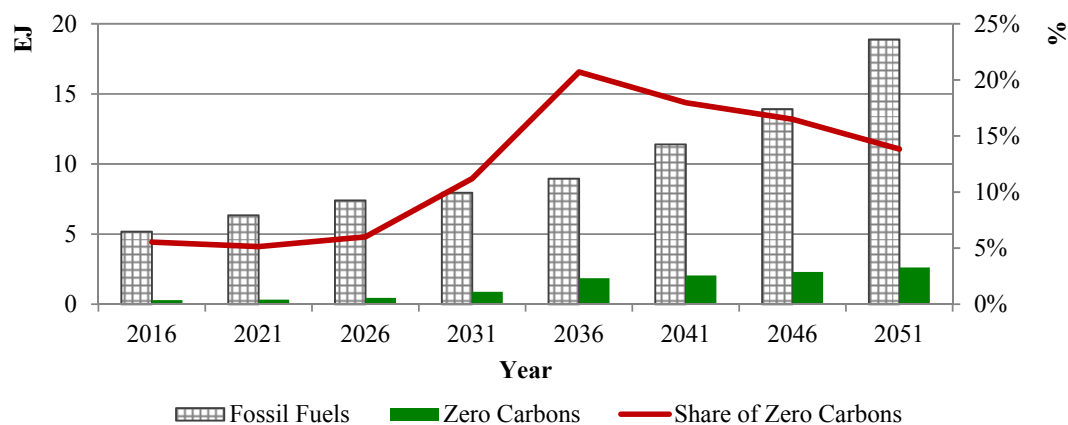


Figure 7.36. Fossil and zero carbon fuel supplies predicted in the IMP scenario.

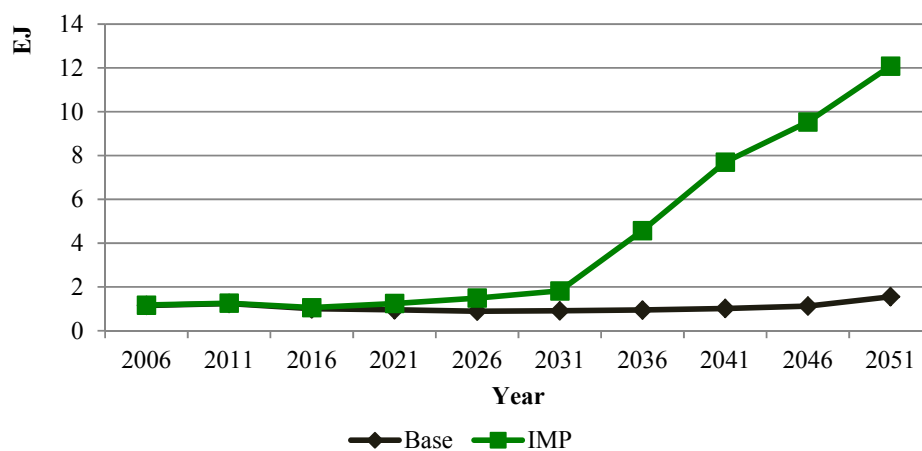


Figure 7.37. Natural gas supplies predicted in the IMP scenario.

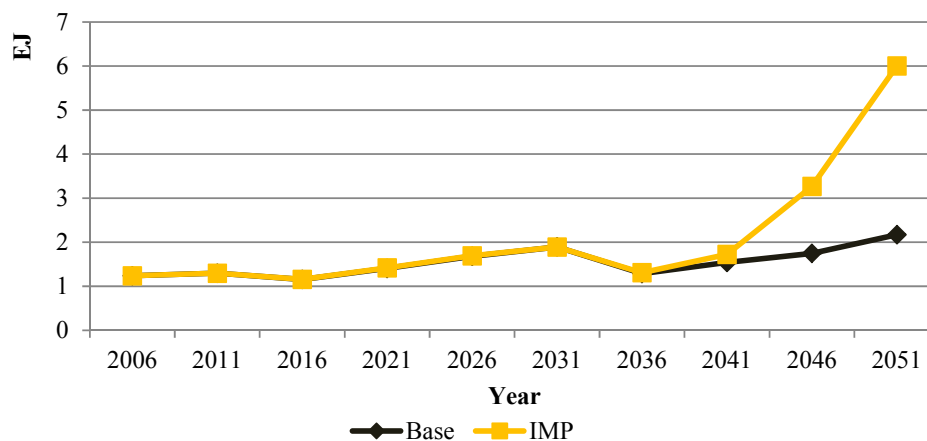


Figure 7.38. Oil supplies predicted in the IMP scenario.

Efficiency improvement starts in 2016, the year in which the scenario requirements become active. After this year improvement in efficiency continues to grow in accordance with the increase in efficient technology usage.

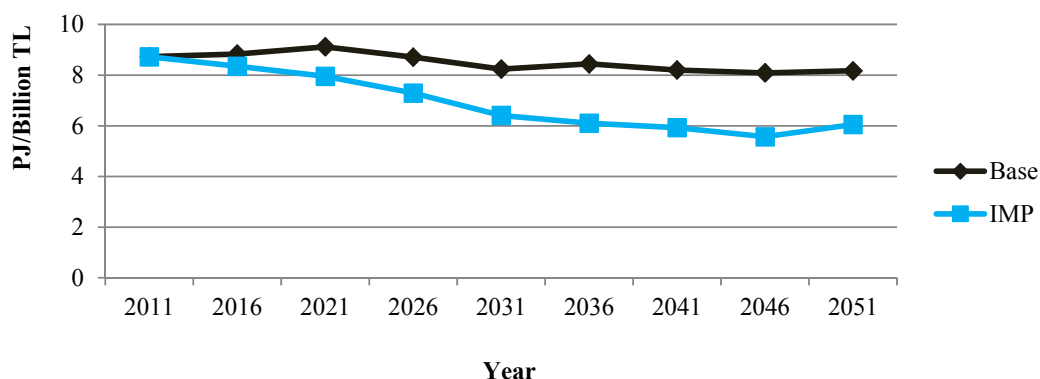


Figure 7.39. Energy intensities predicted in the Base and IMP scenarios.

As intended, Turkey's dependence on imports of fossil fuels sharply drops from 70% in 2006 to 42% in 2016 under the IMP scenario, which is about 11% lower than in the Base Scenario. Then, with the increase in natural gas usage as a substitute of coal, dependence on imports rises again. However, the dependence level still stays below the level in the Base scenario. Additionally, regarding later periods of the planning horizon, this scenario delays the increase in import levels compared to the emission restriction and penalty scenarios.

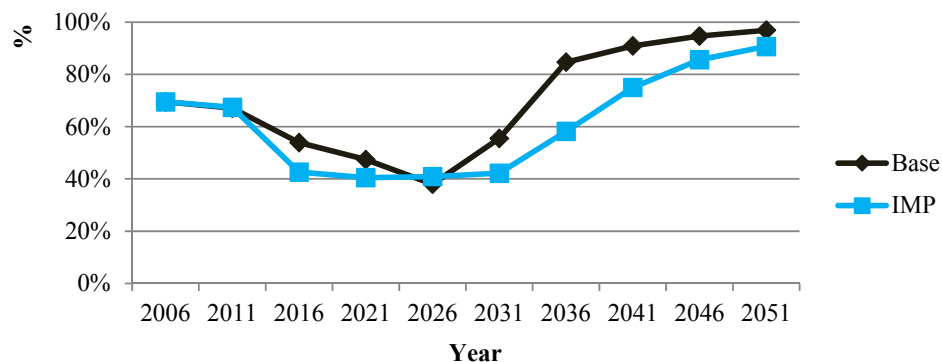


Figure 7.40. Import dependence rates predicted in the Base and IMP scenarios.

7.4.2. Electricity Generation

The use of electricity is also reduced in the IMP scenario (as can be seen from Figure 7.41). This is primarily the result of unavailability of coal power generation. Electricity generation becomes relatively expensive with alternative fuels. The electricity generation levels are 24.8% lower in 2026 and 28.2% lower in 2046 (compared to the Base scenario).

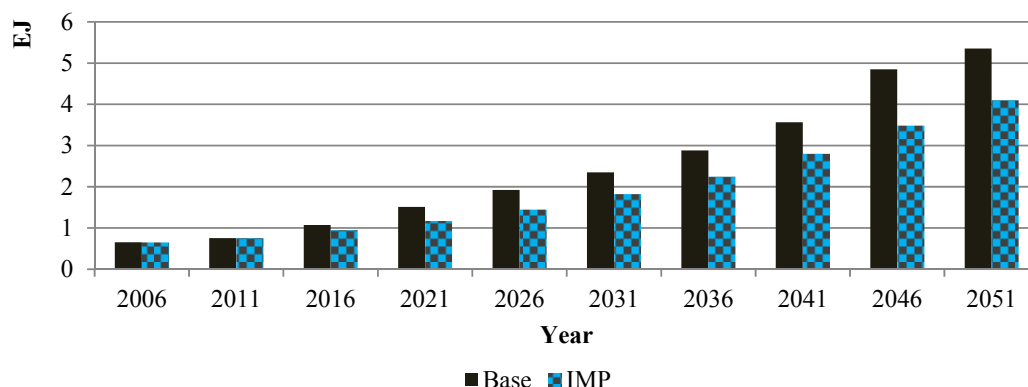


Figure 7.41. Electricity generation levels predicted in the Base and IMP scenarios.

Coal fired electricity generation goes to zero with the unavailability of coal imports (as can be seen from Figure 7.42). Hydro and wind energy resources together dominate power generation until 2036 (as can be seen from Table 7.19). Hydropower energy source reaches its potential in 2031 while wind energy resource in 2036. From this year onwards, natural gas turns to be the primal resource of electricity generation.

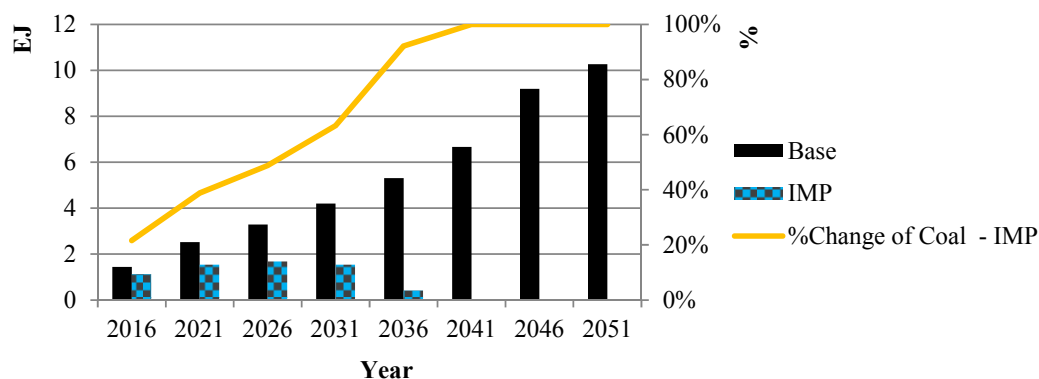


Figure 7.42. Coal supplies to electricity generation predicted in the Base and IMP scenarios.

Table 7.19. Installed capacities predicted in the IMP scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	17.3	24.3	32.3	28.9	27.6	26.3	25.1	25.1
Natural Gas	10.0	18.7	19.9	20.7	29.1	30.6	48.9	75.3	107.4	135.4
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	14.0	15.6	15.6	40.0	40.0	40.0	40.0	40.0
Wind	0.1	1.3	1.6	6.6	22.9	43.6	83.6	83.6	83.6	83.6
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	35.8	50.5	55.4	69.8	102.4	145.6	200.2	225.4	256.2	284.2

7.4.3. Renewable Energy Sources

The share of renewable energy sources in electricity generation increases, peaking at 11% in 2036, which is the period in which coal unavailability starts. Therefore, the IMP scenario relies more on renewable energy sources after this period. In addition, in the second half of the planning horizon the share of renewable energy sources remains higher than those in the emission restriction and penalty scenarios.

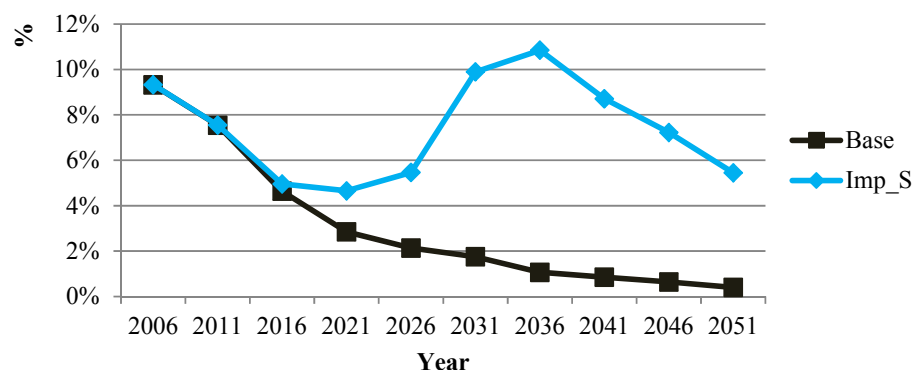


Figure 7.43. Renewable and nuclear energy shares predicted in the Base and IMP scenarios.

7.4.4. Emissions

It is interesting to note that the import restrictions have a significant impact on reducing emissions (as can be seen from Figure 7.44). Emission reduction levels are around 50% between 2036 and 2051, which is a better performance than those of the emission restrictions and penalty scenarios. In 2026, 2036, and 2046, for example, the reduction levels in IMP scenario are 22.7%, 48%, and 52%, respectively. This result is primarily due to the abundance of coal (coal having the highest emission factor), greater usage of efficient technologies, and heavier reliance on low and zero carbon fuels, in this scenario. On the other hand, when hydropower and wind energy sources reach their full potentials in 2046, the reduction trend changes its direction with the more usage of natural gas (which is not a zero emission fuel like renewable energy resources) .

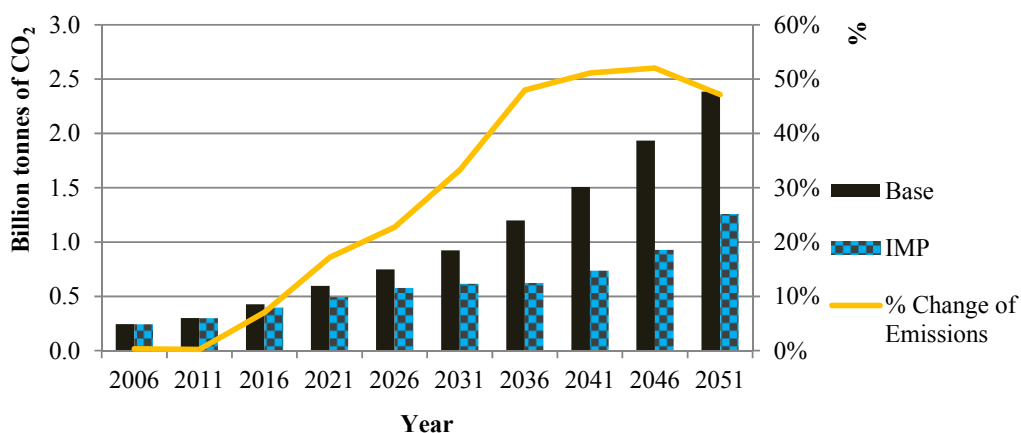


Figure 7.44. CO₂ emissions predicted in the Base and IMP scenario.

7.4.5. Costs

The additional investments into efficient and zero carbon fuel technologies increase the investment costs of the import restrictions scenario compared to the Base scenario levels. Shifting from the cheapest fuel coal, to other alternative fuels also increases fuel expenses. Therefore, the total system cost is higher under the import restriction scenario throughout the planning horizon.

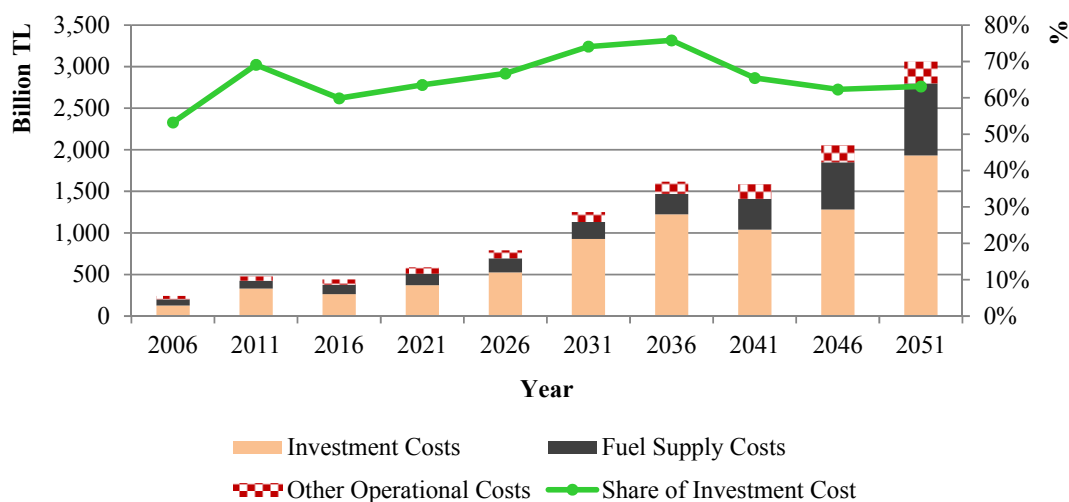


Figure 7.45. Undiscounted system costs predicted in the IMP scenario.

As can be observed from Figure 7.46, emission abatement costs peak twice under the IMP scenario; in 2031 (when large investments on wind and hydro power technologies are realized), and in 2051 (when large investments on petroleum product fueled technologies are realized).

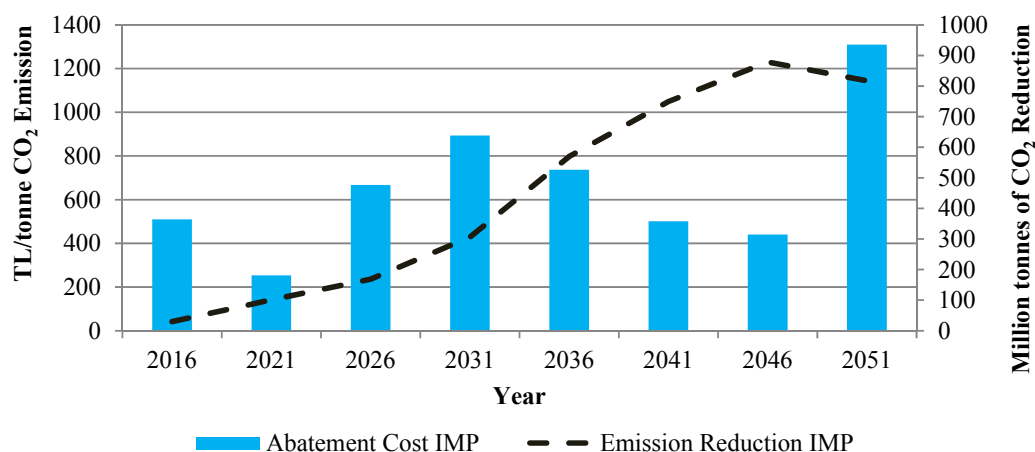


Figure 7.46. Cost of CO₂ emissions predicted in the IMP scenario.

7.5. The Base Macro Scenario Results

In this section, results of the Base scenario under the Macro module integrated TES-BUEM model are discussed. As discussed in Section 4.2, the BUEM framework uses exogenous demand series (with the absence of Macro module). Thus, the original Base

scenario is run with exogenously provided energy demand services. The average GDP growth rate is 5.1% throughout the planning horizon. However, in the real world, demand services are under the effects of price changes. It is expected that increase in prices decreases the demand for energy services. On the other hand, in this model setting combined with Macro module, demands are endogenously produced based on the relations between bottom-up and macro modules. This way, GDP growth rate, so the energy demand services, are generated under the impacts of energy prices. In the Base Macro scenario, the average GDP growth rate becomes 4.1% (as can be seen from Figure 7.47). The oscillations of GDP growth can be explained with the high investments on system technologies. The periods, in which useful lifetimes of most of the technologies are over and so large investments are necessary (such as 2011 and 2036), are followed by a decline on GDP growth rate (thus declines on demand services).

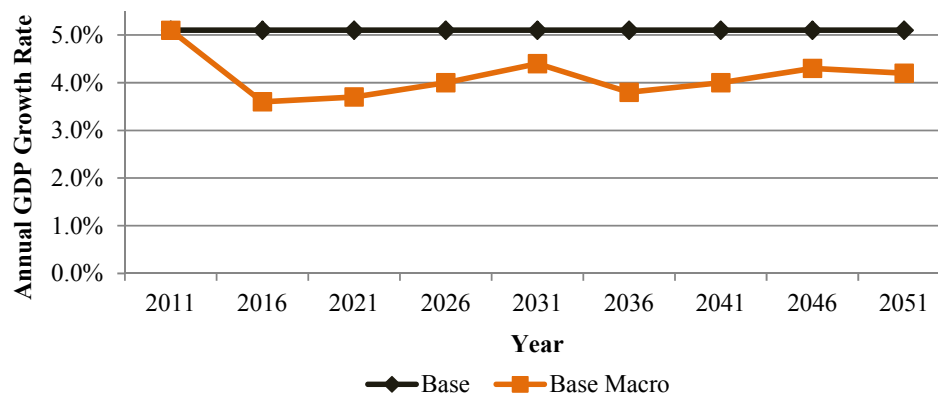


Figure 7.47. Annual GDP growth rates used in the Base scenario and predicted in the Base Macro scenario.

The realized sectoral demand services can be seen from Table 7.20. Since Base Macro scenario generates lower growths each period, except 2011, compared to the average exogenous growths of the original Base scenario, all sectoral and sub-sectoral demands, with a few exceptions, are fairly lower. The exceptions come from the different treatment of sectoral demand services in the original Base scenario for some demand services. For example, agricultural demand is increased at an average rate of 3% instead of 5.1% and service sector demand is increased at a rate of 2.6% in 2011. These differences

explain the single surpass of Base Macro scenario in 2011 (as can be seen from Figure 7.48).

Table 7.20. Demands services used in the Base scenario and predicted in the Base Macro scenario (in PJ).

		2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base Scenario	Agriculture	12.6	14.1	16.2	18.3	21.5	25.4	30.1	35.8	42.5	43.9
	Industry	1142.6	1454.4	1882.9	2442.2	3156.3	4070.3	5244.8	6758.5	8705.2	11208.2
	Residential	414.3	554.2	695.1	838.1	984.1	1124.4	1265.7	1444.1	1605.0	1769.2
	Service	205.5	231.7	299.9	387.9	500.3	644.6	830.1	1068.4	1374.9	1769.0
	Transport	103.4	145.9	193.2	249.7	322.8	417.7	543.1	706.1	917.4	1191.4
Base Macro Scenario	Agriculture	12.6	16.1	18.9	22.7	27.5	34.0	41.2	50.2	61.9	75.7
	Industry	1142.6	1462.5	1715.5	2056.3	2494.9	3082.9	3733.9	4548.5	5615.4	6862.9
	Residential	414.3	586.6	635.9	702.3	787.7	902.2	1029.0	1187.7	1395.5	1638.5
	Service	205.5	263.0	308.5	369.8	448.7	554.4	671.5	818.0	1009.9	1234.2
	Transport	103.4	132.4	155.3	186.1	225.8	279.0	337.9	411.7	508.2	621.2

Figure 7.48 displays demand projections under the Base Macro scenario. The difference from the original Base scenario rises throughout the planning horizon, from 8.2% in 2016 to 34.7% in 2051. Thus, it is clear that this model generates a different demand structure under the effects of energy prices. This significantly reduced demand profile naturally has various key impacts across the energy sector as discussed in the following subsections.

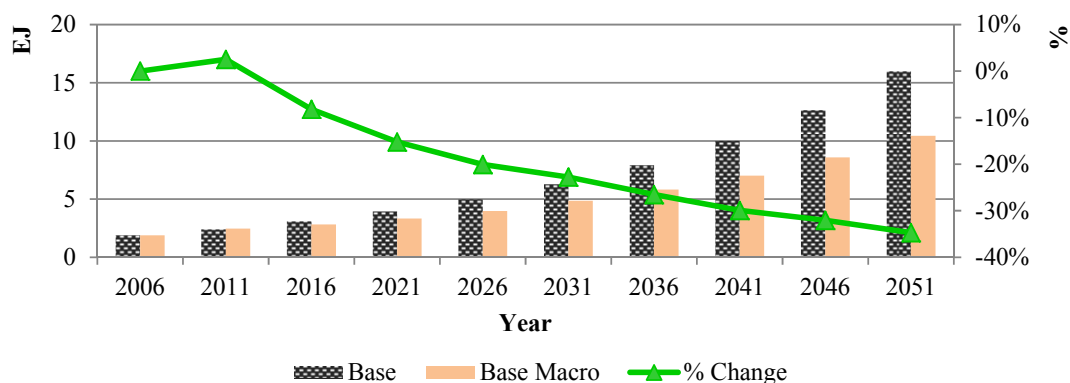


Figure 7.48. Total demands used in the Base scenario and predicted in the Base Macro scenario.

7.5.1. Energy Supply

The Base Macro scenario produces lower total energy supply levels, compared to the original Base scenario (as can be seen from Figure 7.49 and Table 7.21). This lower energy consumption is the result of the lower demand volumes in the Base Macro scenario. Since the demand gap is highest in 2051, so is the total energy supply gap.

Since these two scenarios are run with highly different energy demand series, it would not be proper to compare the magnitude of the results. Therefore, results of the two scenarios will be compared according to their behavioral trends.

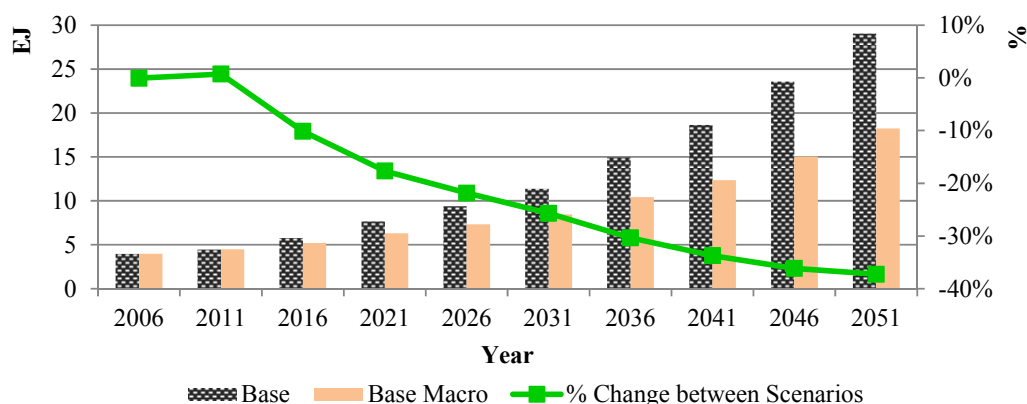


Figure 7.49. Total energy supply predicted in the Base and Base Macro scenarios.

Table 7.21. Change of Total Demand Levels and Total Energy Supply Levels in the Base Macro Scenario (when Compared to the Base Scenario).

	2011	2016	2021	2026	2031	2036	2041	2046	2051
Change of Total Demand (%)	2.5%	8.2%	15.2%	20.1%	22.8%	26.5%	29.9%	2.1%	34.7%
Change of Total Energy Supply (%)	0.7%	10.2%	17.6%	21.9%	26.0%	30.3%	33.7%	36.1%	37.4%

Coal is the dominant fuel in the Base Macro scenario as well (see Figure 7.50 and Table 7.22). Consumptions of fossil fuels are in lower levels which is in accordance with the lower demand levels. Renewable energy sources, on the other hand, feature similar supply profiles. This is due to the model calibrations, which do not change between the two scenarios.

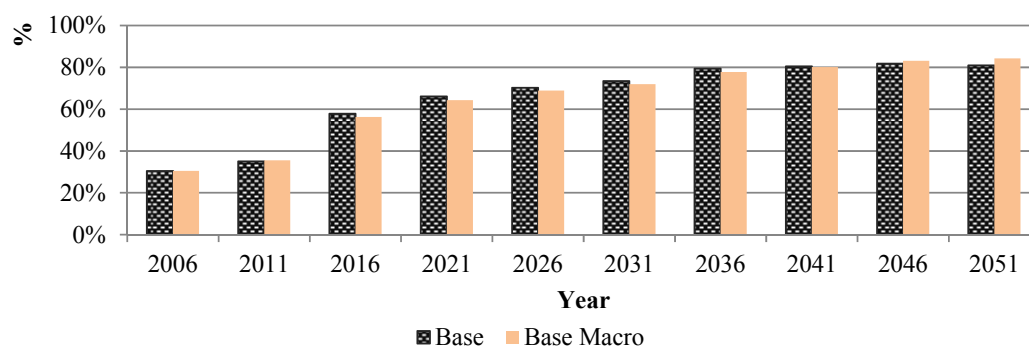


Figure 7.50. Coal shares in total energy supply in the Base and Base Macro scenarios.

Table 7.22. Energy supplies predicted in the Base Macro scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1594.5	2918.8	4058.4	5049.5	6054.1	8108.6	9903.6	12522.6	15313.5
Natural Gas	1157.5	1336.5	1035.8	941.0	832.9	834.3	835.5	858.6	909.8	1077.8
Oil	1235.0	1208.1	956.7	1078.3	1228.8	1318.7	919.6	931.4	815.6	827.0
Hydro	164.8	196.8	176.5	156.1	156.2	166.8	146.5	149.9	145.0	111.9
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	386.9	485.7	640.0	830.2
Wind	0.4	13.6	13.6	13.6	13.6	16.4	4.1	4.1	4.1	4.1
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	3.9	2.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.1	4491.2	5195.3	6311.7	7326.8	8424.7	10428.6	12356.2	15057.3	18183.0

Energy intensity gap between the two scenarios changes from 0.8 to 1 PJ/Billion TL. The differences are the joint result of change in GDP growth series and change in total energy supply levels. The Base Macro scenario generates lower GDP levels. Due to the lower GDP growth rates, energy demands are lower and due to the lower energy demand volumes, the total energy supply levels are lower. There is an inverse relationship between GDP and energy intensity; a decrease in GDP increases the intensity. On the other hand, there is a direct relationship between total energy supply level and energy intensity; a decrease in total energy supply level, decreases the intensity. In this case, the level of decrease in energy intensity due to the decrease in total energy supply is greater than the level of increase in energy intensity due to the decrease in GDP values. Thus, the net result becomes decrease in energy intensity (which means increasing energy efficiency levels).

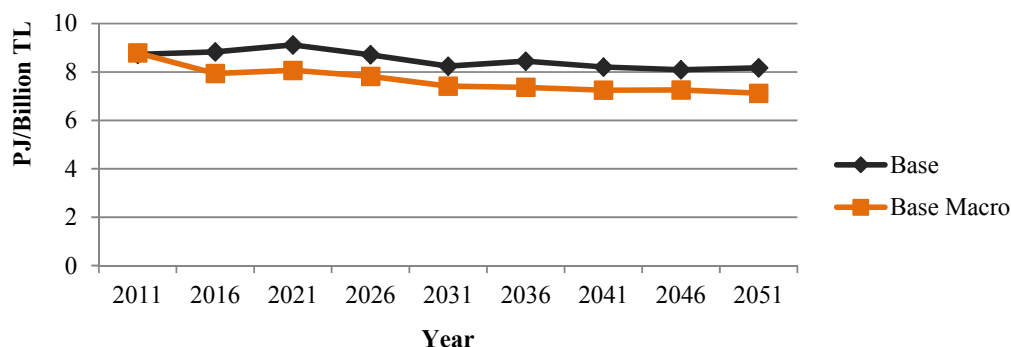


Figure 7.51. Energy intensities predicted in the Base and Base Macro scenarios.

Import dependence rate of the two scenarios follows the same trend until 2026, at which time national coal reserves of the Base scenario are exhausted. On the other hand, since fuel needs are lower in the Base Macro scenario (because of the lower demand profile), coal reserves still exists. This unused coal reserves in the Base Macro scenario delay coal unavailability. Thus, import dependence rates stay low. However, in later periods the Base Macro scenario also suffers from coal unavailability. Thus, it can be said that both scenario results display similar behavior in this regard.

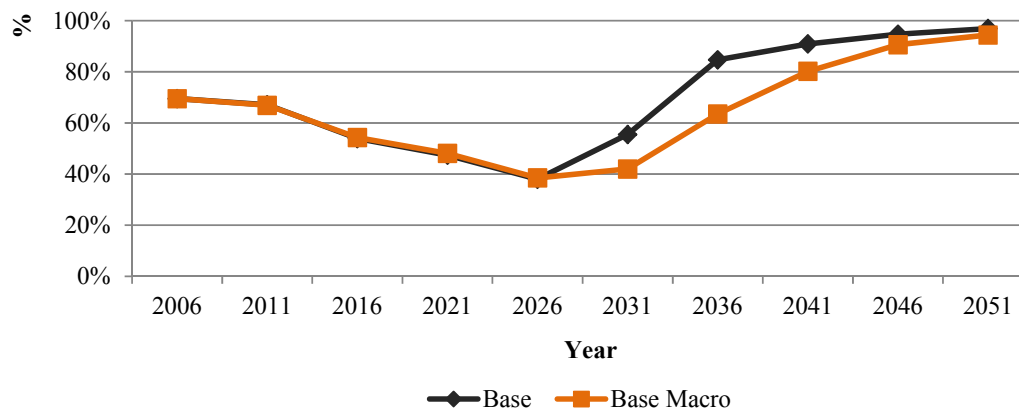


Figure 7.52. Import dependence rates predicted in the Base and Base Macro scenarios.

7.5.2. Electricity Generation

The electricity generation in the Base Macro scenario stays below the original Base scenario throughout the planning horizon (as can be seen from Figure 7.53) with gaps increasing in later periods. For example, 15% decline in electricity generation in 2016 goes

up to 25.7% in 2036 and 35.3% in 2046 (compared to the Base scenario). Since the reduction in demand levels is higher in later periods, this result is expected. As realized in the original Base scenario, coal becomes the dominant fuel choice of power generation starting in 2011. This fast-growing trend is the result of the cheap supply price of coal. The consumption patterns of other energy sources also looks like the original Base scenario. The only difference is the minimal increase in electricity generation from wind energy resource in later periods (electricity generated by this resource increases to 4.07 PJ in 2036 (from 1.23PJ in 2021) and stabilizes there. The total installed capacity in the Base Macro Scenario decreases to 78.6 GW (a 23.2% decline) in 2026 and to 151.1 GW (a 34% decline) in 2046 (as can be seen from Table 7.23).

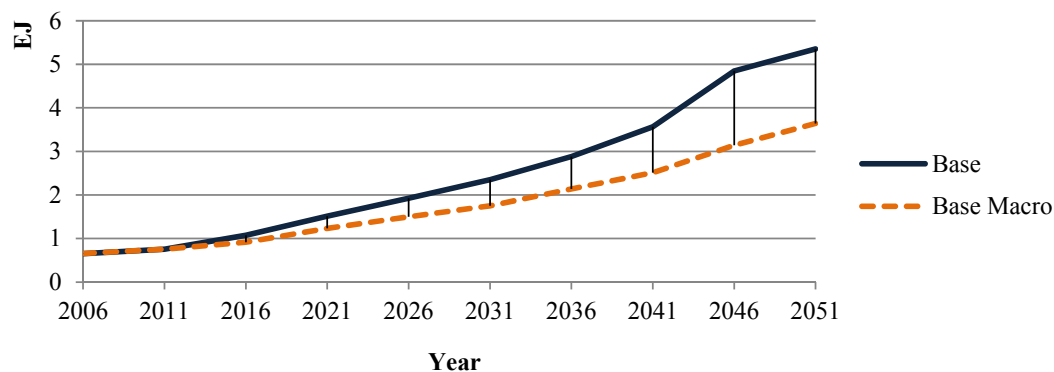


Figure 7.53. Electricity generations predicted in the Base and Base Macro scenarios.

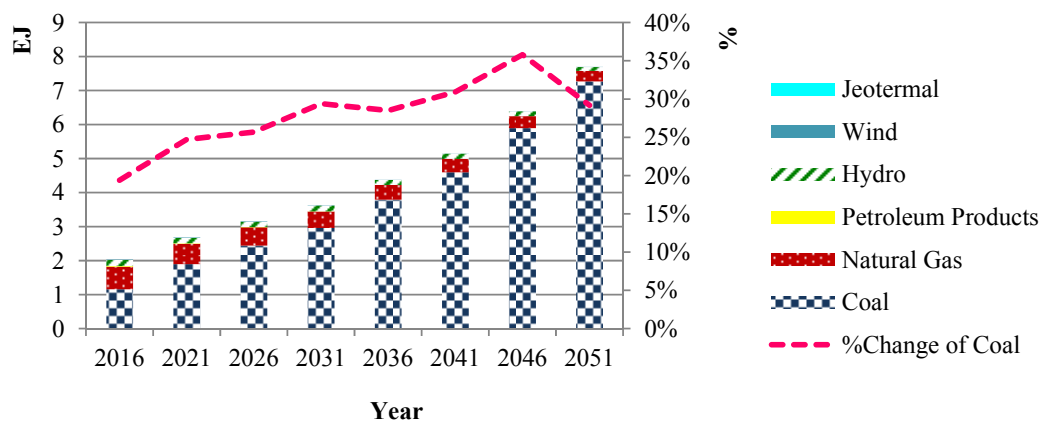


Figure 7.54. Energy usage for electricity generation predicted in the Base Macro scenario.

Table 7.23. Installed capacities predicted in the Base Macro scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	16.6	30.0	42.5	48.9	64.8	77.3	99.1	118.7
Natural Gas	10.3	18.7	18.6	20.3	19.8	24.4	29.3	33.2	40.0	44.4
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	14.0	12.4	12.4	13.2	11.6	11.9	11.5	8.9
Wind	0.1	1.3	1.3	1.3	1.3	1.6	0.3	0.3	0.3	0.3
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
TOTAL	36.1	50.5	53.1	66.6	78.6	90.6	106.2	123.0	151.1	172.5
%Change of Total Capacity	-0.7%	0.0%	10.3%	16.7%	23.2%	23.5%	24.4%	28.3%	34.1%	31.2%

7.5.3. Renewable Energy Sources

Since the calibration levels of renewable energy resources (in the Base scenario) are maintained in the Base Macro scenario, the changes in energy demand services between two scenarios do not affect their consumptions profiles. The renewable energy resources realize almost the same supply levels with the original Base scenario. However, since the energy supply levels are lower (due to the lower energy demands), their shares become higher (as can be seen from Table 7.24).

Table 7.24. Shares of renewable energy sources predicted in the Base Macro scenario.

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base	9.32%	7.54%	4.64%	2.85%	2.13%	1.75%	1.07%	0.85%	0.64%	0.40%
Base Macro	9.33%	7.49%	5.16%	3.46%	2.73%	2.35%	1.53%	1.28%	1.00%	0.64%

7.5.4. Emissions

Lower demand profiles lead to lower total energy supply and lower emission levels (compared to the Base scenario). As the demand reduction in the Base Macro scenario increases over the periods, emission reductions increase, too. The difference is 22.3% in 2026 and 35.7% in 2046.

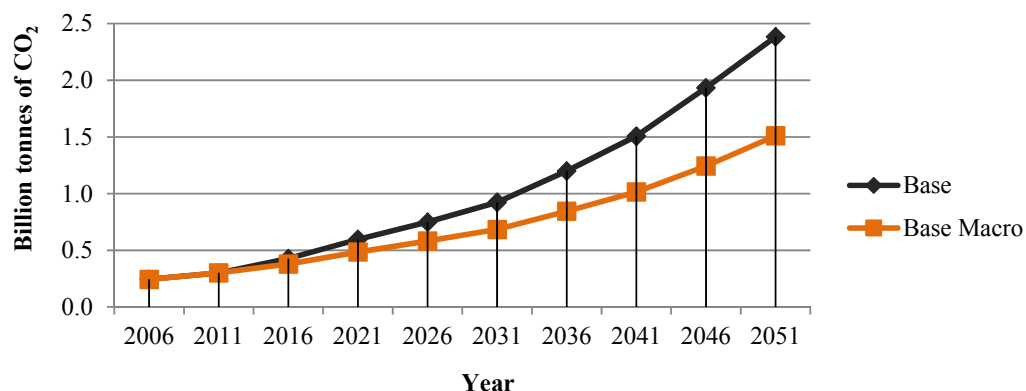


Figure 7.55. Total CO₂ emissions predicted in the Base and Base Macro scenarios.

7.5.5. Costs

The system costs follow the same trends in the Base and Base Macro scenarios. However, the cost magnitudes become fairly low in the Base Macro scenario. Lower demand profiles lead to lower costs compared to the Base scenario. As the demand reductions in the Base Macro scenario increase throughout the planning horizon, the differences between total system costs get larger.

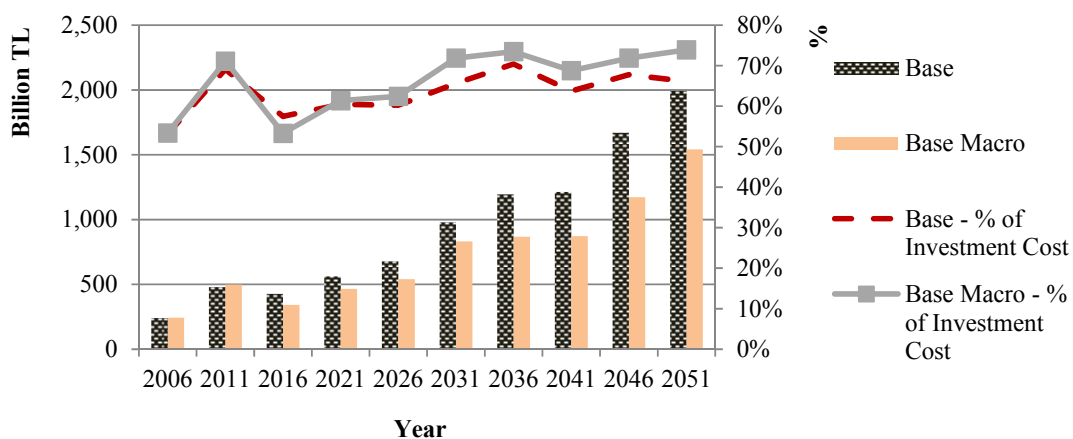


Figure 7.56. Undiscounted system costs predicted in the Base Macro scenario.

7.6. Results of the Emission Restriction Macro Scenarios

In this section, the results of the emission restrictions scenarios under the Macro module integrated TES-BUEM model are discussed. The same reduction target that is used in the original Base scenario is applied and the results are analyzed by focusing on the share of renewable energy sources and improvements in efficiency as well. Accordingly, the following two scenarios are defined (to be compared against the Base Macro Scenario).

- (i) EM1 Macro Scenario: Emissions are restricted 30% below of those in the Base Macro scenario (the restrictions to become active after 2016).
- (ii) EM2 Macro Scenario: Emissions are restricted 30% below of those in the Base Macro scenario; additionally, investment into nuclear and CCS technologies are allowed up to a limit. The same limitations of the original emission restrictions scenarios (discussed in Section 7.2) on nuclear energy and CCS plants are used as well (the restrictions to become active after 2016).

As can be seen from Figure 7.57, GDP growth rates decline as soon as the restrictions are applied in 2016. Thus, as an initial conclusion, it can be said that as the emissions are restricted, the system prefers to shrink the economy. This way, the energy demand comes down, so does the costs of energy consumptions. However, from this period onward, they approach to the Base Macro scenario levels.

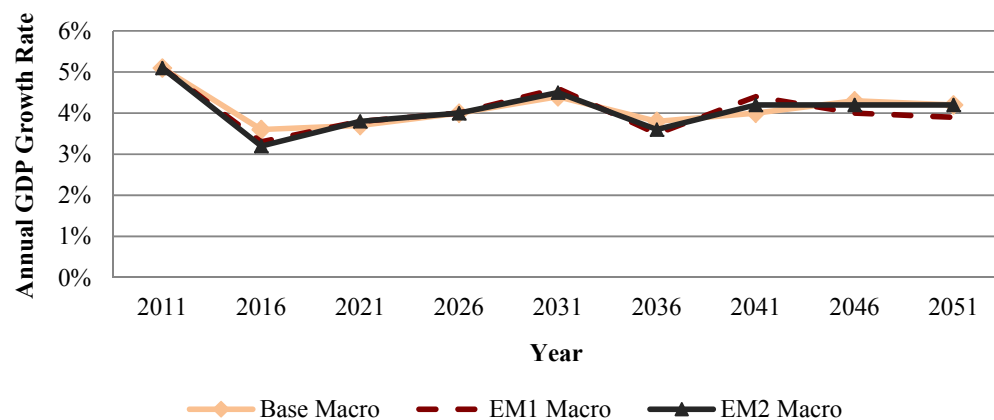


Figure 7.57. Annual GDP growth rates predicted in the EM1 Macro and EM2 Macro scenarios.

7.6.1. Energy Supply

As can be seen from Figure 7.58, both of the emission restrictions scenarios reduce the total energy supply of the system, compared to the Base Macro scenario results. The decline profiles/trends are similar to the original emission restrictions scenario results. There is a 20% decrease in the EM1 Macro scenario (compared to 22% decrease of the original EM1 scenario) and 17.9% decrease in the EM2 Macro scenario (compared to 19% decrease of the original EM1 scenario) in 2026. After 2031, on the other hand, the declines in total energy supply levels are only slightly lower compared to the original emission restrictions scenarios. In 2031, the reductions are 16.2% and 13.4% in the EM1 Macro and EM2 Macro scenarios, respectively (compared to 19.3% and 15.4% in the EM1 and EM2 scenarios). These declines are the joint results of the economic shrinkage and investments on more efficient and zero/low emission technologies.

Figure 7.59 and 7.60 show the changes in the share of zero carbon fuels in each scenario implementation. The average share of zero carbon fuels throughout the planning horizon increases from 5.7% in the Base Macro scenario to 15%. The share in the EM2 Macro scenario is lower than the EM1 Macro scenario until 2031. This is the result of the CCS technology capability in this scenario after 2016 (with the availability of CCS technologies). The system does not need to invest on zero carbon fuels. However, from this year onwards, a significant nuclear power capability becomes available, which reverses the trend. The shares of zero carbon energy sources gets higher than the EM1 Macro scenario and remains above 19% in the last four periods. This shows that there is a high chance to reach the 20% target of the EC with minor incentives on investments on renewable energy technologies.

Unable to deploy nuclear power and the CCS technologies, the EM1 Macro scenario naturally relies more on efficient and low emission technology usage. Hydro power and wind energy resources approach their maximum potentials in the later periods of the EM1 Macro scenario. On the other hand, with the increase of reliance on nuclear power and CCS technologies especially in later periods, the EM2 Macro scenario deploys lower hydro and wind energy capacities. Thus, the maximum potential of hydro power is

approached in 2041, compared to 2031 of the EM1 Macro scenario, while the maximum potential of wind energy resource is never reached. Although the technologies that have high availability factors are used in full capacities, technologies with low availability factors (which form almost half of the potential) are not preferred. Thus, the half of the potential is still available at the end of the planning horizon.

Table 7.25. Energy supplies predicted in the EM1 Macro scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1508.6	1417.8	2082.1	2923.7	3841.3	5575.4	6938.2	8562.3	10403.5
Natural Gas	1157.5	1298.8	1371.5	1230.0	1143.5	1206.1	1307.3	1249.8	1514.7	1672.4
Oil	1235.0	1208.1	819.0	989.2	1039.8	1020.4	523.8	497.6	389.9	439.0
Hydro	164.8	196.8	294.8	362.0	413.8	504.0	504.0	504.0	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	397.8	529.6	681.4	781.1
Wind	0.4	41.1	223.1	249.1	249.1	353.2	353.2	536.7	567.6	567.6
Bio	178.7	111.0	100.0	73.9	77.0	71.4	59.7	68.1	100.0	95.2
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.1	4395.1	4251.2	5007.8	5866.1	7014.3	8738.2	10340.5	12336.1	14478.8

Table 7.26. Energy supplies predicted in the EM2 Macro scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1544.1	1512.2	2288.1	3255.0	4058.4	5863.3	7540.6	9329.3	11390.2
Natural Gas	1157.5	1272.9	1250.4	1108.2	955.0	900.2	893.6	952.1	1253.6	1604.4
Oil	1234.9	1208.1	859.2	986.3	1090.7	1220.3	786.7	693.8	614.4	582.2
Hydro	164.8	196.8	294.8	294.6	294.8	499.5	499.3	504.0	504.0	501.2
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	390.2	492.6	637.6	803.1
Wind	0.4	41.1	197.0	242.4	249.1	249.1	249.1	275.7	275.7	269.1
Bio	178.7	111.0	100.0	73.9	57.7	47.6	41.3	64.3	70.6	69.1
Nuclear	0.0	0.0	0.0	40.6	97.9	180.2	285.9	418.3	602.5	958.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.0	4404.8	4238.6	5055.6	6019.4	7173.27	9026.5	10958.0	13303.9	16193.8

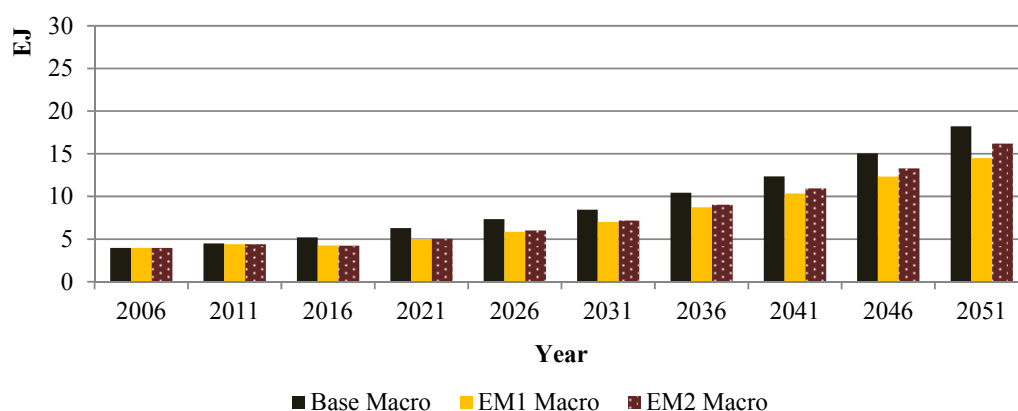


Figure 7.58. Total energy supplies predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

Coal is the largest contributor of the emissions, so the system chooses to shift away from coal and invest in alternative fuels when there are severe restrictions on emissions. The results of EM1 Macro and EM2 Macro scenarios are very similar to the original emission restriction scenarios. In 2026, coal share drops from 68.9% in the Base Macro scenario to 49.8% in the EM1 Macro and to 54.1% in the EM2 Macro scenario. Due to CCS technology availabilities, the EM2 Macro scenario relies on coal supply in higher levels.

As can be seen from Figure 7.62, the EM1 Macro scenario is the more efficient. This scenario has the lowest total energy supply levels and the difference is even larger in later periods. However, in this scenario group, besides the changes in total energy supply levels, GDP levels also change (as can be seen from Table 7.27). Thus, GDP levels may also have severe effects on the results. An increase in GDP implies a decrease in energy intensity levels, so an increase in energy efficiency levels (as discussed earlier in Section 7.5). However, the EM1 Macro Scenario still produces the most efficient results, even though it has the lowest GDP among the three scenarios. This shows that the impact of changes in total energy supply levels is greater compared to changes in GDP levels. In addition, the gap between the total energy supplies continues to grow in later periods, which results in more improvement in energy efficiency levels after 2041 (in the EM1 Macro scenario). In addition, the EM1 Macro scenario approaches 20% improvement target on energy efficiency in most of the periods while the EM2 Macro scenario does not.

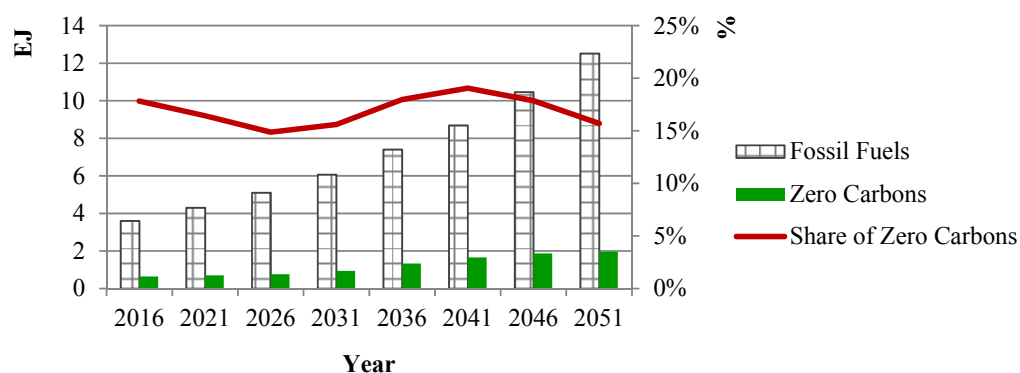


Figure 7.59. Fossil and zero carbon fuel supplies predicted in the EM1 Macro scenario.

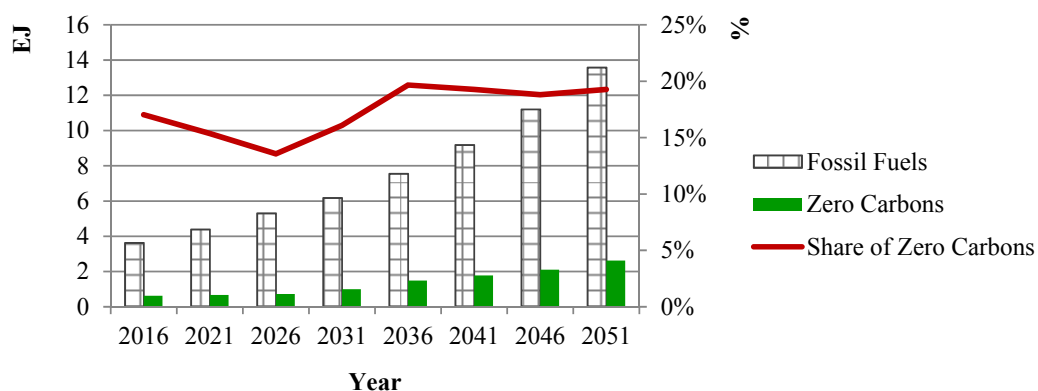


Figure 7.60. Fossil and zero carbon fuel supplies predicted in the EM2 Macro scenario.

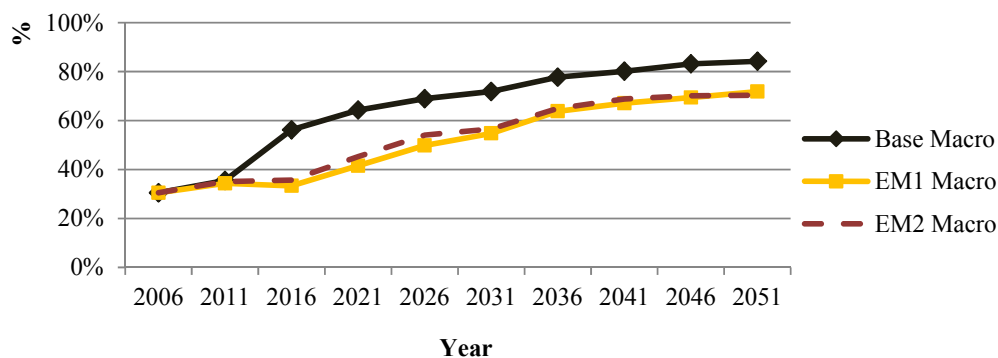


Figure 7.61. Coal shares in total energy supply predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

Table 7.27. GDP levels predicted in the emission restriction scenarios (in Million TL)

	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base Macro	510.8	655.0	781.8	937.5	1140.6	1414.6	1704.6	2073.9	2559.8
EM1 Macro	510.8	655.0	766.8	924.0	1124.1	1400.9	1671.9	2053.7	2522.8
EM2 Macro	510.8	655.0	770.5	928.5	1129.6	1414.4	1679.9	2083.5	2534.9

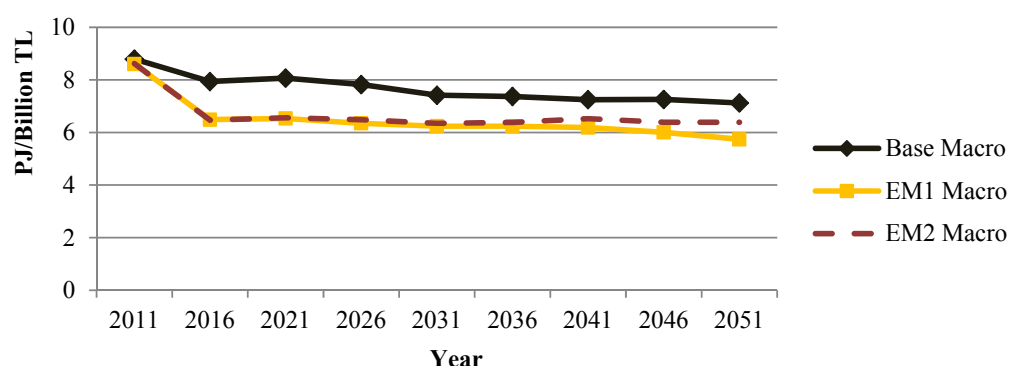


Figure 7.62. Energy intensities predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

Emission restrictions scenarios delay the depletion of coal reserves, thus significantly impact the import levels. The results are very similar to the original emission restriction scenarios until 2031 (as can be seen from Figure 7.63). Since the energy demands are lower in both of the scenarios compared to the Base Macro scenario, coal usages are less. Thus, the exhaustion of national coal reserves is delayed one additional period more (to 2036) under these scenarios, compared to the Base Macro scenario. The EM1 Macro and EM2 Macro scenarios feature the same import dependence rates until 2031, in which significant capacities of nuclear power and CCS technologies become available in the EM2 Macro scenario. From this year onward, the EM1 Macro scenario has lower dependence rates (by keeping investing on renewable energy and efficient technologies).

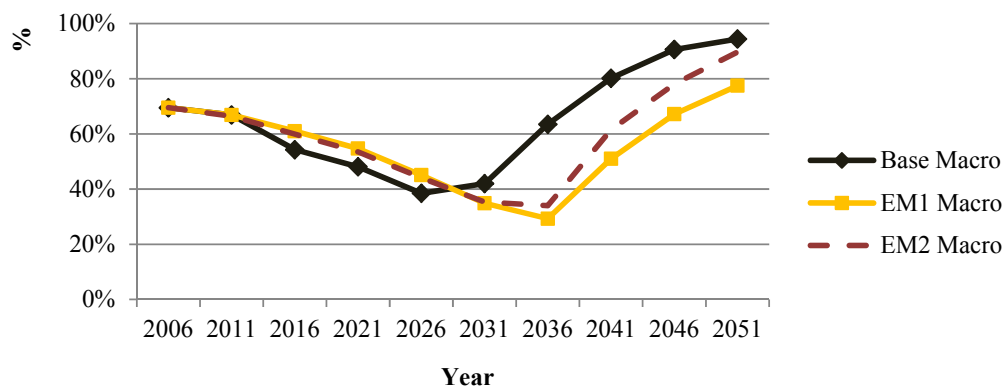


Figure 7.63. Import dependence rates predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

7.6.2. Electricity Generation

Electricity generation levels stay below the original Base scenario throughout the planning horizon. After 2016, power generation decreases, mostly because of shifting to efficient technologies and also shrinking in the economy. The EM1 Macro scenario generation levels stay higher than the EM2 Macro scenario levels until 2031. There are large investments on hydro and wind electricity technologies over the early periods of the EM1 Macro scenario. After 2031, on the other hand, significant nuclear power investments and CCS plant capacities reverse the trend. Electricity generation levels in the EM2 Macro scenario exceed the EM1 Macro scenario levels.

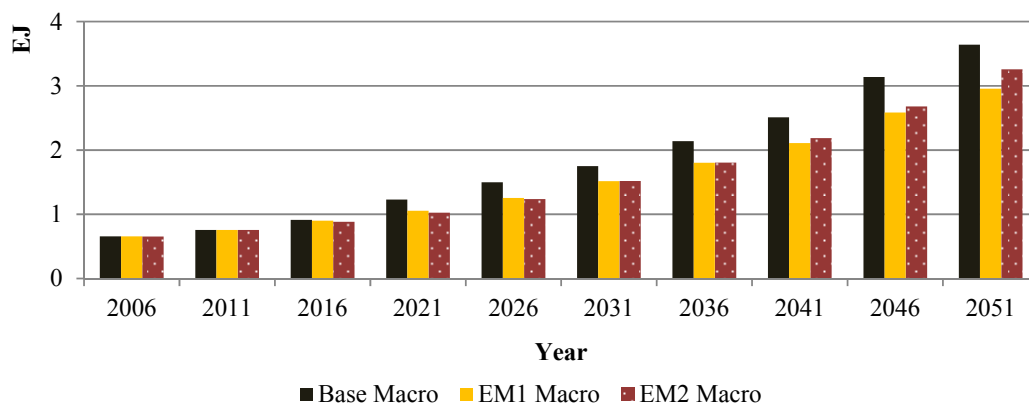


Figure 7.64. Electricity generation levels predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

In 2016, coal supply to power generation is 94.1% less in the EM1 Macro scenario and 91.4% less in the EM2 Macro scenario compared to the Base Macro scenario results. Then, through the periods these differences are reduced. Since the maximum potentials of renewable energy resources and limits of nuclear capacity are approached, coal is preferred again. Coal is consumed more in the EM2 Macro scenario (as can be seen from Figure 7.65).

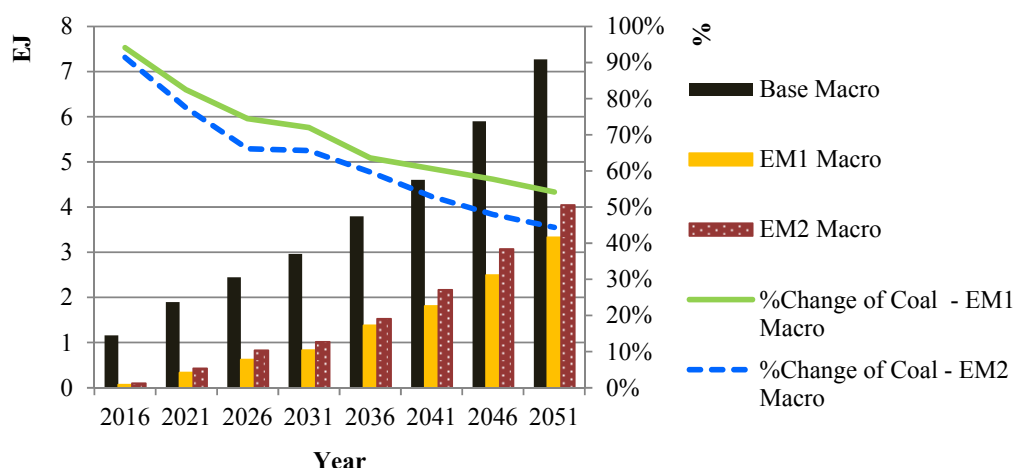


Figure 7.65. Coal supplies to electricity generation predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

Coal power capacity is mainly replaced with hydro, wind, and nuclear energy sources (as can be seen from Table 7.28 and 7.29). Because of the low annual availabilities of hydro and wind electricity technologies, total installed capacities are higher than the Base Macro scenario levels in both emission scenarios. The only exceptions are the last two periods of the EM2 Macro scenario. In these periods, the capacity and share of nuclear plants (which have the highest availability rates) are increased.

7.6.3. Renewable Energy Sources

Renewable energy sources are effectively used in electricity generations in all emission restriction scenario applications. In the EM1 Macro scenario, the share of renewable energy sources jump to 14.8% in 2016 from 8.3% in 2011 (as can be seen from Figure 7.66). Then, through the periods, even though the renewable energy resource supply

levels are still high (hydro and wind energy sources reach their maximum annual potentials) the share of renewable energy sources becomes lower in the total energy supply levels. However, it is clear that both emission scenarios forces renewable energy resource usage. In the EM2 Macro scenario, since some renewable energy resources are replaced with nuclear and CCS technologies, share of renewable energy sources are reduced.

Table 7.28. Installed capacities predicted in the EM1 Macro scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	11.0	9.8	17.5	17.6	26.4	43.1	59.3	59.5
Natural Gas	10.3	18.7	29.0	28.9	28.4	27.0	33.6	32.6	32.8	49.0
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	23.4	28.7	32.8	40.0	40.0	40.0	40.0	40.0
Wind	0.1	4.1	25.4	28.6	28.6	43.6	43.6	77.8	83.6	83.6
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	36.1	53.4	91.4	98.5	109.9	130.7	143.7	193.6	215.9	232.2

Table 7.29. Installed capacities predicted in the EM2 Macro scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.2	12.3	12.2	11.0	20.0	19.5	27.2	38.7	53.4	69.2
Natural Gas	10.3	18.7	29.0	28.9	28.4	25.0	31.5	34.9	40.3	46.2
Oil	2.4	2.4	2.4	2.4	2.4	2.4	0.0	0.0	0.0	0.0
Hydro	13.1	15.6	23.4	23.4	23.4	39.6	39.6	40.0	40.0	39.7
Wind	0.1	4.1	22.2	27.8	28.6	28.6	28.6	32.4	32.4	31.6
Nuclear	0.0	0.0	0.0	0.5	1.1	2.0	3.2	4.9	7.3	12.0
Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	36.1	53.3	89.4	94.0	104.1	117.3	130.3	151.1	173.6	198.9

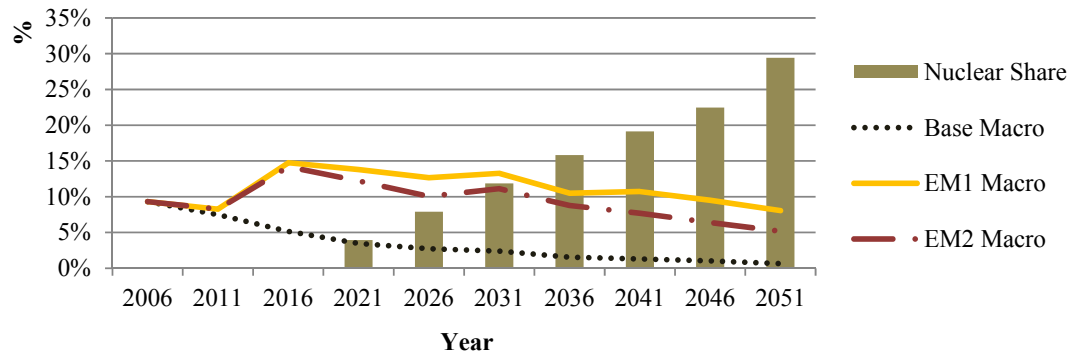


Figure 7.66. Renewable and nuclear energy shares predicted in the Base Macro, EM1 Macro, and EM2 Macro scenarios.

7.6.4. Costs

Investment costs have the largest share in each emission restrictions scenarios. The highest gaps, 27.7% and 26.0%, are observed in 2016 for the EM1 Macro and the EM2 Macro scenarios, respectively. In this period, great investments on efficient and renewable energy technologies are realized. On the other hand, between two emission restrictions scenarios, all system costs are higher in the EM1 Macro scenario. Since the investment costs of renewable energy technologies are relatively expensive and their installments are needed in high capacity levels, this result is expected.

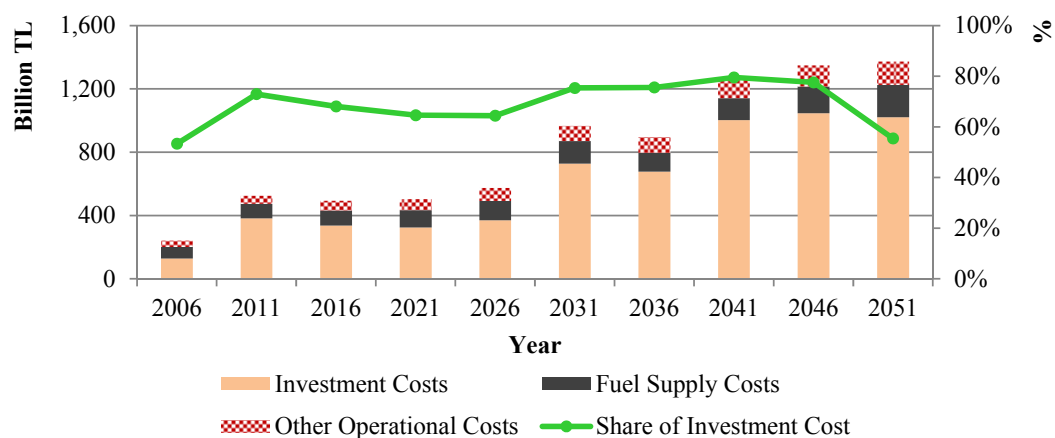


Figure 7.67. Undiscounted system costs predicted in the EM1 Macro scenario.

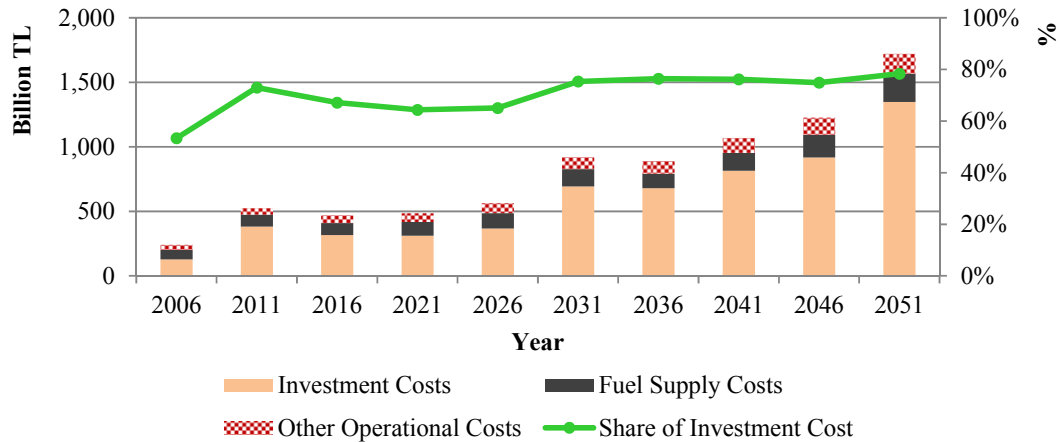


Figure 7.68. Undiscounted system costs predicted in the EM2 Macro scenario.

The EM1 Macro scenario features higher emission reduction costs; 1117.6 TL in 2016, 166.1 TL in 2026, and 103.4 TL in 2036. This is because CCS technologies are cheaper compared to the renewable energy technologies and decreases the need for renewable energy investments.

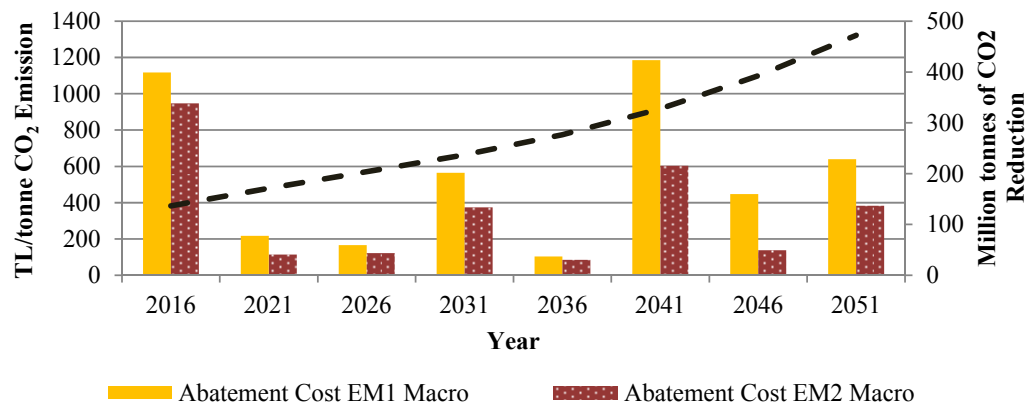


Figure 7.69. Cost of CO₂ emissions predicted in the EM1 Macro and EM2 Macro scenarios.

7.7. Results of the Emission Penalty Macro Scenarios

In this section, the results of the emission penalty scenario under the Macro module integrated TES-BUEM model are discussed. The same penalty is used and the results are analyzed by focusing on the share of renewable energy sources and on the improvements

in technology efficiencies as well. Accordingly, the following scenario is defined (to be compared against the Base Macro scenario).

- (i) PE Macro Scenario: 235 TL is applied on per tonne of CO₂ emissions exceeding available permits, which is 30% below of those in the Base Macro scenario (the restrictions to become active after 2016).

Table 7.30. Levels of emission penalties.

	2016	2021	2026	2031	2036	2041	2046	2051
Penalty Fine (TL/ton CO₂ emission)	235	235	235	235	235	235	235	235

As can be seen form Figure 7.70, GDP growth rates decline as soon as the penalty fine is applied in 2016. The differences get even larger in 2021. From this period onward, the growth rate stabilizes around 4%. Thus, as an initial conclusion, it can be said that as the penalty fine is applied on excess emissions, the system prefers to shrink the economy. The magnitude of the economic shrinkage is even greater compared to the emission restriction scenarios. The average annual GDP growth rate drops from 4.1% to 4%. This means that penalty implementation on excess emissions decreases the demand for energy, and also the costs of energy consumptions.

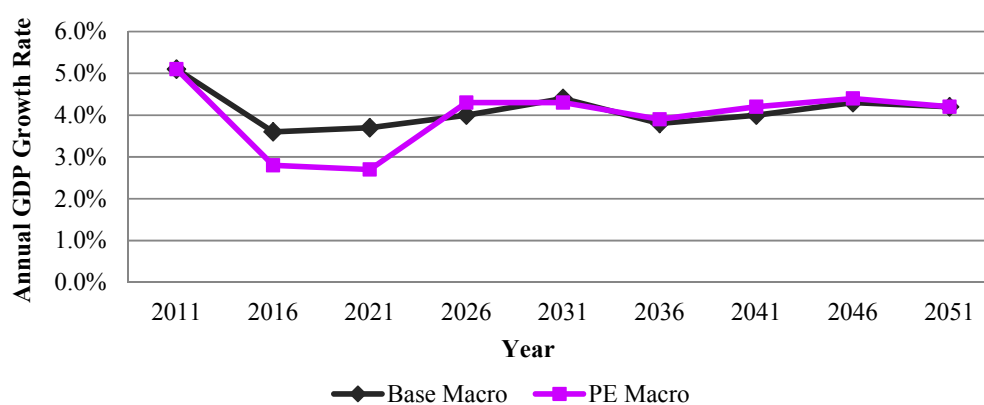


Figure 7.70. Annual GDP growth rates predicted in the PE Macro scenario.

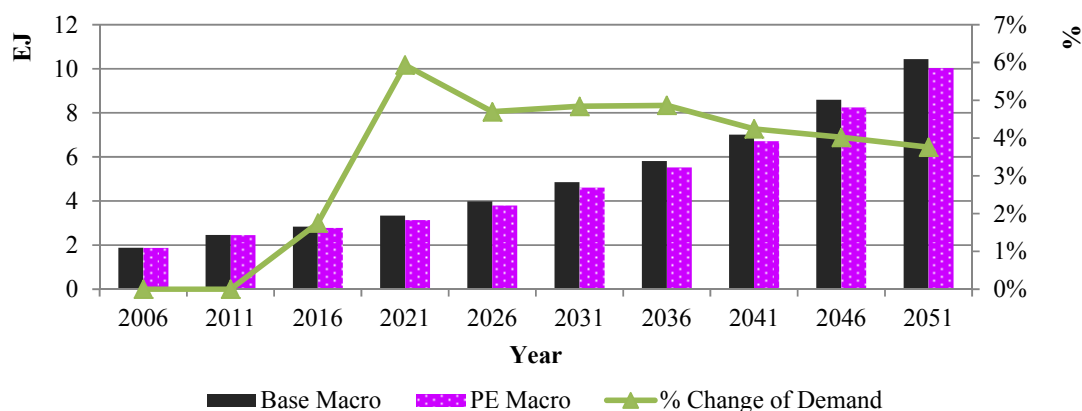


Figure 7.71. Total demands used in Base Macro scenario and predicted in the PE Macro scenario.

7.7.1. Energy Supply

Figure 7.72 displays the total energy supply projections under the emission penalty scenario. The reduction in supply levels rises through the planning horizon; 8.6%, 13.1%, and 15.6% less energy supply in 2026, 2036, and 2046, respectively (compared to the Base Macro scenario). The reduction is due to the combination of economic shrinkage (and associated demand decrease) and improvements in efficiency. The energy demand levels decrease 4.3% per period on average throughout the planning horizon. Compared to this, total energy supply levels decline 11.1% per period on average. The difference is the result of efficient technology usage.

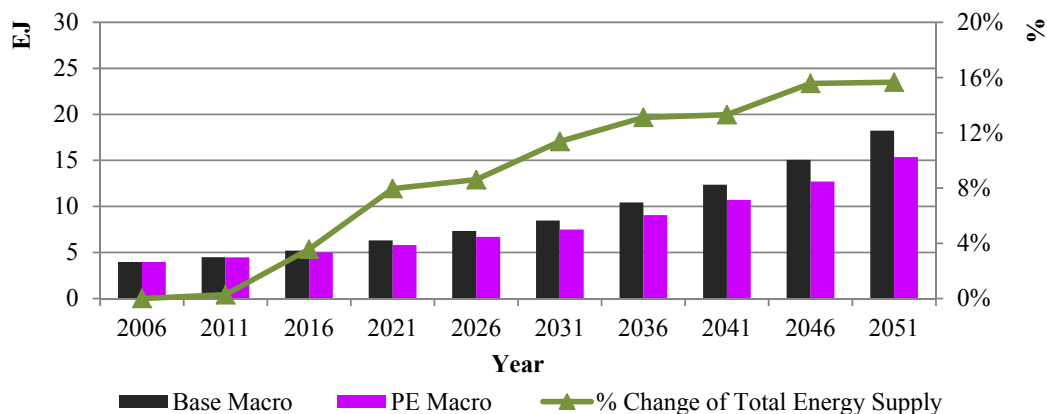


Figure 7.72. Total energy supplies predicted in the Base Macro and PE Macro scenarios.

Table 7.31. Energy supplies predicted in the PE Macro scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1212.7	1594.5	2736.5	3605.2	4535.6	5054.9	6667.7	8159.8	9420.8	11664.1
Natural Gas	1157.5	1318.8	1027.5	924.2	828.6	830.5	832.8	879.7	1227.7	1517.8
Oil	1235.0	1208.1	960.6	1012.9	1114.1	1229.8	800.7	728.5	598.9	558.4
Hydro	164.8	196.8	176.5	176.5	156.2	196.8	196.6	196.6	504.0	504.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	379.3	475.3	621.7	785.7
Wind	0.4	18.7	18.7	21.6	21.6	150.7	150.7	249.1	249.1	249.1
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	68.7	77.6
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3976.1	4478.7	5013.8	5804.7	6702.0	7497.1	9055.3	10711.9	12707.1	15372.7

As can be seen from Figure 7.73, the share of zero carbon fuels in the PE Macro scenario increases to 3.5% in 2026 and 13% in 2046 (the highest of the planning horizon). Still, these rates are fairly below the emission restrictions scenario levels. The share never drops below 15% in emission restriction scenarios. This result shows that imposing a penalty fine on excess emissions is more influential on economic growth (so the demand growth), rather than investing on zero carbon fuels. In other words, under the effect of this scenario, the optimization process prefers to shrink energy demand growth in order to pay less for emission penalties.

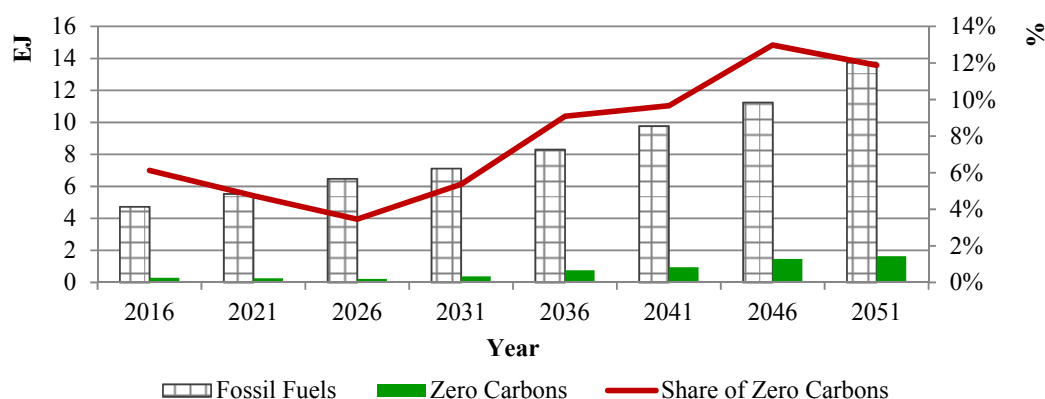


Figure 7.73. Fossil and zero carbon fuel supplies predicted in the PE Macro scenario.

The shares of coal in total energy supply are similar to those in the Base Macro scenario until 2026 (as can be seen from Figure 7.74). From this year onwards, there are reductions on the share (e.g. 4.1% less in 2036 and 9% less in 2046). However, the changes are not as remarkable as the emission restriction scenarios. These results again show that the emission restrictions scenarios prefer to abandon coal, which is the greatest contributor of the emissions, and invest on zero carbon fuels, while the PE Macro scenario prefers to shrink the economy to pay less penalty.

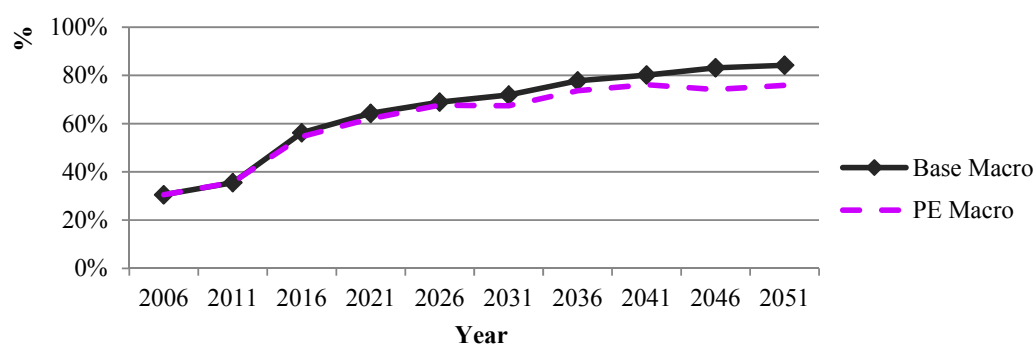


Figure 7.74. Coal shares in total energy supplies predicted in the Base Macro and PE Macro scenarios.

The PE Macro scenario improves the efficiency (as can be seen from Figure 7.75). However, the improvement rates are fairly lower than that of the emission restriction scenarios, which again supports the conclusion that a penalty application implies an economic shrinkage instead of investing more on efficient technologies or low/no emission fuels. The PE Macro scenario produces the lowest GDP levels (as can be seen from Table 7.32).

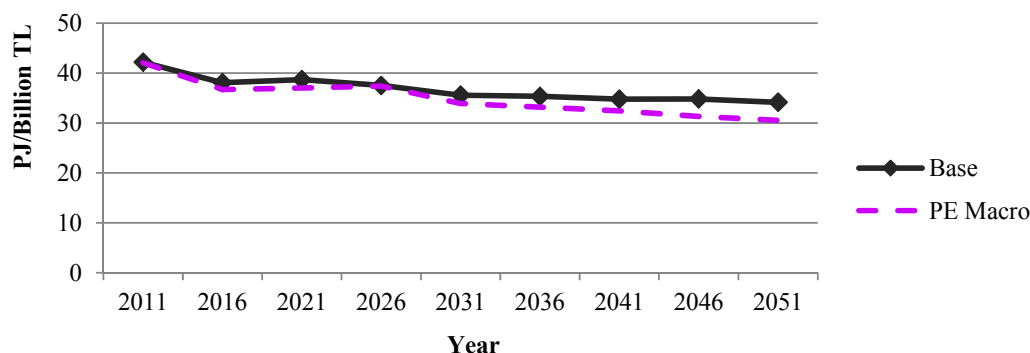


Figure 7.75. Energy intensities predicted in the Base Macro and PE Macro scenarios.

Table 7.32. GDP levels predicted in the emission scenarios (in Million TL).

	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base Macro	106.5	136.6	163.0	195.4	237.8	294.9	355.3	432.3	533.6
EM1 Macro	106.5	136.6	159.8	192.6	234.3	292.0	348.5	428.1	525.9
EM2 Macro	106.5	136.6	160.6	193.5	235.5	294.9	350.2	434.3	528.4
PE Macro	106.5	136.6	156.8	179.1	221.1	272.9	330.4	405.9	503.4

The PE Macro scenario has the same energy supply profile with the Base Macro scenario for almost 4 periods. Since coal share also becomes similar with the Base Macro scenario until 2026, import dependence rates do not change. Then, (in the second half of the planning horizon) with the depletion of coal reserves, import dependence rates increases. However, like in efficiency case, emission restriction scenarios are more effective.

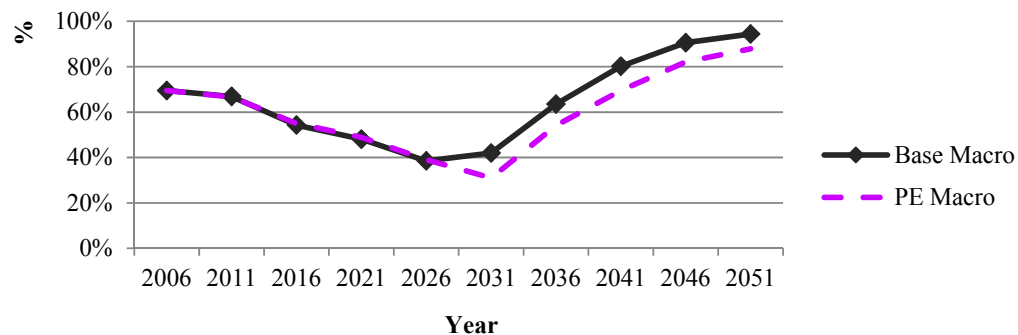


Figure 7.76. Import dependence rates predicted in the Base Macro and PE Macro scenarios.

7.7.2. Electricity Generation

Economic shrinkage shows its effect on electricity generation as well; demand for electricity generation drops. Electricity generation levels stay below of the Base Macro scenario throughout the planning horizon (as can be seen from Figure 7.77). The generation level decreases 9% in 2021 (in the short term), 10.9% in 2031 (in the medium term), and 14% in 2041 (in the long run).

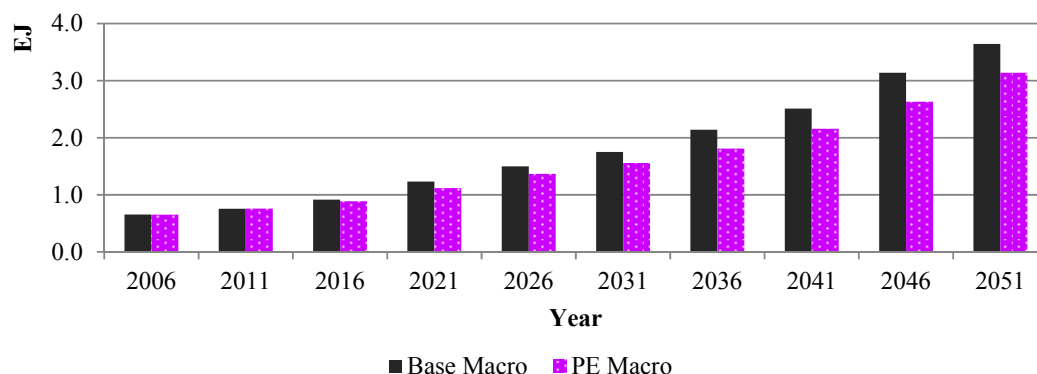


Figure 7.77. Electricity generation levels predicted in the Base Macro and PE Macro scenarios.

Electricity generation levels of emission restriction scenarios are lower than the levels of the PE Macro scenario until 2031 (as can be seen from Figure 7.78). Emission restriction scenarios support usage of more efficient technologies up to this point. However, from 2031 onwards, the PE Macro scenario has the second place right after the EM2 Macro scenario. Large investments into nuclear energy source and CCS technologies (which results cheaper electricity generations) in the EM2 Macro scenario supports these results.

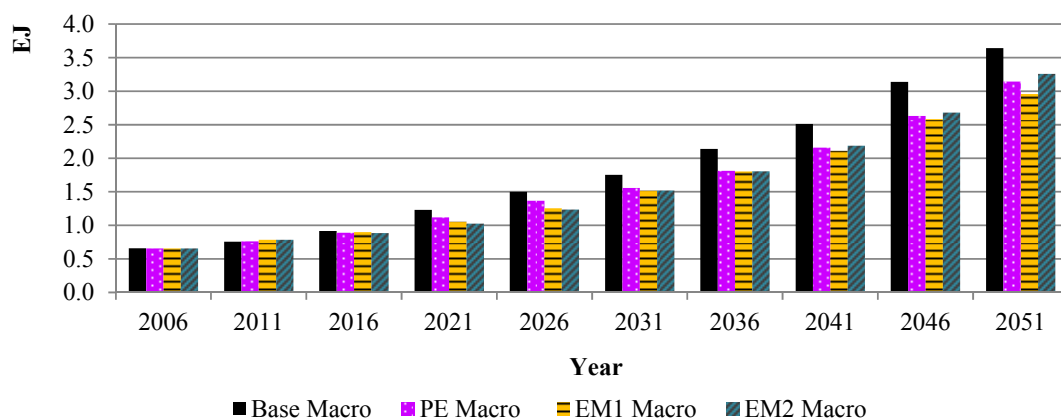


Figure 7.78. Electricity generation levels predicted in the Base Macro, PE Macro, EM1 Macro, and EM2 Macro scenarios.

The PE Macro scenario reduces the power generation from coal (as can be seen from Figure 7.79). However, the reduction volume become considerably small compared to the emission restriction scenarios. For example, coal supply is 12.5% less than those in the

Base Macro scenarios in 2016 (while this share is 94.1% and 91.4% in EM1 Macro and EM2 Macro scenarios, respectively). The highest decrease in the PE Macro scenario over the planning horizon (which is 44% at period 2046) is the lowest decrease of the EM2 Macro scenario. This implies that the PE Macro scenario produces almost the same generation levels by using more coal.

Coal power capacity is mainly replaced with hydro and wind energy resources in the PE Macro scenario (especially in later periods).

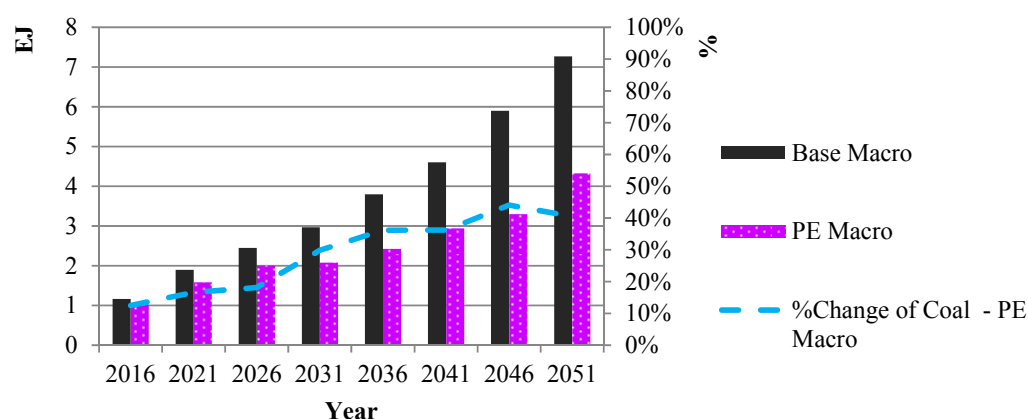


Figure 7.79. Coal supplies to electricity generation predicted in the Base Macro and PE Macro scenarios.

Table 7.33. Installed capacities predicted in the PE Macro scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.20	12.30	15.55	24.98	37.50	36.78	60.20	68.34	73.68	92.45
Natural Gas	10.28	18.72	18.60	19.14	27.81	24.42	15.13	21.05	26.35	30.87
Oil	2.42	2.42	2.41	2.41	2.39	2.38	0.00	0.00	0.00	0.00
Hydro	13.06	15.60	13.99	14.00	12.38	15.60	15.59	15.59	39.95	39.95
Wind	0.10	1.85	1.85	2.10	2.10	16.60	16.60	28.60	28.60	28.60
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	36.06	51.06	52.58	62.81	82.37	95.96	107.70	133.75	168.76	192.05

7.7.3. Renewable Energy Sources

The share of renewable energy sources in power generation follows the same trend with the Base Macro scenario until 2026. After the depletion of coal reserves in 2031, hydro and wind energy resources are actively used in electricity generation. These explain the increases in total renewable energy share after 2031. However, the share of renewable energy sources (between 2033 and 2051) never approaches those in the emission scenarios.

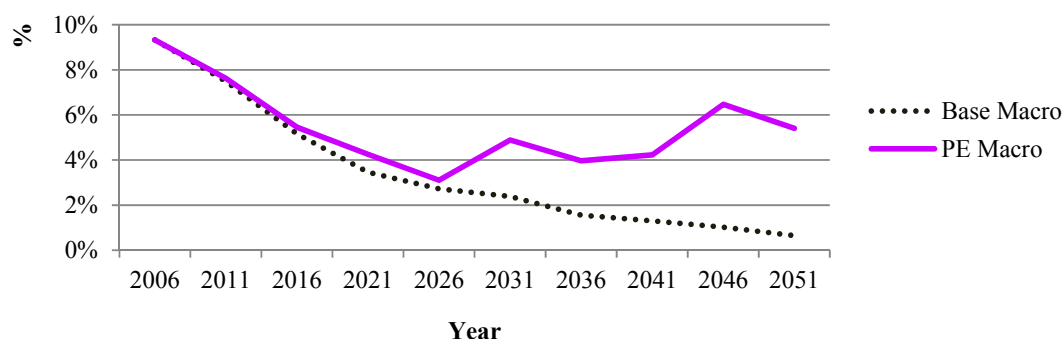


Figure 7.80. Renewable energy shares predicted in the Base Macro and PE Macro scenarios.

7.7.4. Emissions

The PE Macro scenario decrease the level of emissions compared to the Base Macro Scenario throughout the planning horizon (as can be seen from Figure 7.81). The difference between two scenarios increases in the later periods and results 16.7% in 2036 and 22.4% in 2046. The lower demand for energy is the major reason of the reduction in emissions. However, there are some investments on zero carbon fuels in the later periods which support the emission reductions, as well.

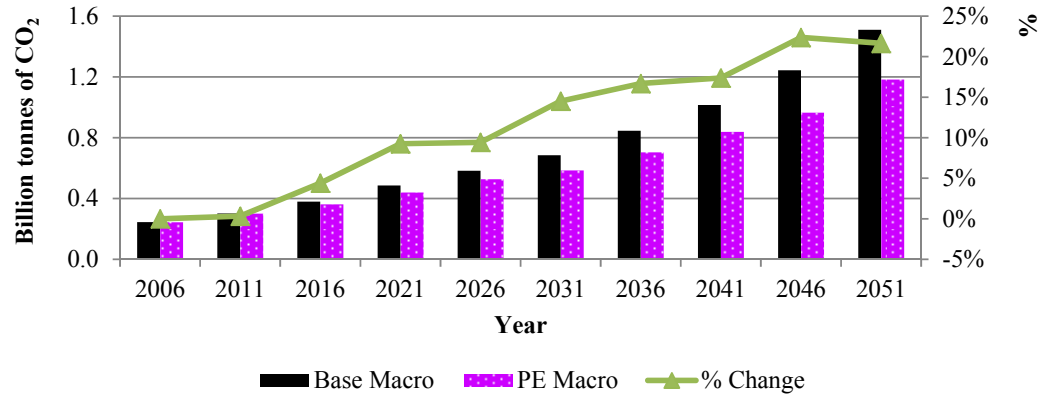


Figure 7.81. Total CO₂ emissions predicted in the Base Macro and PE Macro scenarios.

7.7.5. Costs

The sharp decreases on energy demands in 2016 and 2021 severely affects investment costs. As can be seen from Figure 7.82 and 7.83, investment costs of the PE Macro scenario are higher than those in the Base Macro scenario, except these two years. On the other hand, in agreement with the other scenarios, investment costs have the largest share in this scenario as well. The shares of investment costs increase throughout the planning horizon.

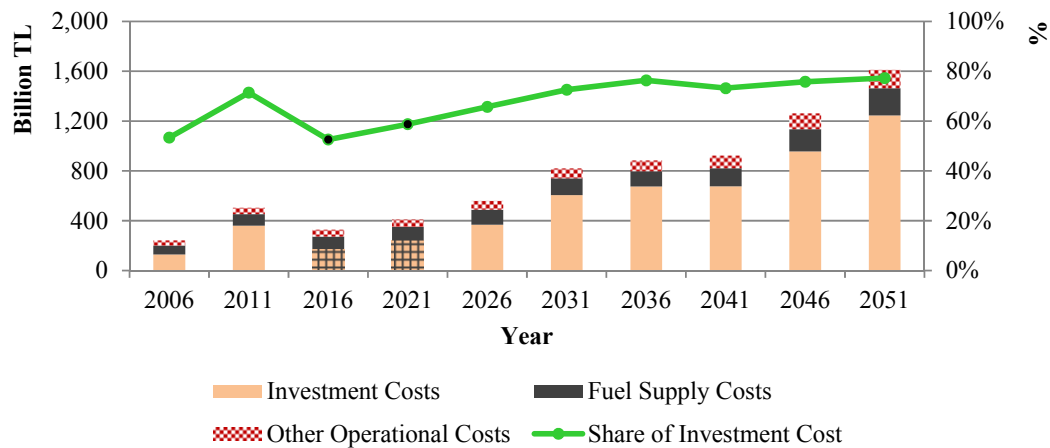


Figure 7.82. Undiscounted system costs predicted in the PE Macro scenario.

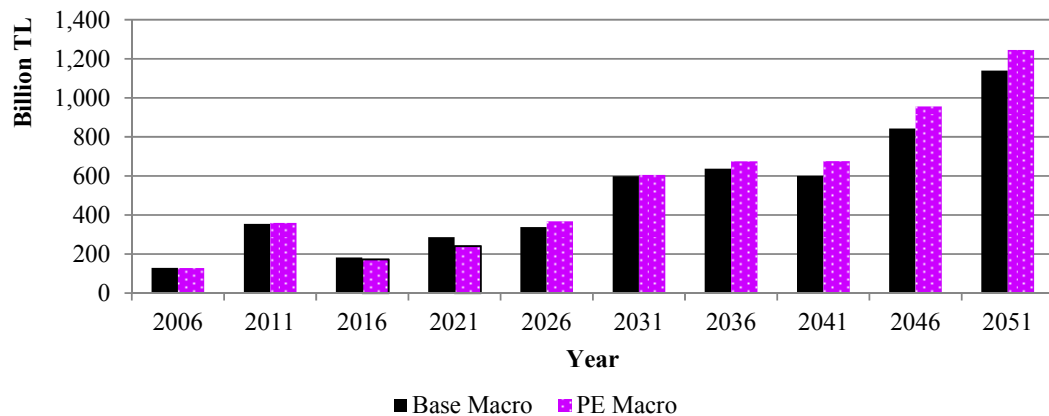


Figure 7.83. Investment costs predicted in the Base Macro and PE Macro scenarios.

The drastic shrinkage of economy in 2016 and 2021 severely affects the abatement costs as well. In these years, abatement costs realize negative values. Improvement on energy structure increases the abatement cost in the later periods (as happened in the other scenarios), but not in 2016 and 2021. Therefore, the negative costs in these periods reflect the economic s, but not improvement in the energy infrastructure.

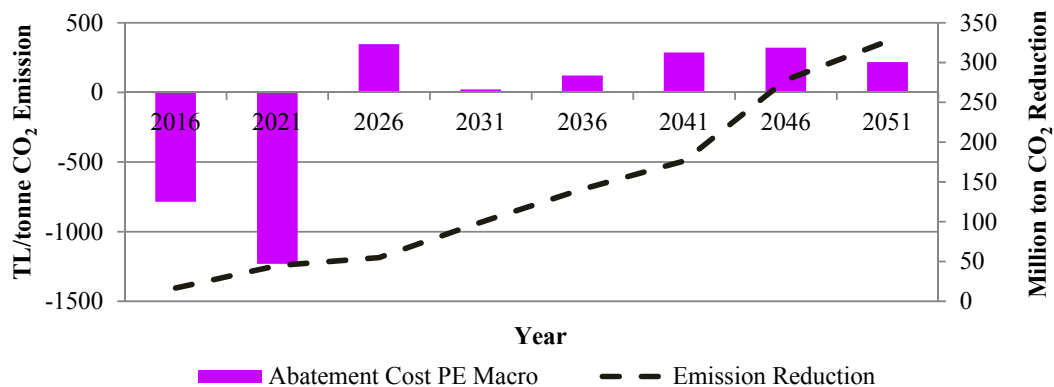


Figure 7.84. Cost of CO₂ emissions predicted in the PE Macro scenario.

7.8. Results of the Emission Penalty on Consumer Utility Scenarios

In this section, results of another emission penalty scenario, in which the penalty is directly applied on consumer utility as a nonlinear power function,¹¹ are discussed. The penalty is executed on each tonne of emissions instead of excess emission. This way, the effect of emission penalties on consumption is directly observed. To compare the results with the PE Macro scenario (in which the emission penalties are treated under the environmental cost item in the total cost function), the same emission penalty levels (which is 235 TL) are used. Accordingly, the following scenario is defined (to be compared against the Base Macro Scenario).

- (i) PEU4 Macro Scenario: A penalty of 235 TL is applied on per tonne of CO₂ emissions (the restrictions to become active after 2016).

Table 7.34. Levels of emission penalties on utility.

	2016	2021	2026	2031	2036	2041	2046	2051
PEU4 Macro (Euro/ton CO₂ emission)	235	235	235	235	235	235	235	235

This penalty scenario (i.e. nonlinear penalty applications) sharply decreases the economic growth. As can be seen from Figure 7.85, the growth rate turns to be a negative value as soon as the PEU4 Macro scenario is applied in 2016 (there is a 2% decline in GDP). In 2021, the trend reverses and the growth rate becomes positive again, but the rate stays close to zero from this period onward. The average economic growth becomes 0.9% on average for the planning horizon.

Since this penalty level changes the energy demands drastically, lower penalty rates are also applied to observe the impacts of penalty on consumer utility: in the PEU3 Macro Scenario, penalty is 23.5 TL; in the PEU2 Macro Scenario, penalty is 2.35 TL; in the PEU1 Macro Scenario, penalty is 0.235 TL. Those penalty scenarios (PEU1 Macro- PEU3 Macro) produce higher GDP growth rates compared to the PEU4 Macro scenario. However, the growth rates never goes above 2% per annum. Demand levels for different

¹¹ The penalty power function is a function of the form $f(x) = C^{penalty}$, where C is the consumption and $penalty$ represents the total emission penalty.

penalty fines can be seen from Figure 7.86. Those results show that even the lowest fine, which is 1000 times smaller than the PEU4 Macro scenario penalty, severely reduces the demand for energy.

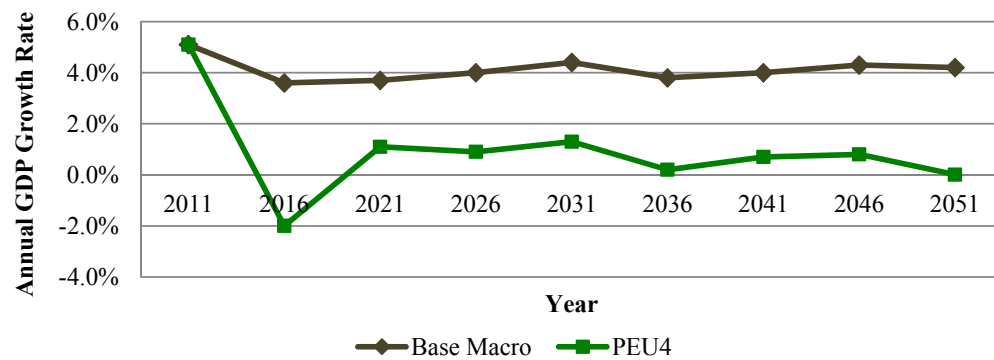


Figure 7.85. Annual GDP growth rates predicted in the Base Macro and PEU4 Macro scenarios.

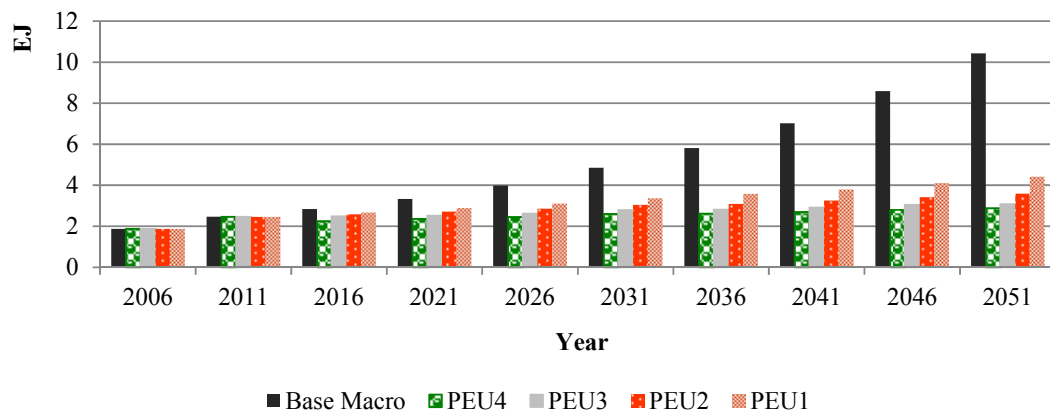


Figure 7.86. Total energy demands predicted in the Base Macro, PEU1 Macro, PEU2 Macro, PEU3 Macro, and PEU4 Macro scenarios.

7.8.1. Energy Supply

The sharp demand reductions decrease the need for energy supplies. Thus, total energy supply levels are fairly low, compared to the other scenarios (applied under the Macro module integrated TES-BUEM model) discussed in earlier subsections.

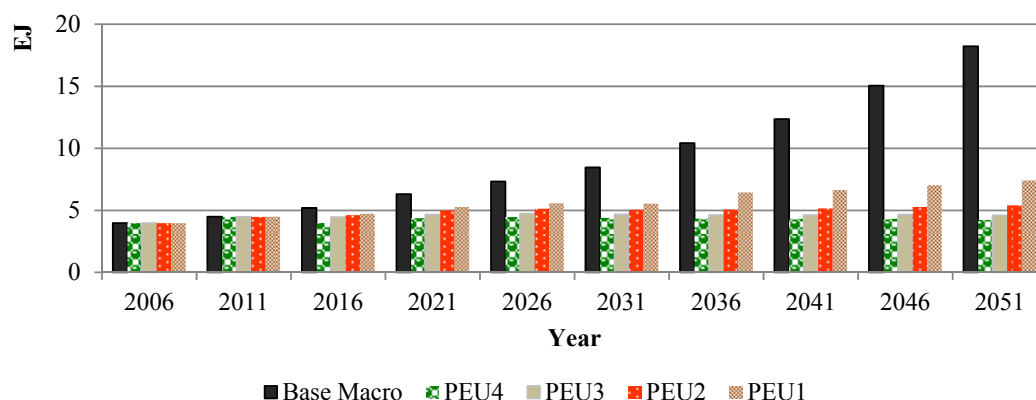


Figure 7.87. Total energy supplies predicted in the Base Macro, PEU1 Macro, PEU2 Macro, PEU3 Macro, and PEU4 Macro scenarios.

Table 7.35. Energy supplies predicted in the PEU4 Macro scenario (in PJ).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	1214.6	1571.7	1815.5	2469.2	2774.6	2953.7	3096.9	3151.2	3197.0	3188.9
Natural Gas	1157.5	1352.0	1137.0	905.1	707.5	658.1	614.2	566.3	527.9	501.8
Oil	1234.5	1208.1	756.5	769.5	769.0	602.1	306.5	280.5	265.2	215.6
Hydro	164.8	196.8	176.5	156.1	156.2	144.1	146.5	149.9	145.0	111.9
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	152.5	160.2	169.1	203.9
Wind	0.4	13.6	13.6	13.6	13.6	12.3	0.0	0.0	0.0	0.0
Bio	178.7	111.0	68.9	42.8	26.6	16.5	10.2	6.4	3.9	2.5
Solar	27.0	15.1	9.4	5.8	3.6	2.2	1.4	0.9	0.5	0.3
Geothermal	0.0	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
TOTAL	3977.6	4483.9	3992.9	4377.8	4466.6	4404.8	4343.9	4331.1	4324.5	4240.6

Since the supply levels of wind and hydro energy resources remain at the same level with the Base Macro Scenario (due to the model calibration at the beginning of the planning horizon), while total energy supply severely decreases, share of zero carbons looks like increasing (as can be seen from Figure 7.88). However, these results may be misleading.

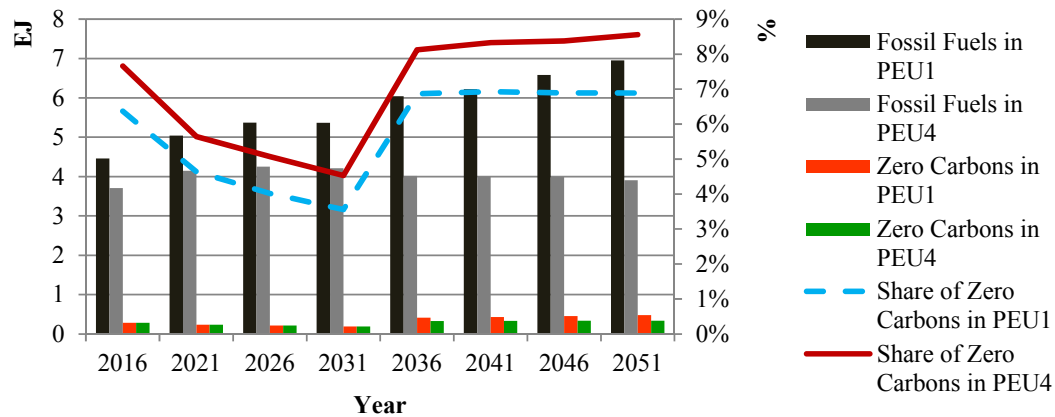


Figure 7.88. Fossil and zero carbon fuel supplies predicted in the PEU1 Macro and PEU4 Macro scenarios.

Coal share follows a similar trend with those in the PE Macro scenario (linear penalty application scenario) as can be seen from Figure 7.89. However, the results show that the PEU4 Macro scenario produces the least coal share compared to the other scenarios. In other words, even though the PEU4 Macro scenario drastically decreases the energy demand levels to decrease the level of penalties, it also invests more on efficient technologies (compared to the other penalty scenarios discussed).

Surprisingly, the PEU4 Macro and PEU1 Macro scenarios results higher energy efficiency levels (the PEU4 Macro scenario featuring and even higher energy efficiency level than the PE Macro Scenario), which means that less energy is supplied per unit spending (see Figure 7.90 and Table 7.36).

Table 7.36. GDP levels predicted in the Base Macro, PEU1 Macro, and PEU4 Macro scenarios (in Million TL).

	2011	2016	2021	2026	2031	2036	2041	2046	2051
Base Macro	106.5	136.6	163.0	195.4	237.8	294.9	355.3	432.3	533.6
PEU4 Macro	106.5	136.6	123.4	130.4	136.3	145.4	146.9	152.1	158.3
PEU1 Macro	106.5	136.6	147.8	160.0	172.4	186.7	219.6	231.9	251.1

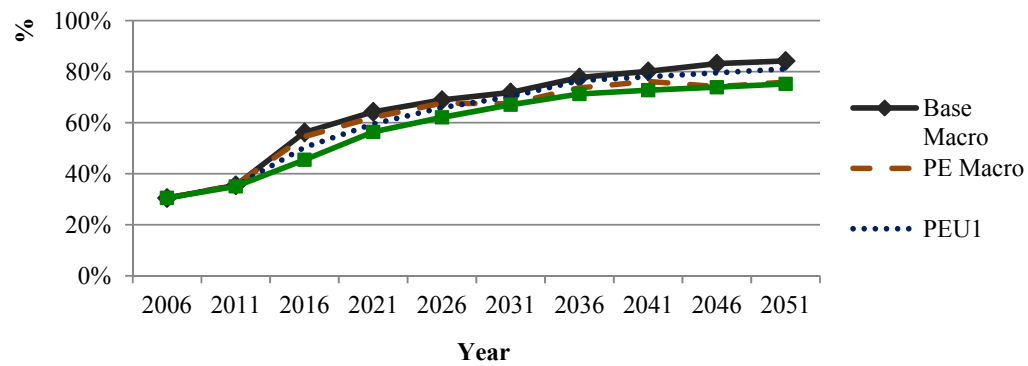


Figure 7.89. Coal shares in total energy supplies predicted in the Base Macro, PE Macro, PEU1 Macro, and PEU4 Macro scenarios.

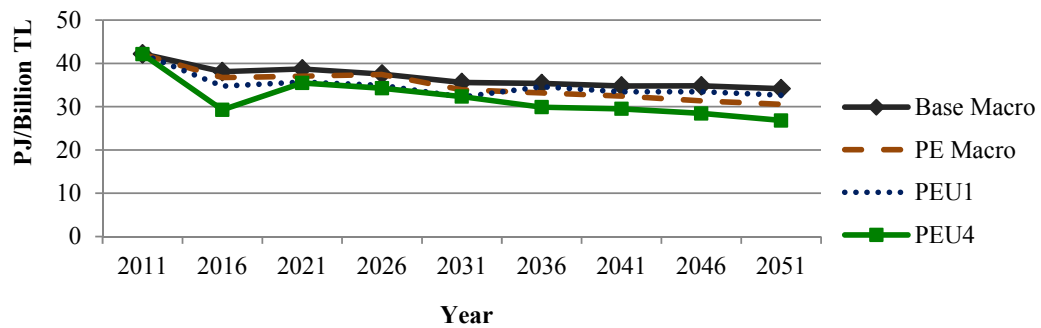


Figure 7.90. Energy intensities predicted in the Base Macro, PE Macro, PEU1 Macro, and PEU4 Macro scenarios.

Since demands are too low in the nonlinear penalty application scenarios, depletion of the national coal resources is further delayed. Thus, the import dependence levels of the PEU4 Macro scenario are lower than the other scenarios (as can be seen from Figure 7.91). Since the coal share is lowest in the PEU4 Macro scenario this result is expected.

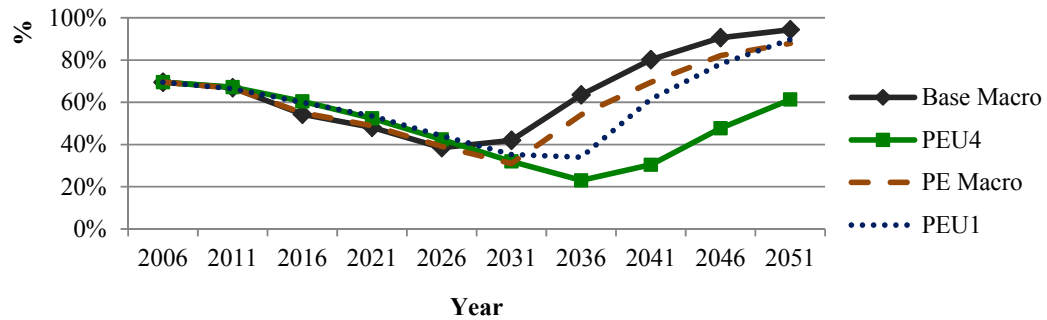


Figure 7.91. Import dependence rates predicted in the Base Macro, PE Macro, PEU1 Macro, and PEU4 Macro scenarios.

7.8.2. Electricity Generation

Corresponding to the demand decrease in nonlinear penalty scenarios, electricity generation and installed capacity levels decrease as well. Electricity generation level never goes above of 2 EJ in any of the nonlinear penalty scenarios (as can be seen from Figure 7.92 and Table 7.37).

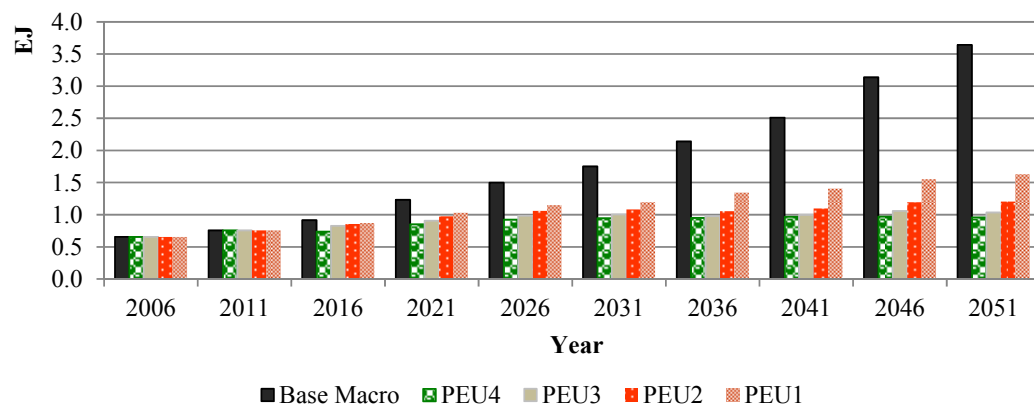


Figure 7.92. Electricity generation levels predicted in the Base Macro, PEU1 Macro, PEU2 Macro, PEU3 Macro, and PEU4 Macro scenarios.

Table 7.37. Installed capacities predicted in the PEU4 Macro scenario (in GW).

	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Coal	10.20	12.30	11.03	16.16	19.35	20.45	21.83	22.65	22.71	23.26
Natural Gas	10.28	18.72	18.60	18.48	18.07	15.97	17.33	17.02	17.02	17.02
Petroleum Products	2.42	2.42	2.41	2.41	2.39	2.38	0.00	0.00	0.00	0.00
Hydro	13.06	15.60	13.99	12.38	12.38	11.42	11.62	11.88	11.49	8.87
Wind	0.10	1.32	1.32	1.32	1.32	1.22	0.00	0.00	0.00	0.00
Geothermal	0.00	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
TOTAL	36.06	50.53	47.52	50.93	53.69	51.61	50.95	51.72	51.39	49.32

7.8.3. Renewable Energies

Because of the model calibrations at the beginning of the planning horizon, wind, geothermal, and especially hydro power energy sources are supplied at the same levels with the Base Macro Scenario, while the other fuels decrease. Thus, the shares of renewable energy sources are higher in these scenarios. The PEU4 Macro scenario generates the highest renewable energy shares since it has the lowest energy demand profile. However, as expected, the decrease trends are similar (as can be seen from Figure 7.93). Apart from the calibration impositions, there is no new investment of renewable energy technologies in the system (the system does not rely on expensive renewable energy technology investments).

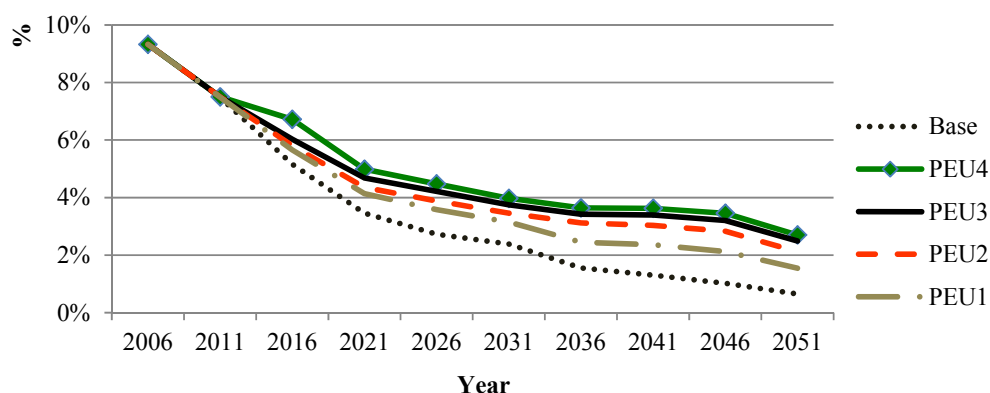


Figure 7.93. Shares of renewable energy resources predicted in the Base Macro, PEU1 Macro, PEU2 Macro, PEU3 Macro, and PEU4 Macro scenarios.

7.8.4. Emissions

As expected, since the demands are lower, the emissions are also lower. In addition, total emissions almost stabilize after 2021 (corresponding to the stabilization in demand levels), except the PEU1 Macro scenario.

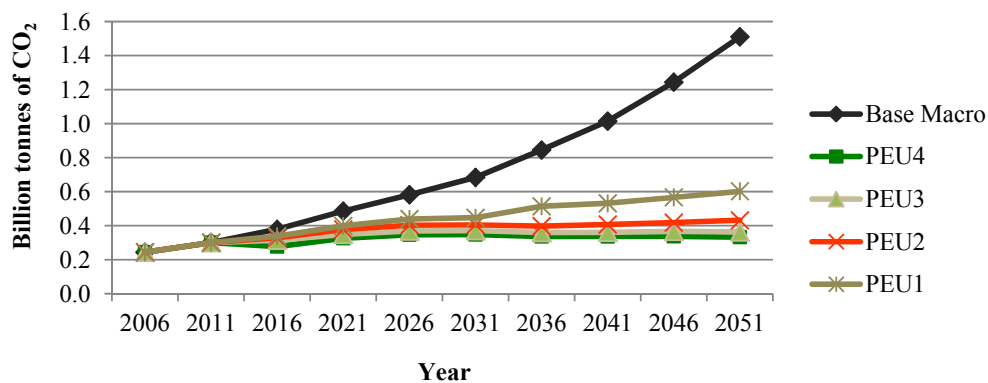


Figure 7.94. Total CO₂ emissions predicted in the Base Macro, PEU1 Macro, PEU2 Macro, PEU3 Macro, and PEU4 Macro scenarios.

8. CONCLUSION

This thesis study primarily features the development and implementation of a new large-scale energy modeling framework. The purpose of building this framework has been to focus on the mechanisms and relationships that would mimic a national energy system as realistically as possible, but without unnecessary, insignificant detail that would primarily hinder data compilation and result analysis phases. From this perspective, the BUEM (Bottom Up Energy Model) framework is designed as a simple, flexible, general purpose, linear optimization modeling framework.

The main feature of the BUEM framework is its simple and straightforward structure that allows the user to analyze the economic and environmental impacts of alternative policies in a transparent fashion. Complicated linkages of any energy related technology and facility, either in itself or with other technologies and facilities, are simplified in a comprehensive way. The open structure of the BUEM framework, on the other hand, provides a flexible and favorable environment to add new relations or constraints to the system (based on what the user wishes to analyze and on scenario requirements).

The BUEM framework is designed to have the ability to perform national or sectoral analysis. The main modeling system is a unified structure of submodules and this modular structure allows the user to work either on narrow or wide scope projects. That gives the framework its ability to support specific energy studies, e.g. hybrid vehicle share in transport sector, or more general policies, e.g. import dependence of a country for energy.

The basic philosophy behind the BUEM framework is mostly inspired by a well-known energy modeling tool, MARKAL. However, they differ in many points. For example, MARKAL's data requirements are immense. In most cases, the user has to compile extensive data sets that most likely will contain details that neither be needed in the policy analysis nor can be reliably assembled, but have to be provided in order to run the model. Such unused data and relations amplify the size of the model, which results in increasing memory requirements and computational challenges on model runs and increasing complexity and difficulty on result analysis. In addition, the modeling flexibility

and functional forms provided in some of the relationships may lead to unnecessary mathematical complexity, misunderstandings, and misrepresentations. Enabled detail is mostly not necessary. From this perspective, the number of parameters, variables, and relationships/constraints are reduced in the BUEM framework: it provides for five types of decision variables (compared to nine in the MARKAL) and 17 types of constraint sets (compared to 28 in the MARKAL), combines or eliminates rarely used parameters (in the MARKAL), eliminates rarely used relationships (in the MARKAL), and represents the existing relationships in simpler fashions (in the MARKAL). In other words, especially considering large energy systems, typical representative models generated by this framework are considerably smaller, thus reducing data compilation, handling and result analysis efforts.

A Turkish Energy Sector model (TES-BUEM Model) has been developed on the BUEM framework as a case study analysis. This model has been used for two primary purposes: (i) a validation practice for the BUEM framework, (ii) a scenario analysis tool. The validation of the TES-BUEM model has been done by comparing the model results with the results of a TES-MARKAL model (which is another, independent Turkish Energy Sector model developed and run under the MARKAL modeling framework). In order to enable a more realistic comparison, the same structure, data set, and details are used in the two models. The results show that although the TES-BUEM model is considerably simpler, smaller, and less data demanding than the TES-MARKAL model, the TES-BUEM model run results turned out to be very close to the TES-MARKAL model results. This conclusion validates that the aggregations and simplifications suggested in the BUEM framework do not lead to loss of precision in the results. Since the data requirements of the larger and more detailed frameworks are mostly not available or accessible, those types of frameworks do not bring more refinement or sophistication on generated model results.

The TES-BUEM model results are also compared with the realized statistics. The results show that the 2009 realized statistics (which are the most updated and trustable energy data) are in the 2006 - 2011 estimation interval of the TES-BUEM model.

On the other hand, although the BUEM bottom-up modeling framework itself evaluates the energy sector in a very rich technological detail, it does not address the interactions between energy sector and rest of the economy. There is not any relationship linking the energy demand and the energy prices. Instead, all demand services are treated as exogenous parameters to be inputted to the system by the user. However, in the real world, just like all other goods and services, energy demands are severely affected with changes in energy prices. It is expected that any increase in prices decreases the demand for energy services. Therefore, an extension of the bottom-up framework, namely the macro module, is developed with the intension of endogenously generating energy demand projections under the effects of energy prices.

The thesis study also contains a thorough description of the new modeling framework along with a full-scale application on the Turkish energy sector and several scenario analysis. The modeling application identifies the energy projections of Turkey, associated CO₂ emissions, system costs and many other energy system characteristics that have been discussed along the way.

A first major conclusion is that coal would dominate the energy system after a few periods, independent from the scenario assumptions. The primary reason of this result is the relatively cheap prices of coal and related process technologies. On the other hand, even when through subsidies and other inducements, as expressed via various scenario assumptions, renewable sources are made attractive, most renewable energy sources quickly approach their maximum annual potentials indicating that those potentials are alone not sufficient to satisfy the growing energy demands. The optimization process invests again into coal (because of the cheap prices), to satisfy the remaining demand. Therefore, the energy system is dominated by coal in each scenario. However, the level of domination changes between scenarios.

A second conclusion refers to the import dependence of the country. The optimization process initially uses national coal reserves (as the cheapest alternative) in each scenario until reserves are depleted. The exhaustion year changes from scenario to scenario. However, once domestic coal is no longer available, the cost minimizing model

invests on imported coal as the second cheapest alternative. As a result, the import dependence rate sharply increases and approaches 100% in the later periods. In addition, it is interesting to note that in the last periods of the planning horizon, import levels of all scenarios resemble the Base scenario results. This means that once the national reserves are exhausted, all scenarios feature very similar import levels. This observation illustrates that Turkey will be extremely dependent on imported fuels in the mid-future, if the current energy profile and dynamics do not change. The country needs to establish new and alternative sources of energy supply.

Besides the Base scenario, the TES-BUEM model has been run under five different scenarios: two emission restrictions scenarios, two emission penalty scenarios, and a coal import restriction scenario. Additionally, the macro module integrated TES-BUEM model is also run under these scenarios (and the base) and the results of the Base scenario run under the Macro module integrated TES-BUEM model is compared with the other scenarios: two emission restriction scenarios, an emission penalty scenario, and a scenario that applies emission penalties on consumer utility. Additionally, some of the scenarios considered feature the availability of investment options regarding nuclear power and CCS plants.

Comparing emission restrictions and penalty scenarios with each other, it is found that the emission restrictions scenarios are more effective than the emission penalty scenarios in many aspects. Total energy supply levels are the lowest in the emission restriction scenarios (which feature the higher investments on efficient technologies). Emission restriction scenarios change the energy generation and usage profiles as soon as 2016. Low and zero emission technologies are heavily invested and used. However, after the maximum potentials of those technologies are reached, high emission fuels, mostly coal again, become favorable (because of the relatively cheap prices). On the other hand, in the penalty scenarios the optimization process prefers to pay some penalties in the early periods, instead of investing on efficient and zero and low emission technologies under the current penalty cost profile. These outcomes indicate that higher penalty fines are needed to obtain a similar behavior in the earlier periods.

In addition, the effects of the CCS technologies and nuclear energy sources are clearly observed in the emission scenario results. The CCS technologies feature more coal consumption (while at the same time reducing CO₂ emissions), thus reduce the need for efficient technology deployment. In the emission scenarios where the CCS technologies are active, total energy supply levels are higher and efficiency levels are lower. Nuclear energy sources, on the other hand, significantly increases the share of zero carbon fuels and decrease the dependence on imports.

On the other hand, the coal import restriction scenario focuses on the changes of energy system dynamics under coal unavailability. This scenario does not impose any conditions nor restrictions on efficiency improvements, renewable energy resource deployment, or emission reductions, but, nevertheless, the results are remarkably better than those of the emission restrictions and penalty scenarios. Decreases in total energy supply and emission levels are significant, compared to the emission scenarios. The heavier reliance on efficient technologies as well as low and zero emission fuels (due to the unavailability of coal) leads to this result.

The emission scenarios which are run under the Macro module integrated TES-BUEM model display another perspective. In these scenarios, energy demands are endogenously produced in the system in accordance with the energy prices. Therefore, the immediate reaction of those scenarios are to reduce demand levels (instead of investing on expensive but low and zero emission energy sources and technologies). All scenarios lead to economic shrinkage. The level of demand reduction is greater in emission penalty scenarios, compared to the emission restriction scenarios. The penalty on consumer utility, on the other hand, shrinks the economy the most and provides extreme results. In this scenario, the penalty fine is directly applied on consumer utility as a power of consumption in the utility function (instead of being executed as a component of the total system cost like in the regular penalty scenarios). In addition, the fine is imposed on each tonne of emissions instead of excess emission. The results show that with this type of penalty application, optimization process prefers extreme reductions on energy demand levels in order to avoid paying high penalties. It is clear that impact of the nonlinear penalty application on consumer utility is more drastic than a linear penalty application (indirect effect on consumer utility).

During the development of this thesis several other scenarios, besides those herein presented, such as different emission restriction levels, higher penalty fines, higher coal prices, and so many others, have been analyzed as well. The results of those scenarios are displayed in the “Sensitivity Analysis” folder of the Appendix CD. On the other hand, there are also a number of possible topics that can be taken up as future work related to the research done in this thesis study. For example, one of the major areas that are not addressed in this thesis and suggested as future study is the extension of the framework for regional studies. The trading relationships among multiple regions over the energy sources that include energy source transmissions, transportation distances and costs, and tariff prices are considered as good extensions of the BUEM framework. In addition, development of a tax mechanism within the Macro module that will allow the consideration and management of emission penalty payments of the BUEM framework as government revenues that can be rechanneled to expand the general economy and thus energy demand is suggested as another possible future extension of the thesis study.

APPENDIX A: OTHER CONSTRAINTS OF THE MARKAL FRAMEWORK

(i) *Electricity Balance Constraints:*

$$\begin{aligned}
 & \sum_s qhr_{zy}(w) * r_{tsep}(s, t) + \sum_{ce} r_{tezy}(ce, w, t) \\
 & + \sum_{ceh} \left(ceh_{zy}(ceh, w, t) * \left(\frac{1}{elm(ceh, t)} - 1 \right) * r_{tczyh}(ce, w, t) \right) \\
 & + \sum_d qhr_{zy}(w) * moent(d, t) * capunit(d, t) * cf(d, t) \\
 & * r_{cap}(d, t) \\
 & \geq \sum_s inpent(s, t) * qhr_{zy}(w) * r_{tsep}(s, t) \\
 & + \sum_p inpent(p, t) * qhr_{zy}(w) * r_{act}(p, t) \\
 & + \sum_{ce} inpent(ce, t) * r_{tezy}(ce, w, t) \\
 & + \sum_{ch} inpent(ch, t) * \left(\frac{qhr_{zy}(w)}{qhrz(z)} \right) * r_{thz}(ch, z, t) \\
 & + \sum_d maent(d, t) * capunit(d) * cf(d, t) * qhr_{zy}(w) \\
 & * r_{cap}(d, t) / eff(d, t)
 \end{aligned} \tag{A.1}$$

(ii) *LTH Balance Constraints:*

$$\begin{aligned}
 & \sum_s qhr_z(z) * r_tsep(s, t) + \sum_{ch} r_thz(ch, w, t) \\
 & + \sum_{ceh} r_tczyh(ceh, w, t) \\
 & + \sum_d moent(d, t) * capunit(d, t) * cf(d, t) * qhr_z(z) * r_cap(d, t) \\
 & \geq \sum_d maent(d, t) * capunit(d) * cf(d, t) * qhr_z(z) \\
 & * r_cap(d, t) / eff(d, t)
 \end{aligned} \tag{A.2}$$

(iii) *LTH Peak Reserve Constraints:*

$$\begin{aligned}
 & \frac{teent(e, t)}{(1 + hreserv(e, t))} \\
 & * \sum_c peakcon(c, t) * capunit(c) * qhr_z(z) * af(c, t) * r_cap(c, t) \\
 & \geq \sum_d maent(d, t) * capunit(d) * cf(d, t) * qhr_z(z) \\
 & * r_cap(d, t) / eff(d, t)
 \end{aligned} \tag{A.3}$$

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