OPTIMIZATION OF ENERGY MIX CONSIDERING SUSTAINABILITY CHARACTERISTICS AND ITS APPLICATION TO TURKEY

by

Aybike Alkan

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This is to certify that I have examined this copy of a master's thesis by

Aybike Alkan

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

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Metin Türkay, Ph. D. (Advisor)

____

Pelin G. Canbolat, Ph. D.

____

Şuhnaz Yılmaz, Ph. D.

Date: ____________________________

ABSTRACT

Increasing energy demand and harmful emissions from primary energy sources are the most important problems for environmental sustainability. If energy policies do not change, this problem is poised to create dramatic problems in the future. Energy mix is one of the crucial decisions to take into consideration in controlling environmental effects of primary energy sources. A careful design of energy mix gives the opportunity to consider sustainability indicators and cost of different energy sources. In this thesis, we analyse the power generation systems considering CO_2, NO_x, and SO_2 emissions, energy demand projections into the future and cost estimates for the primary energy sources. We consider seven different energy sources; oil, natural gas, coal & lignite, wind, solar, geothermal and hydro energy. The optimization model is formulated as a Multi-Objective Mixed Integer Linear Programming (MOMILP) problem. We consider two main objectives: cost and GHG emissions under demand and budget constraints. The resulting bi-objective optimization model is solved using the epsilon-constraint optimization method. The solution of the model suggests which energy sources, when and where should be built over a long term planning horizon and whether shifting the fuel to natural gas in a coal power plant is a right move in terms of cost and emission objectives. The Turkish power generation system provides a real case study to test our model empirically. A sensitivity analysis is performed to determine how the optimum solution is sensitive to a change in one of the parameters assigned for real life application. The effect of wind turbine power coefficient, investment level, natural gas prices are examined within the scope of sensitivity analysis.

ÖZETÇE

Artan enerji talebi ve birincil enerji kaynaklarının yol açtığı zararlı gaz salınımı çevresel sürdürülebilirliğin en önemli problemidir. Eğer enerji politakaları değiştirilmezse, bu durum gelecekte daha büyük problemler teşkil edecektir. Birincil enerji kaynaklarının çevresel etkilerini kontrol etmede ”enerji mix” üzerinde durulması gereken en hayati kararlardan biridir. Dikkatli bir enerji mix dizaynı sürdürülebilirlik göstergelerini ve farklı enerji kaynaklarının maliyetini değerlendirme fırsatını sunar. Biz bu tezde elektrik üretim sisteminin geleceğini, CO_2, NO_x ve SO_2 salınımlarını, enerji talep projeksiyonlarını ve enerji kaynaklarının maliyet tahminlerini göz önüne alarak analiz ettik. Güç üretim sistemi içinde, yedi farklı enerji kaynağını, fuel-oil, doğalgaz, kömür ve linyit, rüzgar, güneş, jeotermal ve hidro enerji olmak üzere inceledik. Optimizasyon modeli çok amaçlı tamsayı-karışık doğrusal programlama problemi olarak formüle edildi. Amaç fonksiyonları ise talep ve bütçe kısıtları altında maliyet ve sera gazı salınımı olarak düşünüldü. Elde edilen optimizasyon modeli epsilon kısıt metodu (epsilon constraint method) kullanılarak çözüldü. Modelin ampirik olarak test edilebilmesi için Türkiye'nin güç üretim sistemi vaka çalışması olarak kullanıldı. Modelin çözümü sonucunda hangi güç teknolojisinin nerede ve ne zaman kurulması gerektiği ve kömür yatan bir termik santralin yakıtını değiştirmenin amaç fonksiyonları bazında tercih edilebilir olup olmadığı belirlendi. Tayin edilen parametrelerden birinde yapılacak bir değişikliğin optimal sonucu ne derece etkilediğini görebilmek amacıyla bir duyarlılık analizi yapıldı. Rüzgar türbininin güç katsayısının, yatırım miktarının ve doğal gaz fiyatının etkileri analiz kapsamında incelendi.

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LIST OF ACRONYMS & ABBREVIATIONS

CCS	Carbon Capture and Sequestration
CO_2	Carbon dioxide
DSM	Demand Side Management
EGS	Enhanced Geothermal System
EIA	US Energy Information Administration
EU	European Union
GAMS	General Algebraic Modeling System
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GW	Gigawatt
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kW-h	Kilowatt-hour
kW-e	Kilowatt electricity
LCA	Life Cycle Assessment
LCD	Load Duration Curve
MIP	Mixed Integer Programming
MMBtu	Million British thermal units
MOLP	Multi Objective Linear Programming
MOMP	Multi-Objective Mathematical Programming
MTA	General Directorate of Mineral Research and Exploration

MW	Megawatt
MWe	Megawatt electric
MWh	Megawatt-hour
MWt	Megawatt thermal
NLP	Non-linear Programming
NO_x	Nitrogen dioxide
O&M	Operating and Maintenance
PDF	Probability Distribution Function
PV	photovoltaic
R&D	Research and development
SO_2	Sulfur dioxide
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
YEGM	Renewable Energy General Directorate of Turkey

Chapter 1

INTRODUCTION

Energy is the most crucial input of social prosperity and economic advancement. Since the industrialization in the 20th century, the increasing energy demand has been the most important actor of our modern lives that also creates many conflicts due to its strong effects globally. On the one side the reserves of conventional energy sources may not be able to meet the energy demand of the world in coming years. On the other side, these energy sources threaten our world by means of global warming which is one of the most crucial problems of our time. The ever increasing amount of greenhouse gas (GHG) emissions has intensified this problem. According to the projections of U.S. Energy Information Administration (EIA), the total world energy consumption will grow by 56% by 2040 [1]. Besides, Figure 1.1 shows the sharp increase according to real data and projected data between 1990 and 2040 [1]. Since more energy consumption implies more GHG emissions, the consumption and production technologies of energy must adopt a sustainable character.

Each country has different energy production policies due to factors such as ecological vulnerability and impacts, geographic opportunities, the presence of national industry champions or not, nuclear production or not, existing infrastructure, national Research & Development (R&D) programs, policy incentives, primary energy resources available locally [2]. Turkey's position does not seem to be pleasant at

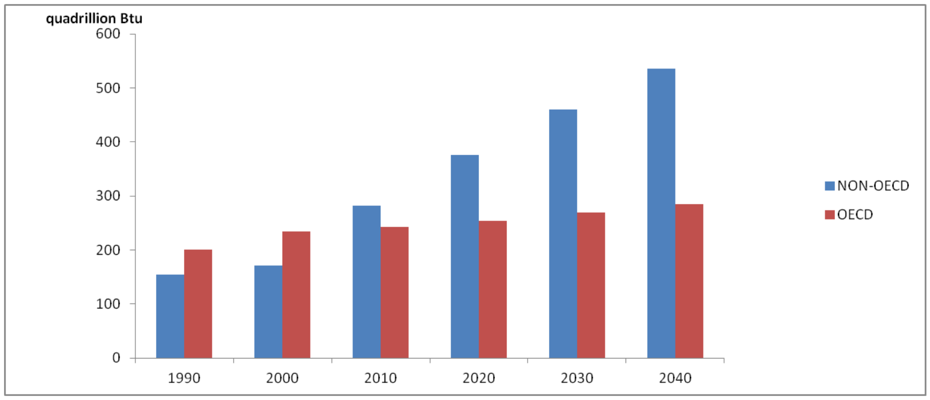


Figure 1.1: World energy consumption, history (1990-2010) and projection (2020-2040)

present. This is mainly because of high energy import rates caused by insufficient reserves of domestic energy sources. Since Turkey is a developing country with a fast economic growth, total imports and the share of energy within total import increases every year. As a result of this high import rate, the current issue is the trade-off between economic growth and current account deficit whose main triggers are the lack of balance between domestic and external demand and the lack of accurate forecast [3]. Figure 1.2 proves the importance of energy imports in the current account deficit.

Although Turkey has low reserves in terms of conventional energy sources like crude oil and natural gas, it has a great renewable energy potential. To convert this potential into reality, Turkey has to make huge investments to increase the percentage of renewable energy sources in her energy mix. This is also crucial for environmental considerations since using fossil fuels to extract energy is the main reason of emissions. As specified in the report of United Nations Framework Convention on Climate change, rise in GHG emissions has reached 72.6% from 1990 to 2006 in Turkey and it is urgent for Turkey to take action. Reducing the amount of fossil fuels is a good move for Turkey not only considering emissions but also considering the increase in natural gas and crude oil prices by 500% in the last 15 years [4].

The objective of our study is to present an optimal mix for electricity generation system of Turkey which ensures economic and environmental welfare leading to a sustainable future. Turkey is a developing country and improving-modernizing the electricity system is the necessary condition for Turkey's development. It is impossible to create a certain recipe for energy mix leading to a sustainable future; however, our objective in this thesis is to develop a systematic approach based on mathematical programming whose inputs can be changed over time to conduct different scenario analysis.

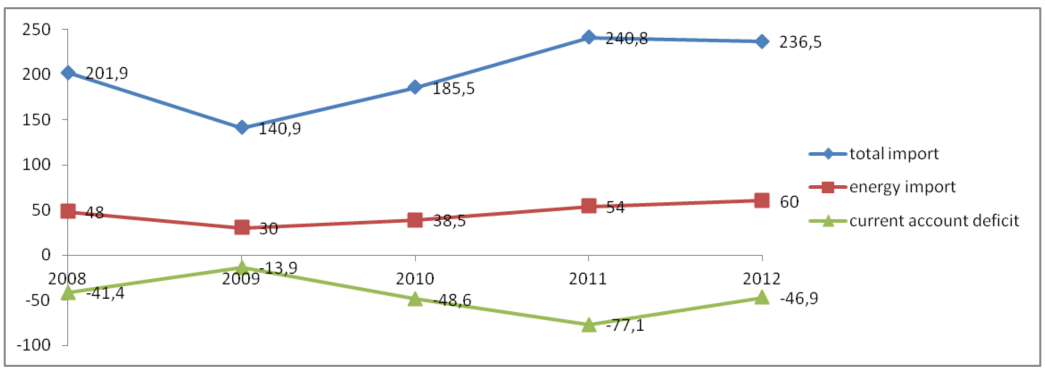


Figure 1.2: Total import, energy import, current account deficit between 2008-2012, data taken from SETA.

Thesis Outline

This thesis is organized as follows: Chapter 1 continues with main information on energy sector. The information includes the types of primary energy sources, environmental impacts exerted by these sources, the general framework of energy industry of Turkey and the policies and legislation on renewable energy utilization. We also explain the optimization theory before concluding the chapter. In chapter 2, we present the evolution of the studies conducted on energy planning. This chapter gives information about the history of optimization models with single or multi-objective problems of energy mix and examines the research performed to deal with the uncertain nature of renewable sources. Chapter 3 gives a brief problem description with the assumptions made and then describes the bi-objective model formulation. Parameter and variables of the model are introduced before the objective function and constraints are explained. In Chapter 4, we present the real life application of the model described in previous chapter. First, how the model implemented into Turkish power generation system is clarified. Then, the results for single objective and multi-objective models are interpreted with figures and tables. At the end of the chapter, effect of key parameters on optimal solution is determined within the scope of sensitivity analysis. Chapter 6 concludes the thesis discussing the results and analysis together with the suggestions of future research directions.

1.1 Primary Energy Sources

The energy to heat our homes, power our electrical appliances or to transport comes to our use after a series of conversions, called the energy conversion chain. Any energy consuming device leans back on one of the three primary sources: fossil-fuels, renewable sources, and nuclear energy [5] which are the raw materials of energy conversion.

The global primary energy production is shown in Figure 1.3 [1]. The chart demonstrates that almost 80% of energy production is based on fossil based fuels. According to the data of EIA, the largest component of fossil fuel slice is oil, followed by coal and natural gas, respectively. On the other hand, biomass power and hydroelectric power are the largest sources of renewable share. The contribution of solar, wind and geothermal power is very limited in the overall picture.

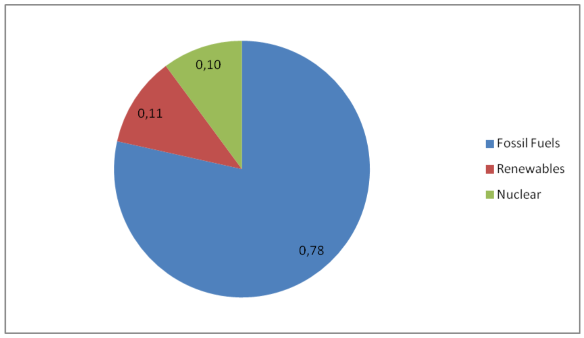


Figure 1.3: World primary energy production by source in 2013.

1.1.1 Fossil Fuels

The fossil fuels are the largest component of primary energy sources including crude oil, coal and natural gas. Oil and natural gas are originated from national processes along the millions of years. Buried animals and plants store the sun energy in carbon, and when exposed to high pressures and heat they release energy. Since they require such a long period to form, longer than they are consumed, they are accepted as non-renewable. As increasing energy consumption demands more fossil fuels to be burned, depletion of these fuels becomes the question. Nevertheless, their high energy density makes them favourable over other primary sources. A little amount of fuel is enough to power a combustion engine to achieve a huge amount of energy production. Today transportation system heavily relies on oil industry while natural gas is the most common way of generating electricity. However, the depletion risk of oil and gas results in a huge increase in prices, and fuel importing countries become very disadvantageous depending upon the consumption of these fuels. Figure 1.4 exhibits the magnitude of the price pattern of oil and natural gas [1]. Because of the depletion risk of traditional petroleum supplies, energy production from heavy oil deposits and oil sands are being utilized to extract crude oil as a synthetic oil [5]. On the other hand, coal is readily available in nature. The reserve to production ratio (R/P) which is the

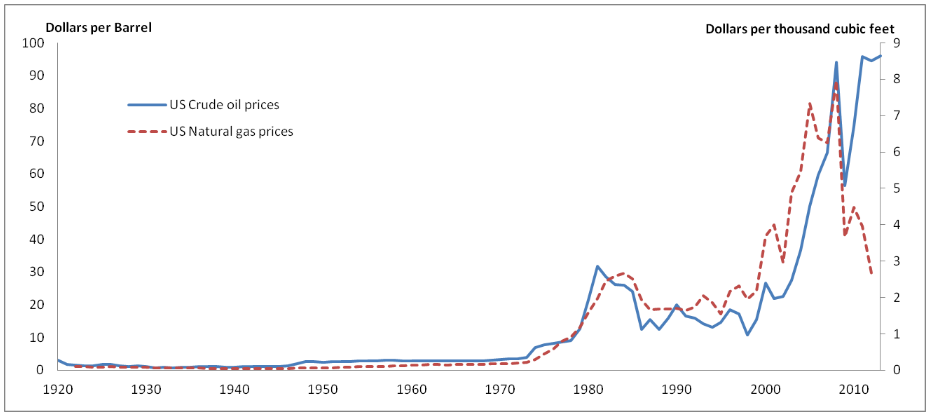


Figure 1.4: US Natural gas and Crude oil prices between 1920-2013.

remaining amount of coal in nature (or any other non-renewable source) is very high, on the order of 200 years [5]. International Energy Agency (IEA) defines the coal as a "variety of solid, combustible, sedimentary, organic rocks that are composed mainly of carbon and varying amounts of other components". Today, coal is responsible of meeting 40% of the world's electricity demand. The developments and high growth rate in China are nourished by the great abundance of coal reserves. However, high utilization of coal energy is not acceptable in the era of global warming and climate change. All types of fossil fuels are responsible for the GHG emissions but coal is the most dangerous fuel in terms of environmental aspects. Technologies to reduce the carbon emissions like carbon capture and sequestration (CCS) seem to be an answer the problem but today their performance is not enough to implement the regulations.

1.1.2 Renewable Energy Sources

Conventional energy sources with which we meet our growing energy demand to heat our residences, fuel our transportation systems and generate our electricity are no longer tenable. Humanity faces the risk of depletion of fossil fuel stock and must search for another way of generating energy, a cleaner way to protect our environment. At this point, renewable energy sources seem to be promising; however, they have lower extractable energy than fossil based fuels and a higher investment level. Nevertheless, as the cost of fossil fuels continues to increase, renewable energy sources become more competitive based on economical concerns.

Renewable means that the sources can be utilized with no risk of depletion. Conforming to Turkish Law 5346 (the law on "utilization of renewable energy sources for the purpose of generating electrical energy"), renewable energy sources are wind, solar, geothermal, biomass, biogas, wave, current and tidal energy sources together with hydraulic generation plants. These sources have the advantage of being environmentally friendly, naturally domestic, clean and free of primary energy charge.

Wind Energy

Approximately 1-2 % of energy released by sun turns into wind energy when it comes to earth. Wind occurs as a result of the pressure differences in air since the air moves from high pressured areas to low pressured ones. Among the characteristics of the wind which change with respect to geographic conditions and time, speed and direction are the most determinant parameters while building a wind farm. Renewable Energy General Directorate of Turkey (YEGM, Turkish acronym) [6] describes the advantages of wind energy as:

- It is a renewable and clean energy source.
- Its source is safe and has no risk of exhaustion or escalation in price.
- It provides employment.
- It has low operating and maintenance costs.

- The raw material of it is entirely domestic, it does not create foreign source dependency.
- Commissioning period is short, relatively.

Despite all these advantages, high capital investment cost, low capacity factor and the unpredictable nature of wind energy obstruct the implementation of wind energy.

Solar Energy

The source of all energy in Earth is the energy released by the sun. Even though the application of solar energy is not common, it has a great potential to satisfy heating and electricity demands of the world. The advances in technology promise the contribution of solar energy to a clean environment.

All of the benefits of wind energy account for solar energy too. These benefits should not be summarized in terms of only environment because application of solar and wind energy assures to ease the political conflict due to limited energy resources. Regarding the wars over the oil reserves of Middle East, the importance of free energy sources increases. In addition, solar energy is modular; it allows the expansion of a small solar system. It does not require to build a new infrastructure, it supports the existing electrical grid. However, the implementation of solar energy brings about some downsides. While the human consumes electricity 24 hours a day, Sun's irradiation is effective approximately 4-5 hours a day to produce energy. However, batteries are already in use to overcome the variability of solar energy for residential heating purposes. The other and more important downside is the cost. Even after the technological developments, solar energy remains to be one of the most expensive ways of producing electricity. In spite of the charming advantages, cost issue posts an obstacle to popularise the utilization of solar power.

Geothermal Energy

Geothermal energy is the thermal heat that originates from Earth. It is the only renewable energy source that does not use energy of the Sun directly. The water with high temperature deep down the Earth contains a significant amount of energy to be used for heating purposes and producing electricity. A geothermal site is more preferable if the resource of high temperature is close to the surface of Earth. According to the information of International Geothermal Association, geothermal energy has been used directly to supply heat for residential or commercial heating commonly since 2000 [5]. In addition, IEA records the installed capacity in 2009 as 10.7 gigawatts and 50.6 thermal gigawatts for electricity production and direct heating, respectively [7].

Although geothermal energy has the downside of high capital cost like the other renewable sources, it is not dependent on weather conditions unlike them. Geothermal sites are available all around the world especially for direct use. Besides, site searching studies has revealed new feasible resources to be used for generating electricity. However, for being competitive in electricity generation, a geothermal energy source must have a temperature above 400 °C. The cost level is affected by resource temperature and pressure, reservoir depth from the Earth's surface, type of technology and drilling market. Right location and right time for market conditions may help to deal with the cost problem. Also, R& D studies can come up with better methods for creating hot reservoirs and better drilling methods which would increase the utilization of geothermal power [7].

Hydroelectric Energy

Hydroelectric energy is one of the most clean and economic ways of generating energy with its mature technology. Hydroelectric energy is obtained using hydraulic turbines through which huge amount of water flows. The operation of hydroelectric energy requires an appropriate geography with a lot of rivers. High-head technologies which water flows from somewhere high to the reservoir cover large areas; therefore, these technologies should be set up remote areas of local residences. Since some areas with large hydroelectricity potential are near to neighbourhoods, small-scale hydroelectric power set-up is a current issue. These small-scale plants are very environmentally friendly because they do not arise concerns of flooding and displacement of population besides having the advantages of large-scale plants [5].

Despite high capital costs compared to that of thermal power plants, having a longer lifetime and being free of fuel charge make hydroelectric power an economic source of energy. According to IEA Energy Technology Perspectives scenarios, electricity generation from hydro-power will double from now to 2050. However, climate change which causes scarcity of water can affect the hydroelectricity potential of the world.

Biomass Energy

Biomass energy is the oldest energy source and has been used since the discovery of fire. Still, it is used by some families to heat their homes and even it is the primary energy source in some non-developed countries of the world. However, today, the utilization of biomass energy is far beyond burning wood and residential usage. Biomass energy is obtained from solar energy stored in plants and animals; therefore, a high variety of materials are the source of bio-fuels [8]. Biomass energy is adopted by industries to produce steam in paper mills, generate electricity by burning solid waste or to obtain biodiesel from corn and grain crops [5].

Biomass energy has the capability to store solar energy in the chemical form and it is the only renewable source to be used to derive solid, liquid and gaseous fuels. This variety gives the way for converting biomass into bio-fuels that are the transportable forms of energy [8]. Although the share of biomass in the overall renewable sources is about 77%, its contribution is about 1% in the overall electricity generation [8]. One of the biggest advantages of biomass is its using waste products to obtain energy that will dissolve the waste disposal problem. High employment of biomass is an answer to the problem of oil importing countries. It will not face a price fluctuation and does not depend on the relationship with other countries since it is domestic.

1.1.3 Nuclear Energy

Nuclear energy is produced by fission process which means splitting uranium atoms. This process presents a remarkable energy production since the nuclear power has a very high energy density. For example, the energy extracted from one kilogram of uranium is equivalent to the energy released by combustion of 2500 tonnes of coal [5]. The more attractive part is that nuclear energy is not dependent on changeable conditions, it can release energy 24 hours a day, every day of a year. Although nuclear power is not renewable, it is considered as sustainable since uranium reserves do not show the risk of depletion. The other dimension of sustainability is that nuclear power does not produce any harmful gases so it is clean and environmentally friendly.

Regarding the economical dimension, nuclear energy competes with other primary sources, especially after carbon taxes are included for burning fossil fuels. Despite having high capital cost, nuclear energy is very advantageous in the long term because the cost of nuclear fuel is low.

With all these characteristics, nuclear energy seems to solve the energy problem of Earth but in fact it will not. Despite all, nuclear energy poses a significant risk to humanity and environment because of the radioactive materials it contains. In the history of nuclear energy, there have been severe accidents which justify the public and government concerns on nuclear energy. The most serious disaster is occurred at

Chernobyl reactor in Ukraine since the facility did not have a containment building which is a basic safety structure. According to United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1800 thyroid cancer cases are associated with the radiation hazard after Chernobyl Disaster [9]. Figure 1.5 presents the nuclear power utilization of EU countries in 2012 but there will be important shifts against nuclear power in the forthcoming years [10]. The Fukushima Daiichi Nuclear Accident paved the way for rethinking the impacts and safety issues related to nuclear energy. After the disaster, Germany declared that it would close all the nuclear plants by 2022, Italy and Switzerland have agreed to abandon nuclear energy. Besides, US has decided to follow a safety enhancement strategy rather than banning the nuclear energy.

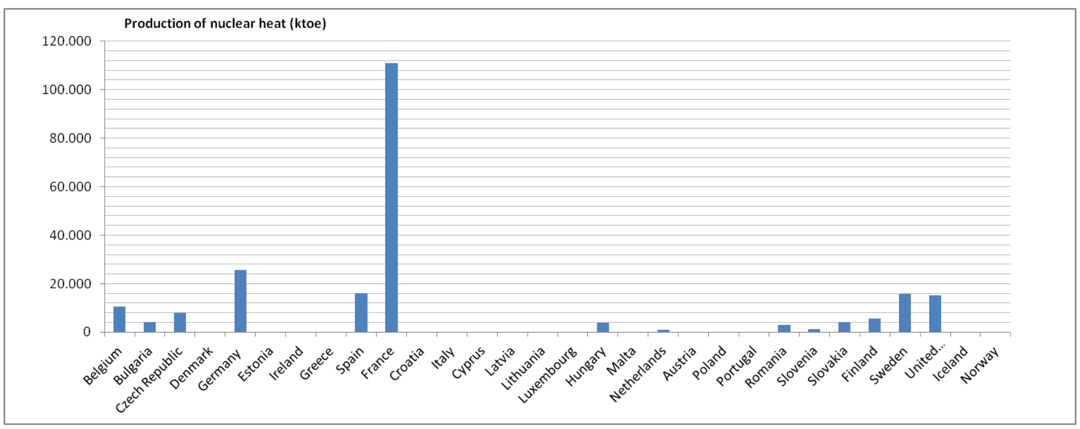


Figure 1.5: Annual nuclear statistics of EU countries in 2012.

1.2 The Environmental Impact of The Energy Industry

1.2.1 Climate Change and Greenhouse Gas Effect

When radiation of Sun comes to Earth's surface, some of it is absorbed and some other part is reflected back through the space as heat. GHG takes in this heat and trap it in the atmosphere. As emissions of GHG continue, higher concentrations are accumulated in the atmosphere leading to more absorption of heat. EIA claims that large scale industrialization drove the increase in the amount of these gases by 25 % in the last 150 years. Another claim of EIA is that about three quarters of CO_2 emissions is originated from burning fossil fuels.

Table 1.1: Global warming potentials of various greenhouse gases

Greenhouse Gas	Residence time (yr)	Global warming potential (molar basis)	Concentration in the atmosphere (ppb)
CO_2	230	1.0	400,000
CO	2.1	1.4	
CH_4	14.4	3.7	1893
N_2O	160	180	0.326
$HCFC-22$	15	810	0.231
$CFC-11$	60	4000	0.236
$CFC-12$	120	10,000	0.527

Each GHG has different properties and effects on climate change. One of these properties is the residence time. Each GHG remains in the atmosphere for different period of time. The longer residence times will cause the higher concentration in the atmosphere. The other important property is their potential to cause impacts. Table 1.1 summarizes the properties of some greenhouse gases and their concentration in atmosphere [11].

Despite the policies and the regulations to lower climate change, the report of Intergovernmental Panel on Climate Change (IPCC) states that GHG level has continued to rise. Increase in the emissions of the last ten year surpasses the emission rate of previous decades. Unless more strict precautions are taken, effects will continue to spread more quickly. Some of these effects are:

- Climate change,
- Acceleration in sea level rise,
- Increasing in wildfires, extreme storm events,
- Occurrence of severe droughts,
- More intense and persistent heat waves,
- Growing health impacts like allergies, insect-borne diseases,
- Serious risks to electrical infrastructure,
- Melting of ice,
- Disruptions to food supplies [12].

The most prominent way of preventing from global warming is reducing the emissions.

1.2.2 Public Health and Community

The main damage of wind energy to public health is related to aerodynamic and mechanical sounds that the turbines make. With the contribution of negative attitude against wind turbines, the sound might sensed as disturbing. European countries adopt different standards to control the noise level. Apart from setting limits, the emerging technology overcomes the noise problem of turbines. New-generation turbines are produced with sound-absorbent materials and have the self control qualification [13].

If the geothermal plant works with open-loop systems, toxic gas mixture including hydrogen sulfide, carbon dioxide, ammonia is released to atmosphere. These emissions pose the danger of several heart and lung diseases. Nevertheless, the toxic emission of geothermal plants are almost 30 times lower than that of coal plants which is the main actor of sulfide based emissions [12]. Geothermal plants may also affect the public health and create the concerns about the earthquakes because hot spots of land have a tendency to face earthquakes. The working principle of geothermal plant necessitates to pump the high pressured water to crack underground hot rock reservoirs. In order to reduce the risk of earthquake, it is essential to build the geothermal plants away from major fault lines.

One of the most controversial issues is about the implementation of nuclear energy due to the significant risks it has. When a nuclear disaster occurred, people and all other living specifies around the nuclear plant will be affected seriously not only because of the fire and explosions but also because of the radioactive materials spread during the accident. Therefore, the hosts of nuclear power are right to worry and protest against it. Nuclear energy is not a safe way to produce electricity but it can be safer if the risks are seriously taken into consideration. Fukushima showed that there is always the possibility of a nuclear disaster even if it seems very unlikely. For this reason, other than the efforts to prevent from an accident, industrialized countries pay close attention to the emergency planning and preparedness for nuclear accidents.

1.2.3 Land use

Although designing renewable energy systems promises a sustainable future, it has its own disadvantages. Wind, solar, hydroelectric and geothermal technologies seem to present a problem with respect to land use. Regarding the wind energy, it is not the wind turbines that cover the land but the space between the turbines which is a must. Each turbine must be set 5-10 rotor diameters (diameter of the turbine blades) apart from the other turbines [12]. However, wind turbines disturb a little part of the land and the remaining part can be used for productive plants.

Considering the location and type of technology, solar energy also poses a problem on land use. However, solar panels can be established to unproductive, low quality areas to reduce the negative land impacts. There is also the possibility to built the panels on top of the commercial or residential buildings and this possibility puts away the problems related to land use.

Another land use problem is caused by hydroelectric systems. If the reservoir of hydroelectric plant is not deep enough, a large space is necessary to hold the water. The worst impact created by a hydroelectric reservoir is flooding land that leads to the destruction of forest, the living species and the productive land. Turkey has undergone such disasters due to the irresponsible and careless implementation of hydroelectric energy.

Lastly, amount of plant capacity, type of energy conversion and cooling systems, the arrangement of drilling and piping systems affect the land area used by a geothermal plant. If the geothermal site is near to ecological lands, this creates another problem.

A nuclear plant with 1000 MW power covers approximately 200 acres land while a wind or solar farm with same power needs a much larger area, not less than 100 square miles [9]. Therefore, nuclear enery is more environmentally friendly in terms of land use.

1.2.4 Waste Disposal

The most dramatic effect is posed by nuclear energy in terms of waste disposal. Most of the nuclear plants use solid uranium pellets which are efficient for a few years. After fission, uranium splits into several products; some of which decay in a short period and some of which continue to be radioactive for centuries. This radioactive waste must be set apart from the environment until they are no longer active. In their book, Krivit and Lehr claim that the longest decay period lasts 300 years and designing storage structures can overcome the waste problem of inefficient uranium parts [9]. Besides, existing technology allows to recycle the larger part of used fuel, namely the uranium and plutonium. Most countries including the United Kingdom and France (the largest producers of nuclear power in Europe) re-use uranium pellets after exposing chemical processes. However, this recycling procedure is not implemented in US where radioactive waste of nuclear power plants and nuclear weapons have been accumulated for almost 60 years [9]. This huge amount of waste poses a great danger for humans and environment.

1.3 The Present Situation of Turkey

Mainly two factors affect the present situation of Turkey in terms of energy requirements: population and growth rate. As Table 1.2 displays, both population and growth rate increase too piercingly that current status of technology and utilization of energy sources are insufficient.

Table 1.2: Population, Economy and Energy in Turkey

Years	Population	GNP/Capita	Total Energy Demand (Mtoe)	Energy Capita (Kep)	Energy intensity
1973	38,072,000	1994	24.6	646	81
1990	56,098,000	2674	53.7	957	50
1995	62,171,000	2861	64.6	1039	44
2000	67,618,000	3303	82.6	1218	40
2010	78,459,000	5366	153.9	1962	35
2020	87,759,000	9261	282.2	3216	33

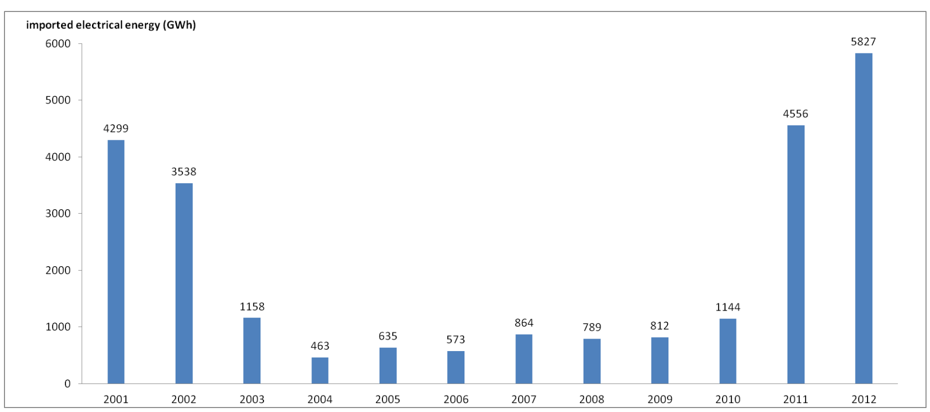


Figure 1.6: Imported electrical energy by years

Turkey is located at the meeting point of Europe, Asia and Africa. Its geographical condition presents a variety of resources but employment of these resources is very limited. Table 1.3 validates this claim by showing the gap between the natural potential of resources and utilization of them. The low utilization of domestic sources makes Turkey dependent on other countries to import energy resources, mainly oil and natural gas. The other dilemma of Turkey is that the employment of energy resources (even the imported ones) lags behind the social and economical development. Figures 1.6 and 1.7 show the imported electrical energy with respect to time and countries from which the electricity is imported [14].

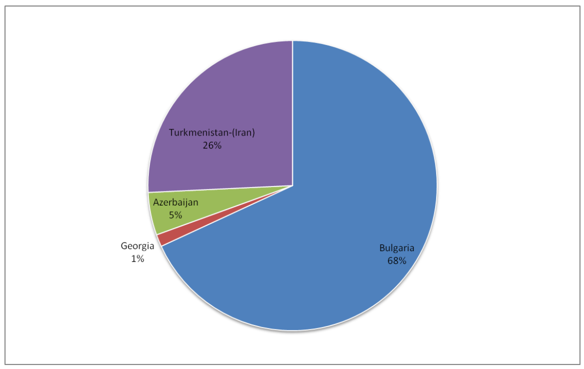


Figure 1.7: Imported electrical energy by countries

Table 1.3: Renewable energy potential of Turkey

Energy type	Usage purpose	Natural capacity	Technical capacity	Economical capacity	Installed capacity
Solar energy	Electric (TWh)	977,000	6105	305	81
	Thermal (mtoe)	80,000	500	25	25
Hydro power	Electric (TWh)	430	215	124.5	124.5
Wind (land)	Electric (TWh)	400	110	50	50
Wind (off shore)	Electric (MWe)	-	-	-	27.4
Geothermal	Electric (MWe)	2000	-	-	93
	Thermal (MWt)	31,500	7500	2843	1342
Biomass	Total (mtoe)	120	50	32	33

Although Turkey is dependent highly on other countries to meet its energy demand, it can gain its independence if it uses its renewable energy potential wisely.

1.3.1 Renewable Energy Sources of Turkey

According to the statistics published by Turkish Electricity Transmission Corporation, 17% of electricity is obtained from renewable sources (Figure 1.8 [14]). This is a very low value with respect to the sources Turkey has which is the topic of this section.

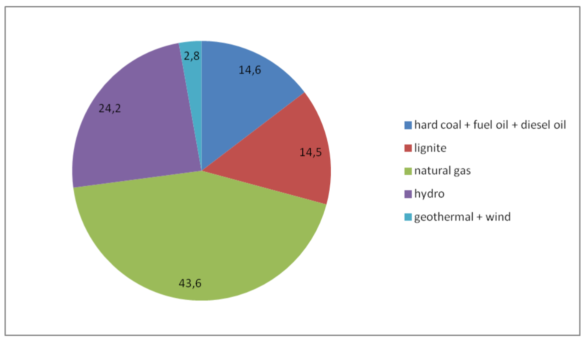


Figure 1.8: Turkey's electricity generation by share of primary energy sources

- **Hydro energy sources:**

  According to the data given by the Ministry of Energy and Natural Sources, Turkey has 167 hydroelectric power plants generating 57.8 TWh electricity annually (according to 2012 data). Except from this, some plants which got licence but not be operationalized are projected to generate 46 TWh electricity. This amount of electricity with the big hydro energy slice on Figure 1.8 proves hydro energy to be most important renewable energy source of Turkey.

- **Wind Energy Sources:**

  Feasibility reports on wind energy potential of Turkey affirm that Turkey has a crucial amount of economical reserves (Table 1.3). With the hydroelectric energy, Turkey trusts its wind potential mostly as an alternative way of electricity production. The sharp change in the installed capacity of wind power (Figure 1.9) is an indication of the importance given by government and private sector to the wind energy.

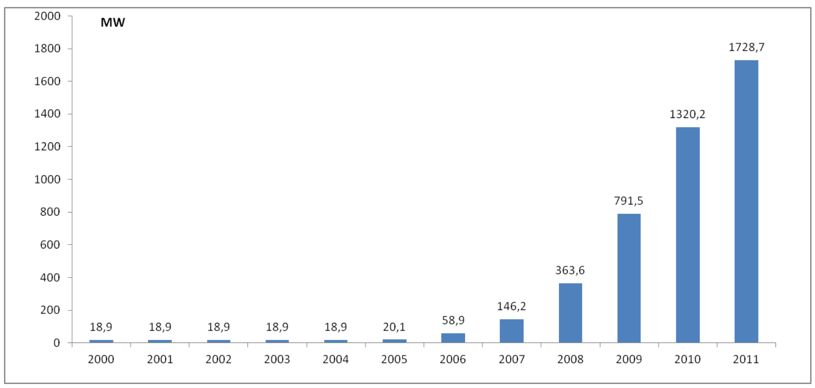


Figure 1.9: Installed capacity of wind power between 2000-2011 (YEGM)

- **Solar Energy Sources:**

  Since Turkey where lies in a sunny belt has a Mediterranean climate, it possesses a significant amount of solar energy potential. It accepts an average solar radiation of 3.6 $kW-h/m^2$ per day and its annual radiation period is approximately 2610 h [15]. However, this high capacity is almost only employed for heating purposes adopting the roof top thermal solar technology. Turkey was one of the leading world based on the employment of thermal solar power in 2001 with an installed capacity of 8.2 $million\ m^2$ which is the collector area while solar electrical energy is generated only from 300 kW capacity [16]. Photovoltaic cells which is a solar electricity generating technology is not common in Turkey due to the lack of investments.

- **Geothermal sources:**

  Turkey possesses a favourable position in terms of geothermal resource potential by being located on a tectonic belt with active volcanism and orogenesis (structural disturbances of Earth's crust). Having 1/8 of the total geothermal energy potential of the world, Turkey has a dominant role in the direct application of geothermal resources [16]. Most of this great potential lies within the Aegean-Central Anatolian region. However, only 9% of the potential seems to be economically feasible according to Table 1.3. Nevertheless, new drilling technologies will undoubtedly pave the way for more economical utilization of geothermal resources. Besides, recent research of General Directorate of Mineral Research and Exploration (MTA, Turkish acronym) has revealed new geothermal sites which can be used for electricity generation. Six of them found to be feasible and taken into tendering process by MTA [17]. In addition, Turkey uses geothermal energy for balneological purposes. There are 215 thermal facilities with a 402 MWt thermal power that is visited by almost 10 million people per year.

1.4 Policies and Legislation on Renewable Energy Utilization

The penetration of renewable energy sources seems to support sustainability in terms of energy production but their share is very low in the overall energy mix. Therefore, the government, private sector and non-governmental organizations must support the utilization of renewable energy sources in a realistic and viable manner. This section presents rules, regulations and policies for effective implementation of renewable energy sources.

1.4.1 Renewable Energy Policies of EU

European Union leaders set some targets in March 2007 to ensure energy security and low carbon economy and published these targets in ”Climate and Energy Package” [18]. Targets named as 20-20-20 targets aim for three main objectives for 2020:

- EU GHG emissions will be reduced by 20% (or 30% if other major economies in the world behave responsibly) from 1990 levels.
- Share of renewable energy sources in the overall energy consumption will be increased to 20%.
- A 20% enhancement in EU energy efficiency will be reached.

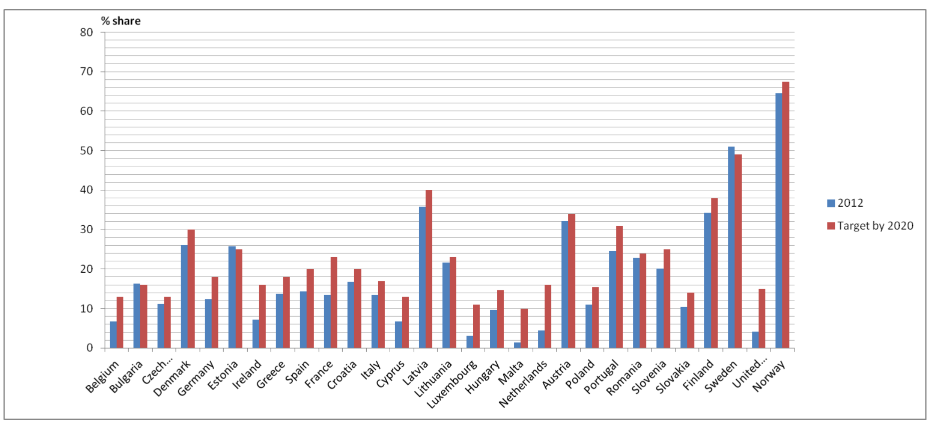


Figure 1.10: Share of renewable energy sources in final energy consumption

Figure 1.10 demonstrates the targets of EU countries based on renewable energy share in energy mix [19].

20-20-20 targets combine the three aspects of energy sector : energy security, competitiveness, sustainability. European Council also dealt with energy efficiency in

2011 and enacted an Energy Efficiency Plan. Regarding this plan, energy efficiency is accepted to be the key category of new energy regulations since using energy efficiently means respecting to earth's resources and improving energy independence and security of energy supply. Proposed acts in the plan to achieve energy efficiency are:

- reducing energy consumption in the construction sector which has the 40 % share in overall energy consumption,
- increasing competitiveness in European industry to stimulate new technology,
- adapting European financing, promoting energy taxation and carbon taxes,
- directing consumers' attention to eco-friendly products, informing them about their energy usage simultaneously,
- enhancing the efficiency of transport sector which is responsible for 32 % of final energy consumption.

[18]

1.4.2 Renewable Energy Policies of Turkey

Growth rate of Turkey's energy demand improves continuously as a result of development projects and population expansion. The allocation of natural gas increases while the allocation of hydro energy is decreasing. Even if the number of geothermal and wind energy plants rises, their share in the total energy production remains limited. Besides, energy is wasted along the processes of electricity production, distribution and ultimate consumption. Improvement in income level has caused a jump in freight and human transportation (cars, buses, air travel). Although the emission level based on transportation is lower than that of developed countries, the present increase rate alarms the serious emission rates due to transportation [20].

Turkey will also face the risk of carbon emission based on electricity and heat production accounting for 30% of total emissions [21]. In 2012 February, the Ministry of Energy and Natural Sources published the Energy Efficiency Strategy Report 2012-2023. Improving the energy efficiency and preventing energy waste is the main scope of the report. The strategic goals are [20]:

- reducing energy intensity and waste in industry and service sectors,
- popularizing the environmentally friendly residential buildings and plants which use renewable energy sources,
- introducing energy efficient products to the market,
- enhancing the efficiency in the electricity production-transmission-distribution chain,
- reinforcing the corporate structures, co-operations and capacities,
- extending the activities of high technology utilization and awareness.

Forecasts on electricity consumption predict the energy demand to be almost 530 TWh and Turkey's 2023 vision imposes the accommodation of 30% of this demand from renewable sources [16]. Table 1.4 presents the breakdown of installed renewable capacity with respect to 2023 Vision [16].

In the case of the utilization of targeted capacity, the expected electricity supply of renewable energy sources is shown on Table 1.5.

Table 1.4: Turkey's 2023 targets on utilized renewable capacity

Source	Installed capacity (MW)
Hydro-power	Full utilization
Wind	20,000
Solar	3000
Geothermal	600

Table 1.5: Electricity generation of renewable sources according to 2023 targets

Source	Electricity Generation (GWh)
Hydro-power	80,000
Wind	70,250
Solar	6750
Geothermal	4750

1.5 Optimization Theory

As the problem of GHG emissions directs the energy sector to renewable sources, the issues of high investment requirement and current account deficit, allocation designs of conventional and renewable resources rise. Among multiple energy sources and technologies, the best alternatives must be adopted regarding the end use of energy. However, "the best" does not only imply the most cost effective alternative. An energy model as a sustainable decision-making support must include social, economical and environmental aspects. The optimization theory seeks for and tries to reveal the most efficient alternatives.

Optimization is a branch of mathematics and computer science that either minimizes or maximizes one or more objectives with respect to some constraints. Its aim is to select the best value by attaining values to real or integer variables of which objectives are the functions. A general optimization model has the form:

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f_0(x) \\ \text{subject to} \quad & f_i(x) \leq b_i,\ i = 1, \ldots, n. \end{aligned}$$

Here f is the objective function which we want to minimize. An optimal solution must be in the feasible region consisting of all possible points satisfying the constraints. If there is more than one objective function, then the problem turns into a multi objective optimization problem. However, only the problems with conflicting objectives are called as multi objective, one of the objective must not imply the optimization of the other [22].

Computational optimization solves wide variety of optimization problems along the process of formulating, modelling and implementing an algorithm. Owing to the developments in computer hardware and in algorithms, computational optimization is applied to a great scope of principles like economics, mechanics, engineering, operations research, industry.

Chapter 2

LITERATURE REVIEW

2.1 Application of Optimization Algorithms to Renewable Energies

Among the options, optimization algorithms seem to be the most popular way to adopt new energy alternatives and to enhance the existing ones. As Figure 2.1 shows, in the last twenty years there has been a tremendous increase in the number of optimization algorithms proposed on renewable energy [23].

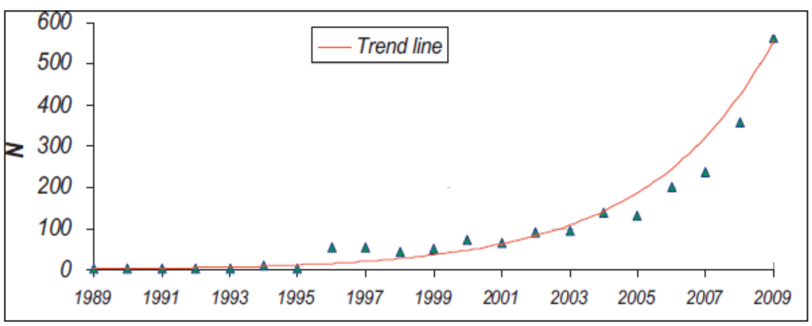


Figure 2.1: Number of articles on optimization algorithms applied to renewable energy sources

The design of energy systems heavily relies on optimization techniques due to their complex and diversified nature. In past, the optimization models on electricity generation was interested only in minimizing the cost. However, the developing problems of the developing world put the environmental issues on the map after 1980

[24]. Thanks to mathematical programming, it is now possible to introduce multiple objectives regarding GHG emissions, life cycle assessment (LCA) parameters, economical viability and social welfare. Literature incorporates several examples of single and multi-objective energy planning problems solved by mixed-integer linear programming (MILP), non-linear programming (NLP), multi objective programming, dynamic programming, and other exact and heuristics approaches. The studies on electricity generation planning also differ in terms of time step of analysis, number and type of objective functions and presence or absence of linearity.

Multi Objective Linear Programming (MOLP) is one of the most common ways to address energy planning. Arnette and Zobel [25] propose to increase the renewable energy share by increasing the utilization of solar and wind power in the Southern Appalachian Mountain region. They use geographic information systems (GIS) to determine potential locations of renewable energy sources. Their model considers the trade-off between environment and economy so they build a bi-objective program similar to that which we use in the current study. The program is integrated with GIS and enables the user to make a comparative analysis in terms of both emission and cost reductions for a single period model. Koltsaklis*et al.* [26] present a more sophisticated model for multi-period time horizon. Their multi-objective MILP model for long-term energy planning decides on the selection of the electricity generating technologies, type of fuels, new plant locations and electricity imports. The results of a real case application of the model show the trend is changing from lignite-fired plants to low-carbon power generating plants.

Meza *et al.* [27] put four objectives into their capacity expansion model to determine the optimal location of new power generation units in a multi-period planning horizon. They consider the simultaneous minimization of cost, environmental impact, imported fuel and fuel price risks. They only take the CO_2 emissions into account for the environmental impact constraint. Another work of Meza *et al.* [28] presents a developed version of the previous multi-objective model but for a single period time step. They examine capacity expansion planning by giving importance to transmission system. Applying Kirchoff's second law they represent the transmission of electricity in a more realist way but the complexity of the problem does not allow to formulate a linear program. Therefore, they handle with a multi-objective bilinear MIP problem.

Some models deal with the emissions by the inclusion of quota restrictions and cost penalties rather than using multi-objective programming. Mirzaesmaeeli *et al.* [29] formulate a multi-period MILP model with the objective of finding the optimal energy mix at minimum cost. They propose to install carbon capture and storage (CCS) technologies to the existing and new plants to mitigate the carbon emissions. The model is applied for two scenarios on Ontario's electricity system to show the impact of CO_2 emission limit which is based on Kyoto target. According to their results, when there is no force exerted on CO_2 mitigation, the model does not prefer any fuel switch or CCS techonology installation for the coal power plants while the presence of CO_2 limitation push the coal plants to undergo fuel-switching rather than installing CCS technology.

Koltsaklis *et al.* [30] monetize the GHG emissions and put it into the cost function of the mathematical model in which they suggest a capacity expansion planning on power generation system of Greece. Their optimization model decides on the location and construction time of new plants over a long-time horizon. The pressure of increasing the renewable energy utilization is built up by including a constraint which specifies the lowest possible share of renewable sources in total electricity system. Another study on Greek power system focusses on the contribution of renewable energy sources on Greek islands to the mainland system [24]. In this study, Georgiou *et al.* reveal the importance of interconnecting the islands power to increase renewable energy employment. Like Koltsaklis *et al.*, they build a single objective program which minimizes the net present value of total cost over the given time period.

Previous models are based on cost minimization objectives, however the model formulation can also be built on maximizing the value. Madlener *et al.* [31] analyse the optimum mix of Turkish power generation system under the objective of net present value maximization. According to their claim, in liberalized markets where the competition is in high levels, investments are done depending upon the market-value maximization. Their maximization model is based on the difference between revenue and the cost of electricity generation. The model is solved in GAMS using MINOS solver under capacity and demand constraints. Their results support the dominance of lignite coal in the mix in contrast to the increasing adoption of natural gas technologies which have higher volatility in prices. However, their model does not include any GHG emission restrictions. A developed version of this model is presented by Kumbaroglu *et al.* [32]. Latter model accounts for stochastic processes for the estimation of price uncertainties, construction lead times and price elasticity of demand. Due to the price volatility included in objective function, these problems are built as dynamic programming problems because linear programming techniques are weak in handling with scale effects of investment and operation costs [33].

2.1.1 Studies on Randomness of Renewable Energy Sources

Renewable energy sources can be divided into two categories in terms of dispatchability. Dispatchable renewables (hydropower, bioenergy, geothemal power) are ready for power generation upon electricity demand while non-dispatchable ones (wind, solar) present a variable nature in electricity generation due to meteorological and technical restrictions [34].

An appreciable amount of the study on renewable energy presents the stochastic nature of renewable energy sources as a serious problem. Unlike conventional energy sources, renewable sources express variability due to random meteorological processes. Therefore, increasing the share of renewable energy sources in the energy mix requires careful thought. Moura and Almedia [35] discuss the complementarities of solar, wind and hydro energy . By fitting the collected data to the distribution models, they argue that the availability of these three sources reduces crucially at different times so that a proper mix overcomes the intermittence problem of renewable sources to a certain extent. Another contribution of Moura and Almedia [35] raises the question of demand-side management (DSM). DSM studies help to handle critical situations caused by randomness problem, especially at the times when load duration curve shows peak. It adjusts customer demand for energy to decrease the energy consumption during peak hours. By using the demand response technique, which is one of the DSM methods, peak demand can be reduced, flattened or shifted. Demand Response allows customers to use electricity in response to peculiar conditions and charges consumer in terms of time-dependent price of utilities.

In reality, not only the energy sources but also the load itself is unpredictable because of exposure to fluctuating conditions such as seasonal changes in weather. This poses a problem for both conventional and renewable energy sources. Therefore, renewable energy plant designs should satisfy the reliability of a conventional supply, which is not 100%. Mitchell *et al.* [36] develop a simulator to be used in both grid-connect and stand alone modes of renewable energy system. They measure the load data for solar and wind energy to create hourly load data and load patterns. The model is run on Excel embedded Visual Basic macros and seasonal fluctuations are simulated. The output data is used to formulate probability distribution functions (PDF) for solar and wind energy. Their study reveals the need for satisfying minimum solar and wind power capacities and the advantage of using predictive controllers to minimize stand-by energy import. However, the interdependency of variables makes the model quite complex and the lack of accurate wind and solar data on hourly basis constitutes a problem.

Transformation of the grid lines can be an answer to the variable power coming from dispatchable renewable sources. Introducing smart grids to the electricity distribution system paves the way for balancing the supply and demand in the presence of variable power. Technology Brief of IEA in 2013 specifies the advantages of smart grid as allowance of electricity flow from very small producers, integration of energy storage when the electricity generation exceeds the demand, implementation of intelligent grid and demand management to decrease peak-demands and provision of flexible, stable and secure supply [34].

Hydro-power plants which consist of more than one reservoirs promise flexibility against fluctuations in demand and electricity generation. When the electricity generation is more than the demand of grid, the flow direction is adjusted from low reservoir to the higher one so that the energy is stored. In the times of peak-demand, the direction is reversed and electricity is generated with approximately 80 % of storage efficiency [37]. Combination of pumped hydro plants with intermittent renewable energy power plants reduces the risk due to uncertainties.

2.2 Contribution

In the scope of this thesis, a multi-objective MILP model is developed for multi-period time horizon on yearly basis to determine the optimal mix of power generation systems. Although there are plenty of models on the same subject with multiple objectives, we try to make a difference by the formulation of a more flexible model which allows to analyse several different scenarios. In order to obtain convincing and applicable decisions, a model must include all of the required constraints. For example, many of the models in literature do not include budgetary constraints. This means that the model will suggest decisions about new plants without knowing up-front capital investments would be enough or not. In our model, we assign values for the annual available investment for the power generation system of Turkey. By changing the investment levels, we are able to see the development in the installed renewable capacity . Since one of our objectives is to minimize GHG emissions, we also consider the fuel switching in coal plants along with the employment of new renewable energy plants. In order to obtain realistic results about the installation of new plants and retrofitting of existing plants, we consider the lead time based on the commissioning of those plants because it is not possible to obtain electricity from a facility at the year the investment is made.

When applying our model for a real case, we pay attention to the input data to be accurate. Energy is a very dynamic sector and it is hard to keep up with the changes related to technologies, new energy sources, policies & regulations and costs of raw materials and production. Therefore, we have often modified our parameters and variables since our formulation was complete.

Chapter 3

PROBLEM DEFINITION & MATHEMATICAL MODEL

3.1 Problem Definition

In this study, we formulate a multi-period MILP problem to determine the optimal mix of a power system under the objectives of minimizing GHG emissions and minimizing total cost of electricity generation over a long time horizon. Fundamental queries analysed by our model are:

- What will be the capacity utilization of existing fossil fuel power plants in each time period?
- What will be the installation time, location and capacity of the new renewable energy plants?
- Which coal plants should be switched to natural gas at which time period?

In our model, we answer these questions by showing how our two conflicting objectives change with respect to each other with the following assumptions:

- (1) Annual electricity demand is projected based on the total annual energy consumption, peak demand periods are not considered.

- (2) Electricity exports will have no effect on the output of our model.
- (3) All investment costs are fully amortized where the loan is annually paid off. The rate is adjustable so payment changes according to interest rate.
- (4) After the amortization, variable and fixed operation & maintenance costs will be the remaining costs. Transmission network cost is not included in the model.
- (5) Required time for shifting the fuel in a coal plant is one year.
- (6) Imported electricity has an emission amount per MWh electricity purchase.
- (7) The length of solar panel and electricity generation from the panel have a linear relationship.
- (8) The amount of electricity generation and GHG emissions have a linear relationship.
- (9) The renewable energy sources are accepted as zero emission energy sources because only the emissions during the operation are taken into account.
- (10) If a coal plant is retrofitted to burn natural gas, then the coal cannot be burned at that plant after the conversion.

Important Notes about the Scope and the Construction of Our Model

⋆ Within the scope of our model, we examined the total electricity generation from primary energy sources including fossil fuels (coal, natural gas, fuel-oil) and renewable energy technologies (solar, wind, hydro and geothermal energy).

- ⋆ All variables in our model have a time dimension in order to be able to include future projections and see the effects of investments done in the following time periods. Time dimension is defined relative to years and the number of years are considered as 10 years in the base case.

- ⋆ The variables related to wind energy have three dimension: location, wind speed category and time. In order to see the effect of wind speed on the electricity generation, power of wind turbines are not taken as constant, equation 3.1 is used to calculate the power of a turbine.

$$pw_k = \frac{1}{2}\,\rho\,\pi r^2\,v_k^3 \quad ,\forall k \tag{3.1}$$

- ⋆ Installation cost of wind energy has additional costs which will reflect the property of the site. We have included a penalty cost for the slope of land.

- ⋆ Hydro-power plants have the longest approval and construction period among the renewable energy technologies. Hydro power potential of a region is generally declared under categories such as final project level, construction level, in-service level. In our model, we have calculated the lead time associated with hydro-power plants considering these project levels. The levels before final project level like feasibility level, master plan level are not included in the model since there is no ultimate decision about the construction of the plants which are on those levels.

- ⋆ For the hydro-power plants and geothermal plants which are on the project level, two different variables are defined to account for the construction time. $HEScon_{ht}$ and $JEScon_{lt}$ indicates whether a project at site h or l is put into practice in the year t. If the value of the variable is 1, then there will be no return and the variable will always be 1 in the forthcoming years. On the other hand, $HESex_{ht}$ / $JESex_{lt}$ points out whether the hydro-power plant h / geothermal plant l is started to generate electricity. Interrelation of these two variables makes the lead time integrated with our model. In order to build the relationship, equations 3.2 and 3.3 are defined:

$$HEScon_{h(t-t_h)}\, M \geq HESex_{ht} \qquad \forall h, \forall t \tag{3.2}$$

$$JEScon_{h(t-t_j)}\, M \geq JESex_{lt} \qquad \forall l, \forall t \tag{3.3}$$

Equation 3.2 / 3.3 ensures that a hydro-power / geo-power plant generates electricity only after t_h / t_j years from the starting time of the construction.

3.2 Mathematical Model

Sets & Indices

h :	hydro-power plant locations on project level	$h \in H$
$h2$:	hydro-power plant locations under construction ,	$h2 \in H2$
i :	possible wind farm locations,	$i \in I$
j :	possible solar farm locations,	$j \in J$
k :	wind velocity categories with respect to velocity of the wind,	$k \in K$
l :	possible geothermal site locations,	$j \in J$
y :	cities on blue line distribution,	$y \in Y$
p :	existing coal-based power generating plants,	$p \in P$
q :	existing natural gas based power generating plants,	$q \in Q$
f :	existing fuel-oil based power generating plants,	$f \in F$
ge :	greenhouse gases emitted by power technologies,	$ge \in GE$

tf :	type of power generating technology,	$tf \in TF$
a :	existing hydroelectric plant locations,	$a \in A$
t :	time period	$t \in T$

Scalars

bl :	blade length of the wind turbine in m
C :	power coefficient of a wind turbine
$Cclw$:	cost of clearing one acre of forest land for wind farm installation
$Cfixw$:	annualized fixed O & M costs per installed kW capacity of wind farm
Ckw :	cost of installing one kW of wind capacity
$Cslw$:	cost per kW capacity and per degree of slope at a wind farm location
$Cvarw$:	annualized variable O & M costs per MWh electricity generation for wind energy
$Durw$:	wind duration per year
$Kturb$:	kW capacity of a wind turbine
Ltw :	lifetime of a wind turbine
MAf :	acres of forested land per kW of installed capacity.
$Mexw$:	MWh electricity generation of existing wind capacity at full utilization
ρ :	air density in terms of kg/m^3
$Cfixs$:	annualized fixed O & M costs per installed kW capacity of solar energy
Cks :	cost of installing one kW capacity of solar farm
$Cvars$:	annualized variable O & M costs per MWh electricity generation for solar energy

$Durs$: sunshine duration per year

Lts : lifetime of a solar panels

$Mexs$: MWh electricity generation of existing solar capacity at full utilization

η_s : efficiency of solar energy

$Cfixg$: annualized fixed O&M costs per installed kW capacity of geothermal plant

Ckg : cost of installing one kW of geothermal capacity

$Cvarg$: annualized variable O&M costs per MWh generation of geothermal plant

η_g : efficiency of geothermal energy

Ltg : lifetime of a geothermal plant

$Mexg$: MWh electricity generation of existing geothermal capacity at full utilization

$Mgeo$: average MWh electricity generation from 1 kWe geothermal capacity

$Upper\_geo$: upper limit of annual geothermal capacity establishment

t_j : construction lead time of a geothermal plant

$Cfixh$: annualized fixed O&M costs per installed kW capacity of hydro energy investment cost

$Cvarh$: annualized variable O&M costs per MWh electricity generation for hydro energy

Lth : lifetime of hydro-power plant

t_h : construction lead time of a hydro plant

Cac : additional cost per MWh generated at a coal plant

Cn : cost per MMBtu of natural gas

$Cretc$: cost of retrofitting a coal fired plant per kW capacity

Ctc : cost (in \$) per ton of coal

Cf : cost per ton of fuel oil

Fo : tons of fuel oil to generate 1 MWh electricity

F : equivalence factor between natural gas and coal

Ctn : cost of transporting one MMBtu one km

$Cang$: additional cost per MWh generated at a natural gas facility

Ng : MMBtu of natural gas to generate one MWh electricity

η : efficiency of natural gas

$Cimport$: cost of imported electricity per kW-h

r : discount rate

Mnc : MWh electricity generation from one MMBtu of natural gas

$Limp$: limitation to the electricity import

$upper\_lim$: GHG emissions cannot exceed the upper limit

$lower\_lim$: GHG emissions cannot fall beyond the lower limit

ϵ : value for the epsilon constraint method

Parameters

pw_k : power of a wind turbine belonging category k in terms of MW

v_k : velocity of the wind belonging category k

Kwe_{ik} : kW capacity at wind farm location i belonging category k

DS_{ik} : average degree of slope at wind farm location i belonging category k

Kse_j : kW capacity at solar farm location j

Ms_{jt} : expected annual MWh generation for a solar farm at location j in year t

Kg_l : licensed geothermal capacity at location l in terms of kW

Mg_l : expected annual MWh electricity generation at geothermal location l

$Mhyd_a$: MWh electricity generation at hydroelectric plant a

$Ccretc_p$: capital investment for co-fire retrofit at coal plant p

Mc_p : MWh electricity generation at coal plant p

T_p : tons of coal used at coal plant p

Kc_p : overall kW capacity of coal plant p

Mtc_p : MWh electricity generation per ton of coal at plant p

Cmn_q : cost per MWh electricity generation at natural gas facility q

Mn_q : MWh electricity generation at natural gas facility q

D_{yp} : distance between city y and location of coal plant p

Cmf_f : cost per MWh electricity generation at fuel oil facility f

Mf_f : MWh electricity generation at fuel-oil facility f

V_t : total amount of capital investment available in year t

Dem_t : demand of MWh electricity in year t

$E_{tf,ge}$: tons of air emission ge from technology tf based on MWh generation

$Mh2_{h2}$: MWh electricity generation of hydro power plant $h2$ which is under construction

Mh_h : MWh electricity generation of hydro power plant h which is at the final project level

$Kh2_{h2}$: capacity of hydro power plant $h2$ which is under construction

Kh_h : capacity of hydro power plant h which is at the final project level

Decision Variables

$total\_cost$: objective function value for electricity cost over the time horizon

$total\_emission$: objective function value for GHG emissions over the time horizon

N_{ypt} : MMBtu of natural gas transported from city y to coal plant p in the year t

U_{qt} : capacity utilization of existing natural gas facility q in the year t

$U2_{ft}$: capacity utilization of existing fuel-oil facility f in the year t

G_{pt} : capacity utilization of existing coal facility p in the year t

$Import_t$: MWh of electricity imported in the year t

$Ccapw_{ikt}$: annualized capital investment for wind farm at location i belonging category k in year t

Mw_{ikt} : expected annual MWh generation at wind farm location i belonging category k in year t

Af_{ikt} : acres of forested land at wind farm location i belonging category k in year t

$Ccaps_{jt}$: annualized capital investment for solar energy at location j in year t

Ks_{jt} : cumulative solar capacity at location j until the year t (including t)

Kst_{jt} : solar capacity addition to location j in year t

$Ccapg_{lt}$: annualized capital investment for geothermal energy at plant l installed in the year t

Nt_{ikt} : number of turbines installed location i belonging category k in year t

Nw_{ikt} : number of turbines installed at location i belonging category k until the year t (including t)

Nst_{jt} : number of panels (having 100 m^2 length) at location j in the year t

Ns_{jt} : number of panels having 100 m^2 length at location j until the year t (including t)

$$Nconv_{pt} : \begin{cases} 1, & \text{if coal plant } p \text{ is converted to burn natural gas in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$HES_{ht} : \begin{cases} 1, & \text{if construction of hydro plant } h \text{ is started in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$HESex_{ht} : \begin{cases} 1, & \text{if hydro plant } h \text{ is in operation in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$HEScon_{ht} : \begin{cases} 1, & \text{if hydro plant } h \text{ is under construction or in operation} \\ & \text{in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$JES_{lt} : \begin{cases} 1, & \text{construction of hydro plant } l \text{ is started in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$JESex_{lt}: \quad \begin{cases} 1, & \text{if geothermal plant } l \text{ is in operation in the year } t \\ 0, & \text{otherwise} \end{cases}$$

$$JEScon_{lt}: \quad \begin{cases} 1, & \text{if geothermal plant } l \text{ is under construction or in operation} \\ & \text{in the year } t \\ 0, & \text{otherwise} \end{cases}$$

3.2.1 Objective Functions

First Objective : Minimizing Cost

The first objective function of our problem is for minimizing the total cost associated with electricity generation. The crucial point is that we only consider the costs which have the effect on our decision variables. This means that the value of this function may be less than the sum of all electricity related costs. In addition, all costs will change year by year considering time value of money.

In this equation, costs are calculated according to the type of primary energy sources. Equations 3.4a, 3.4b, 3.4c, 3.4d specify the costs associated with wind, solar, geothermal and hydro energy, respectively. For these renewable energy technologies, costs are composed of three parts : capital cost, fixed operating and maintenance (O& M) costs (insurance, taxes, repairs) and variable O& M costs (labour costs, costs of goods that are used up in production). All fixed costs are based on installed kW capacity of renewable plants while the variable costs are introduced according to MWh electricity generation. Moreover, there is no fuel cost for renewable energy technologies.

The remaining part of the equation 3.1 incorporates the costs related to traditional energy sources; coal, natural gas, fuel oil and the cost of imported electricity. 3.4e accounts for two possibilities of running a coal plant. If a coal plant is not converted to burn natural gas, then the cost of coal and the additional cost for generating electricity from coal will be counted to the degree of that the capacity is operated. However, switching the fuel to natural gas necessitates a retrofit cost to make the plant technically available to use natural gas. In the condition of conversion, the cost of natural gas which will be burned in the coal plant and the transportation cost are taken into consideration. Natural gas transportation is assumed to be via pipeline. The cost of plants that use fossil-fuels are composed of the fuel cost plus the cost of generating electricity based on the capacity utilization of plants.

$$Z_1 = \sum_i \sum_k \sum_t (Ccapw_{ikt} + Cfixw\, Kturb\, Nw_{ikt} + Cvarw\, Mw_{ikt})\, \frac{1}{(1+r)^t} \tag{3.4a}$$

$$+ \sum_j \sum_t (Ccaps_{jt} + Cfixs\, Ks_{jt} + Cvars\, Ms_j\, Ns_{jt})\, \frac{1}{(1+r)^t} \tag{3.4b}$$

$$+ \sum_l \sum_t (Ccapg_{lt} + Cfixg\, Kg_l\, JESex_{lt} + Cvarg\, Mg_l\, JESex_{lt})\, \frac{1}{(1+r)^t} \tag{3.4c}$$

$$+ \sum_h \sum_t (Ccaph_{ht} + Cfixh\, Kh_h\, HESex_{ht} + Cvarh\, Mh_h\, HESex_{ht})\, \frac{1}{(1+r)^t} \tag{3.4d}$$

$$+ \sum_p \sum_t [Cac\, G_{pt} Mc_p + Ctc\, G_{pt} T_p + \sum_y (Ccretc_p Nconv_{pt} + Cn\, N_{ypt}$$

$$+ Ctn\, N_{ypt} D_{yp} + Cang\, N_{ypt} Mnc)]\, \frac{1}{(1+r)^t} \tag{3.4e}$$

$$+ \sum_q \sum_t (Cmn_q\, Mn_q\, U_{qt} + Mn_q\, Ng\, Cn)\, \frac{1}{(1+r)^t} \tag{3.4f}$$

$$+ \sum_f \sum_t (Cmf_f \, Mf_f \, U2_{ft} + Mf_f \, Fo \, Cf) \, \frac{1}{(1+r)^t} \tag{3.4g}$$

$$+ \sum_t import_t \, cimport \, \frac{1}{(1+r)^t} \tag{3.4h}$$

The capital costs of renewable source plants are amortized over a number of years. Therefore, annualized capital costs in the equation 3.4 are calculated as follows:

$$Ccapw_{ikt} = \frac{Kturb \, Nw_{ikt} \, Ckw}{Ltw} \qquad \forall i, \forall k, \forall t \tag{3.5}$$

$$Ccaps_{jt} = \frac{Cks \, Ks_{jt}}{Lts} \qquad \forall j, \forall t \tag{3.6}$$

$$Ccapg_{lt} = \frac{Ckg \, Kg_l \, JEScon_{lt}}{Ltg} \qquad \forall l, \forall t \tag{3.7}$$

$$Ccaph_{h,t} = \frac{Ckh \, Kh_{ht} \, HEScon_{ht}}{Lth} \qquad \forall h, \forall t \tag{3.8}$$

Ltw, Lts, Ltg, Lth are lifetime of plants for wind, solar, geothermal and hydro energy, respectively.

Second Objective : Minimizing Emissions

Second objective of our model is to minimize GHG emissions arising from electricity generation. Equation 3.9 uses the assumption of linear relationship between the electricity generated and the amount of emissions for every plant. The calculation of emissions is based on ton per MWh electricity generation for coal and non-coal plants. In addition, if coal plants are turned into natural gas plants, then the emissions will depend on natural gas burning.

$$Z_2 = \sum_p \sum_t [(\sum_{ge} e_{coal,ge} \, G_{pt} \, Mc_p)] \tag{3.9a}$$

$$+\sum_t(\sum_{ge} e_{natural\_gas,ge}\, N_{ypt}\, Mnc) \tag{3.9b}$$

$$+\sum_q\sum_t(\sum_{ge} e_{natural\_gas,ge}\, Mn_q\, U_{qt}) \tag{3.9c}$$

$$+\sum_f\sum_t(\sum_{ge} e_{fuel\_oil,ge}\, Mf_f\, U2_{ft}) \tag{3.9d}$$

$$+\sum_t(\sum_{ge} e_{import\_elec,ge}\, import_t) \tag{3.9e}$$

3.2.2 Constraints

Demand Constraint

This constraint guarantees that the installed capacity plus the imported electricity in terms of MWh/year meet the annual electricity demand of the country. This constraint gives the decision maker flexibility to consider high demand and low demand scenarios while planning for future time periods.

$$\sum_i\sum_k(Mw_{ikt}+Mexw)+\sum_j(Ms_j\, Ns_{jt}+Mexs)+\sum_l(Mg_l\, JESex_{lt}+Mexg)+$$
$$\sum_p(Mc_p\, G_{pt}+\sum_y N_{ypt}\, Mnc)+\sum_q Mn_q\, U_{qt}+\sum_f Mf_f\, U2_{ft}+\sum_a Mhyd_a+$$
$$\sum_{h2} Mh2_{h2}+\sum_h(Mh_h\, HESex_{ht})+import_t \geq Dem_t \quad \forall t \tag{3.10}$$

For the existing fossil fuel plants, MWh electricity generation is determined by multiplying the capacity allocation with the MWh generation at full capacity. Besides, MWh electricity generated from renewable energy plants is found by using efficiency factors. Multiplication of the capacity with efficiency and availability gives the MWh electricity generation from that capacity.

Budget Constraint

This constraint is for annual capital investment not to exceed the budget that can be allocated to energy investments. Establishing wind and solar farms, drilling the wells to obtain geothermal energy and retrofitting the coal plants to convert into natural gas require a great deal of investment funds. Different investment scenarios can be analysed by changing the investment levels under the favour of this constraint.

$$\sum_i \sum_k (Ckw \ \ Kturb \, Nt_{ikt} + Cclw \, Af_{ikt} + Cslw \, DS_{ik} \, (Kturb \, Nt_{ikt}) +$$
$$\sum_j Cks \, Kst_{jt} + \sum_l Ckg \, Kg_l \, JES_{lt} + \sum_h Ckh \, Kh_h \, HES_{ht} +$$
$$\sum_p Ccretc_p \, Nconv_{pt} \leq V_t \quad \forall t \tag{3.11}$$

First component of the equation is the cost for establishing new wind farms. The cost is composed of installation cost of the capacity, clearing the land area and penalty cost of the slope of land due to additional land preparation. The land area occupied by wind turbines is determined by the following equation:

$$Af_{ikt} = pw_k \, Nt_{ikt} \, MAf \quad \forall i, \forall k, \forall t \tag{3.12}$$

MAf stands for the acres of forested land per kW of installed capacity. According to our model, slope penalty which is used to estimate the expected installation cost increases one forth of the capital cost by 2.5% per unit degree of slope [38].

On the other hand, capital investment cost of installing a solar farm and geothermal plant is much simpler including only the installation cost. Equation 3.11 includes two new variables , HES_{ht} and JES_{lt} which are defined for not to pay the investment cost more than once. Investment cost is paid only in year of the beginning of construction.

Integration of equations 3.13 and 3.14 guarantees the binary variable HES_{ht} / JES_{lt} is equal to 1 only in year t which is the first time the variable, $HEScon_{ht}$ / $JEScon_{lt}$ is equal to 1.

$$HEScon_{ht} - HEScon_{h(t-1)} = HES_{ht} \quad \forall h, \forall t \tag{3.13}$$

$$JEScon_{lt} - JEScon_{l(t-1)} = JES_{lt} \quad \forall l, \forall t \tag{3.14}$$

Lastly, the investment cost of conversion of coal plants is specified. Retrofitting cost, $Cretc$, is introduced as the cost per kW capacity of the coal plant. In order to rewrite the capacity of plant conforming to natural gas usage, The MMBtu amount of natural gas is converted to tons of coal equivalently by defining the parameter F. The value of F is assigned by assuming 1 barrel (5.4 MMBtu) oil is equivalent to 0.41 metric tons of lignite coal. This capacity conversion makes our program more flexible in terms of the utilization of natural gas in coal plants.

Upper Limit of Electricity Generation at a Coal Plant

This constraint brings a barrier to the natural gas usage in the condition of coal plant conversion. It is not possible to generate more than a specified amount of electricity without making major changes in the power plant. When assigning the cost of retrofitting the coal plant, we assume the addition of a gas nozzle and modification of existing air heaters and heat surfaces. Since the efficiency of burning natural gas in a coal plant depends on the investment level made in the plant, we have assigned the parameter η accordingly, as the efficiency for the changing investment levels.

$$\sum_{y} N_{ypt}\, Mnc \leq Mc_p\, \eta \quad \forall p, \forall t \tag{3.15}$$

Capacity Allocation Constraints for Power Plants

The following constraints represent the capacity allocation of coal, natural gas and fuel-oil plants, respectively. According to the change in load, capacity allocation shifts down not to be exposed to additional costs when electricity demand is low or shifts up to satisfy the power requirement when the demand is high. Additionally, introducing these variables creates the possibility to scale down the electricity utilization at the plants which generate emissions or even to close them (when the variables equal to zero). For the renewable energy plants, only full utilization is permitted to compensate high capital costs.

$$G_{pt} \leq 1 \quad \forall p, \forall t \tag{3.16a}$$

$$U_{qt} \leq 1 \quad \forall q, \forall t \tag{3.16b}$$

$$U2_{ft} \leq 1 \quad \forall f, \forall t \tag{3.16c}$$

Relating Retrofit and Natural gas Usage

In order to use natural gas in a coal power plant, the plant must have already been retrofitted. This constraint ensures this necessity. M is an arbitrarily big value, a value that is bigger than all values that the variable N_{ypt} can take.

$$Nconv_{p(t-1)}\, M \geq \sum_{y} N_{ypt} \quad \forall p, \forall t \tag{3.17}$$

The reason why time of the natural gas usage is one year after the conversion is that it takes approximately one year to prepare the plant.

Constraint on Conversion Condition

Our model assumes the conversion of coal plants as an all-or-nothing decision. If the plant is converted to fuel natural gas, then the capacity utilization of coal will be equal to zero. Since $Nconv_{pt}$ is a binary variable, the case which its value is 1 will automatically make the capacity utilization of coal equal to zero.

$$G_{pt} \leq 1 - Nconv_{pt} \quad \forall p, \forall t \tag{3.18}$$

Capacity Constraint for Wind & Solar Energy

This constraint ensures that number of turbines and the area of solar farm to be installed are limited to the properties of available land. Therefore, the total kW power of turbines / solar farm must be less than the potential capacity for a specific location, Kwe_{ik} / Kse_j.

$$\sum_t Kturb\, Nw_{ikt} \leq Kwe_{ik} \quad \forall i, \forall k \tag{3.19}$$

$$\sum_t Ks_{jt} \leq Kse_j \quad \forall j \tag{3.20}$$

Cumulative Capacity of Wind and Solar Technologies

The costs related to newly constructed plants stem from the construction and the operation phases. In order to prevent from the complexities which may arise from the multiplication of cost parameters and variables, we have introduced additional variables to indicate construction and operation costs separately. In equation 3.21a Nt_{ikt} stands for the number of turbines erected in year t while Nw_{ikt} is the variable defined for the total number of turbines erected until t, including the year t. Equation 3.21b is built with the same logic.

$$Nw_{ikt} = Nw_{ik,(t-1)} + Nt_{ikt} \quad \forall i, \forall k, \forall t \tag{3.21a}$$

$$Ns_{jt} = Ns_{j(t-1)} + Nst_{jt} \quad \forall j, \forall t \tag{3.21b}$$

Imported Electricity Limitation

Even the minimization of GHG emissions requires the low utilization of fossil fuel sources from which the imported electricity is generated generally, the budget constraint makes the imported electricity attractive since it necessitates no investment cost. However, energy imports exposes importing nations to serious economical and political problems like vulnerability to price fluctuations, supply disturbances, political pressure, that we could not integrate with our program. Therefore, we have imposed a limitation to electricity import not to exceed a specific proportion of annual demand.

$$import_t \leq Limp\, Dem_t \tag{3.22}$$

Non-negativity Constraints

No negative values are allowed for the decision variables.

$$N_{ypt}, U_{qt}, U2_{ft}, G_{pt}, Import_t, Ccapw_{ikt}, Mw_{ikt}, Af_{ikt}, Ccaps_{jt}, Ks_{jt}, Kst_{jt}, Ccapg_{lt},$$

$$Nt_{ikt}, Nw_{ikt}, Nst_{jt}, Ns_{jt} \geq 0 \tag{3.23}$$

Integer Constraints

The decision variables which are specified below can only take integer values.

$$Nt_{ikt}, Nw_{ikt}, Nst_{jt}, Ns_{jt} \in \{0, 1, 2, 3....\} \tag{3.24}$$

Chapter 4

COMPUTATIONAL IMPLEMENTATION AND RESULTS

The model described in the previous chapter is applied to power generation system of Turkey. This chapter includes the relevant data and modification of the model, the solution methodology and the computational results of the real life application.

4.1 Relevant Data and Modification of the Model

The data required to solve our model is taken from several sources including;

- Renewable Energy Directorate of Turkey (YEGM, Turkish acronym)
- Ministry of Energy and Natural Resources
- Turkish Statistical Institute (TUIK)
- Turkish Electricity Transmission Company (TEIAS)
- General Directorate of Mineral Research and Exploration (MTA)
- The Energy Market Regulatory Authority (EPDK)
- International Renewable Energy Agency (IRENA)

- National Renewable Energy Laboratory (NREL)
- Open Energy Information (OpenEI)
- Environmental Protection Agency (EPA)

The model is shaped and modified according to available data. Some important remarks about the data assignment are summarized in this section.

- The solar and wind energy potential of Turkey is determined by means of the solar and wind maps published by YEGM. The data of MTA and YEGM is used together to decide on the geothermal potential of Turkey. YEGM have also publicized the potential hydro power plant locations according to the level of the project recently and we use the locations which are under construction or on final project level.
- The location of wind and solar potential is defined relative to provinces. For hydro and geothermal energy, exact plant locations are assigned.
- Input data for wind energy includes the maximum area of forested land with respect to different wind speed categories for each province. Only the sites with a velocity greater than 6.8 m/s are chosen as economically viable; therefore, the wind velocity changes between 6.8 m/s and 9.5 m/s forming four speed categories, k with equal intervals. Moreover, wind speed data belongs to the calculations at 50 m height.
- Electricity that will be obtained from a solar panel with a specific length is known as an approximate value; therefore, the parameter related to MWh generation of a specific length of solar panel is predefined. Multiplying this parameter with the number and efficiency of panels and time factor, capacity of solar

farm is found. Here we make use of the assumption of linearity between panel length and electricity generation.

$$Ks_{jt} = \frac{Ms_j\, Ns_{jt}\, (1000\frac{kW}{MW})}{Durs\eta s} \quad , \forall j, \forall t \tag{4.1a}$$

$$Kst_{jt} = \frac{Ms_j\, Nst_{jt}\, (1000\frac{kW}{MW})}{Durs\eta s} \quad , \forall j, \forall t \tag{4.1b}$$

where Ks_{jt} and Kst_{jt} correspond to cumulative capacity and annual capacity addition, respectively.

- The material of photovoltaic panel is chosen as polycrystalline silica when assigning efficiency and cost parameters due to the reduction in the price of that modules.
- Regarding the countries that Turkey imports electricity, imported electricity is assumed to be generated from natural gas in the calculation of GHG emissions.
- For the demand projection, the growth factor given by EPDK is used. The demand for the future periods is entered to the model as presented on Table 4.1.
- Installed capacity of the primary energy sources is taken from the annual statistics of TEIAS.
- Amount of emissions released by fossil-fuels are employed according to the data of US EPA.
- The parameters presented on Table 4.2 are assigned by using the report of IRENA and the database of OpenEI [39, 40]. OpenEI, supported by US Department of Energy and NREL, has published a cost database which includes

Table 4.1: Energy demand projection of Turkey

Period	Year	Growth factor	Total Energy Demand (GWh)
1	2015	6.5	291,790
2	2016	6.5	310,730
3	2017	6.5	330,800
4	2018	6.4	352,010
5	2019	6.4	374,430
6	2020	6.3	398,160
7	2021	6.7	424,780
8	2022	6.3	451,541
9	2023	6.3	477,282
10	2024	6.5	505,919

Note: Data of EPDK indicates the demand of first seven periods, remaining periods are calculated by extrapolating the previous demands

fixed , variable and capital costs. For geothermal energy, the technology is assumed as Enhanced Geothermal System (EGS) because EGS is used to generate electricity from geothermal power and contribute to base-load electricity of generation system.

4.2 Solution Methodology

For the solution of multi-objective model, an iterative approach is proposed. The ϵ-constraint method which adopts an iterative algorithm is a well known technique to generate efficient solutions for multi-objective problems. In epsilon-constraint method, one of the objectives is selected as the actual objective while the other objectives appear in the model as constraints. The necessary condition to implement epsilon-constraint method is the declaration of the ranges of objective functions. The

Table 4.2: Parameters of Renewable Energy Sources

	Fixed O&M Cost ($/kW)	Variable O&M Cost ($/MWh)	Capital Cost ($/kW)	Average Capacity Factor
Wind (onshore)[1]	18	6	2092	0.40
Solar PV [1]	30	0	3220	0.18
Geothermal[1]	180	5	5500	0.90
Hydro-power [2]	14.8	6	3500	0.50

Note [1]: Data of OpenEI.
Note [2]: Data of IRENA

range of an objective function is used to produce grid points that will act as right-hand-side of that objective function. The problem formulated in the current study is a bi-objective problem. Therefore, we take cost minimization constraint as the original constraint and add the GHG emission minimization objective to the model as a constraint. Table 4.3 includes the required input data for the application of epsilon-constraint method.

Table 4.3: Parameters of Epsilon-Constraint Method

Emission lower limit	0
Emission upper limit	5 billion tons
Iteration Limit	50

In order to implement the algorithm, we define two different models as energymix_cost and energymix_emission. The former model involves the cost objective function with all the constraints defined in previous chapter and an additional constraint which is defined on equation 4.2.

$$\sum_{p}\sum_{t}[(\sum_{ge} e_{coal,ge}\, G_{pt}\, Mc_p)] + \sum_{t}(\sum_{ge} e_{natural\_gas,ge}\, N_{ypt}\, Mnc)+$$

$$\sum_q \sum_t (\sum_{ge} e_{natural\_gas,ge}\, Mn_q\, U_{qt}) + \sum_f \sum_t (\sum_{ge} e_{fuel\_oil,ge}\, Mf_f\, U2_{ft}) +$$
$$\sum_t (\sum_{ge} e_{import\_elec,ge}\, import_t) \leq \textit{emission\_upper\_limit - (epsilon) (iteration\_counter)} \tag{4.2}$$

Besides, the latter model, energymix_emission is comprised of the objective of emission minimization with the constraints defined in previous chapter. After making the necessary modifications, we integrate our model with the algorithm presented on Figure 4.1

4.3 Computational Results

The results are obtained for three different problems. Both P1 and P2 deal with single objective function being minimum cost (Z1) and minimum emission (Z2), respectively. Third problem, P3, is our original bi-objective problem and its solution shows the trade-off between cost and GHG emissions.

All of the three problems are implemented into GAMS software using CPLEX solver. Resource limit is set to 2000 seconds for each iteration under the allowance of 0.01 percent relative gap. Solution statistics and objective function values are presented in Table 4.4.

4.3.1 Results of the Single Objective Problems

In this section the main results of the problems, both P1 and P2 are presented. Figure 4.2 shows the percentage of each primary energy source in total mix in case of regarding only cost or emission. The data is taken for the output of 9th period, 2023

Input :

Epsilon := 0,

iteration_limit = 50

solve energymix_emission problem minimizing total_emission

emission_lower_limit := total_emission

solve energymix_cost problem minimizing total_cost

emission_upper_limit :=

$$\sum_p \sum_t [(\sum_{ge} e_{coal,ge} \, G_{pt} \, Mc_p)] + \sum_t (\sum_{ge} e_{natural\_gas,ge} \, N_{ypt} \, Mnc) + \sum_q \sum_t (\sum_{ge} e_{natural\_gas,ge} \, Mn_q \, U_{qt}) + \sum_f \sum_t (\sum_{ge} e_{fuel\_oil,ge} \, Mf_f \, U2_{ft}) + \sum_t (\sum_{ge} e_{import\_elec,ge} \, import_t)$$

epsilon := (emission_upper_limit - emission_lower_limit) / iteration_limit

n := 0 (n : iteration counter)

while n ≤ iteration_limit **do**

solve energymix_cost problem minimizing total_cost

calculate total_emission

report (total_cost, total_emission)

n ⟵ n + 1

end while

Figure 4.1: Algorithm for the ϵ-Constraint Method

in order to compare the results with 2023 goals declared by the Ministry of Energy.

According to Figure 4.2(a), disregarding the emissions results in the dominance of fossil-fuels in total energy mix, as expected. On the other hand, Figure 4.2(b) shows that an almost equal share of renewable sources and fossil- fuels will be reached when the total cost is neglected.

Table 4.4: Solution Statistics

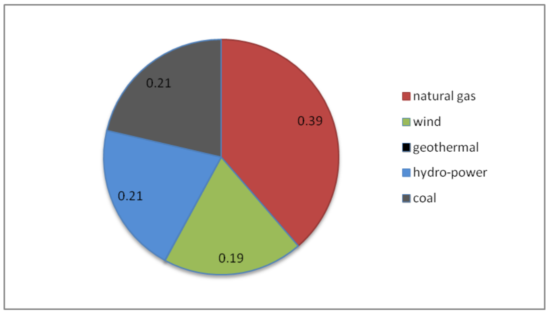
	P1	P2		P3
CPU Time (second)	673	5002	Average :	411
			Total :	20,904
Iteration Count	6,234,625	4,402,959	Average :	1,507,108
			Total :	76,862,513
Relative Gap	0	0	Average :	0.000094
			Total :	0.004722
Single Variables	10,561	10,552		10561
Discrete Variables	3980	3980		3980
Single Equations	8685	8676		8686
Z1	157	218		180
Z2	2.16	1.35		1.50

Note: Z1 and Z2 defined in terms billion dollars and billion tons.
The values of P3 assigned based on mid point of the Pareto set

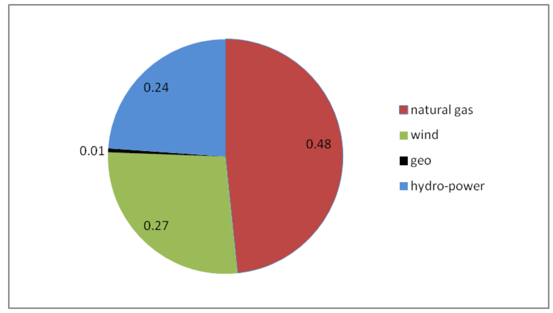
Besides, Figure 4.3 demonstrates the trend of total cost and total emission with respect to time step of analysis based on minimum cost and minimum emission scenarios. Total emission increases for both scenarios because of the growth in demand (Figure 4.3(a)) while total cost decreases due to the integration of interest rate (Figure 4.3(b)).

4.3.2 Results of Multi-Objective Model

Integration of epsilon-constraint algorithm to GAMS model automatically generates a set of feasible solutions for a multi-objective problem. The solution set of our model is presented in Figure 4.4. The red markers on the 4.4 indicate the solutions that are not optimal. Point A / B refers to the best solution in terms of minimum emission/minimum cost scenario. Point C is the resulting point of the equal importance given to minimum cost and minimum emission.

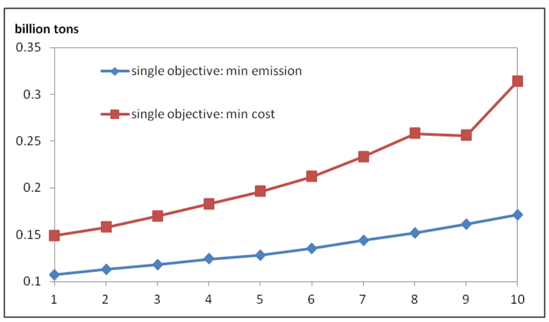


(a) Single objective : Min Cost

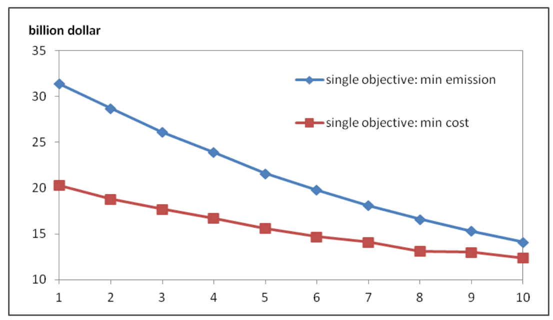


(b) Single objective : Min Emission

Figure 4.2: Share of primary energy sources in total power utilization in 2023



(a) Total emission



(b) Total cost

Figure 4.3: Comparison of total cost and total emission with respect to periods

In order to see how close our results to the 2023 targets, installed capacity and electricity production in 2023 (which corresponds to 9th period) are included on Table 4.5 and Table 4.6, respectively.

Low Demand Scenario

Energy Efficiency is in the scope of energy strategy plans of Turkey; therefore, we consider a reduction of 2% in the energy consumption as a result of the studies on efficient energy usage. If this reduction is achieved, this means Turkey will emit 16.6% less GHG and total energy cost will be reduced by 18.6% over the ten year-time

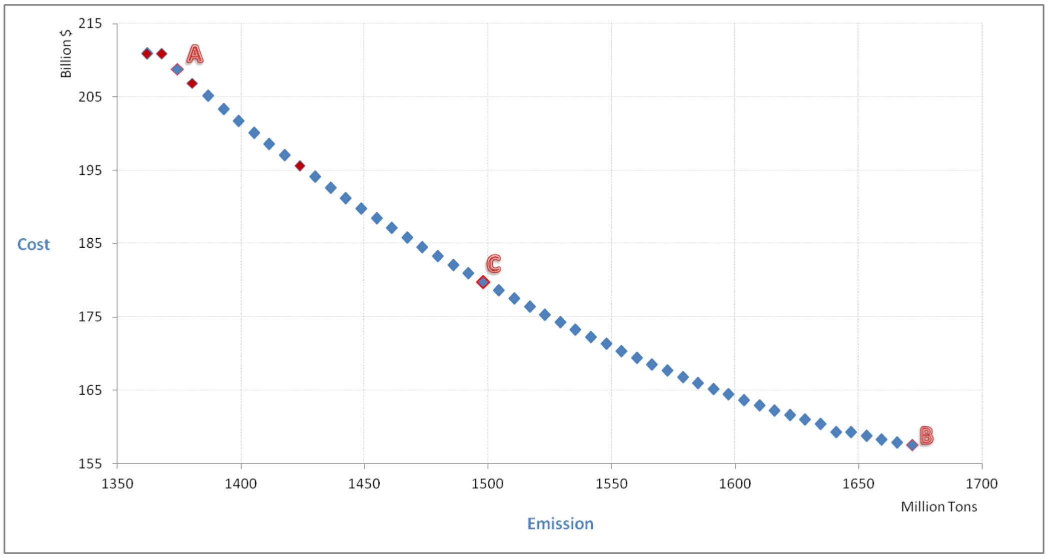


Figure 4.4: Approximation of the efficient frontier for the optimization model

Table 4.5: Projected capacity of renewable sources in 2023

Source	Installed capacity (MW)
Hydro-power	25,996
Wind	20,522
Solar	0.7
Geothermal	427

horizon. Figure 4.5 compares the base case scenario with the low demand scenario and shows the importance of energy efficiency studies.

Integration of Fossil Fuel Plants to be Constructed

In the base case scenario, we only consider the installation of new renewable energy plants; however, the ever increasing amount of energy demand will unfortunately necessitate the installation of new fossil fuel plants, also. The results show that without considering this option, we accept to be dependent on import electricity in

Table 4.6: Projected electricity generation of renewable sources in 2023

Source	Electricity Generation (GWh)
Hydro-power	76,554
Wind	80,724
Solar	0.2
Geothermal	2017

the following years. Therefore, we take the fossil fuel capacity to be installed into account with reference to the data of EPDK. According to this data 6,330 MW of coal plant and 10,513 MW of natural gas capacity is planned to be installed within a few years. Figure 4.5 presents the results.

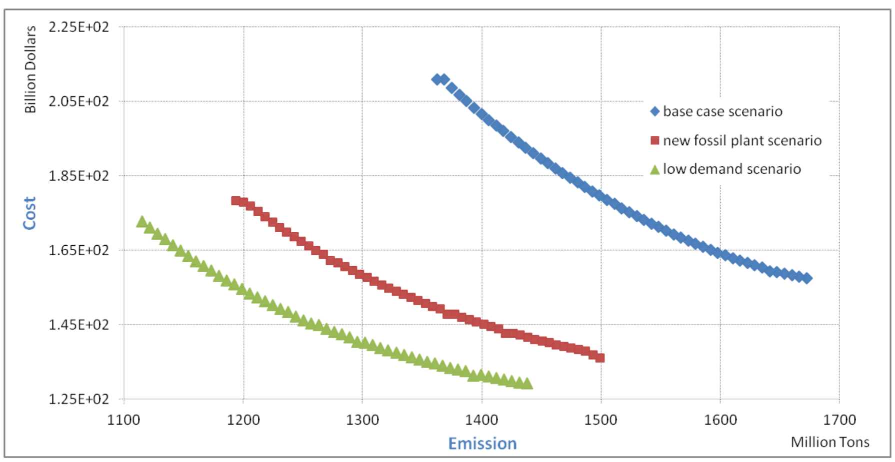


Figure 4.5: Comparision of two low demand and base case scenarios with respect to the approximation of efficient frontier

4.4 Sensitivity Analysis

We conduct a sensitivity analysis to see how the changes in a certain parameter will affect the output of the model. By means of this analysis, we are able to decide on the key parameters of the model and examine a wide scope of scenarios. In this section, the effects of key parameters on the output is presented with figures.

4.4.1 Effect of the Power Coefficient of Wind Turbines

The power coefficient of a wind turbine accounts for the efficiency of a turbine to convert the wind energy into electricity. German physicist Albert Betz calculated the maximum limit of conversion as 59.3 %. The coefficient of wind turbines of current technology generally fall between 0.35 - 0.45. In the analysis, we work with the range of 0.25 - 0.45 and the effect of turbine coefficient on wind power utilization and emission is demonstrated on Figures 4.6 and 4.7, respectively.

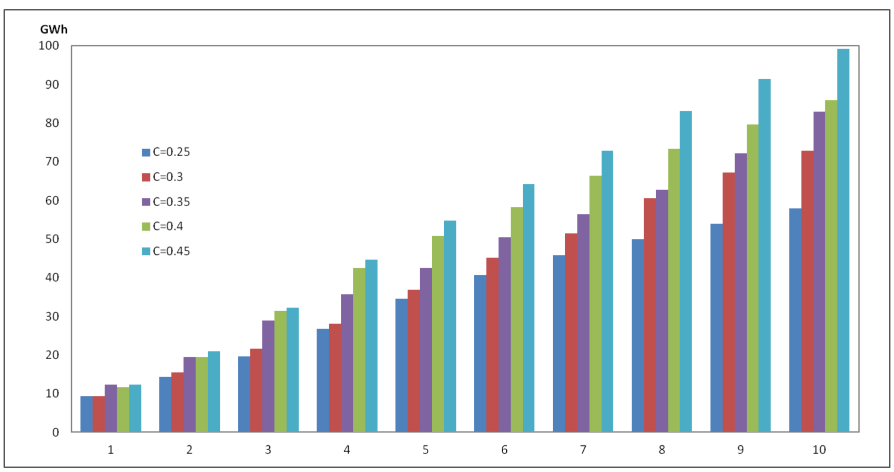


Figure 4.6: Wind power generation with respect to turbine coefficient for point A on the efficient frontier

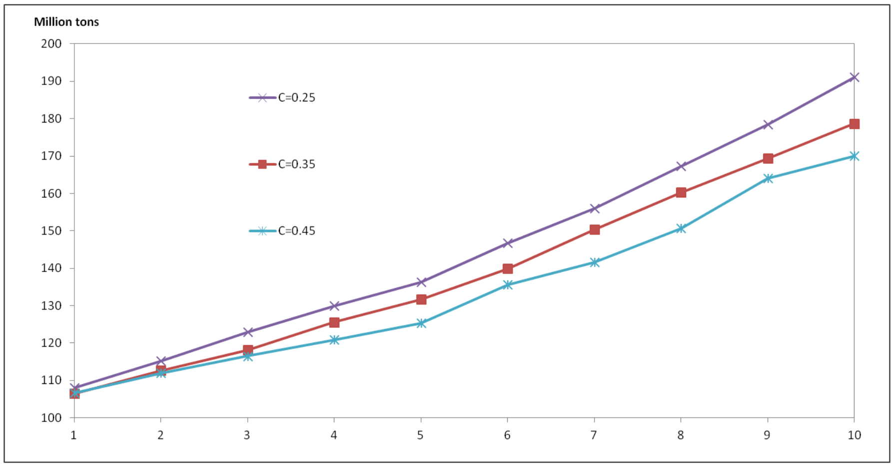


Figure 4.7: Total emissions released by power generation with respect to turbine coefficient for point A on efficient frontier

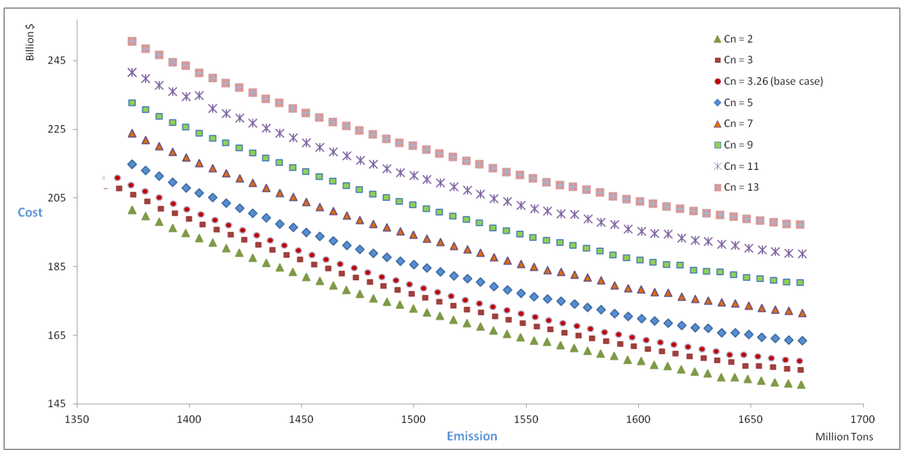


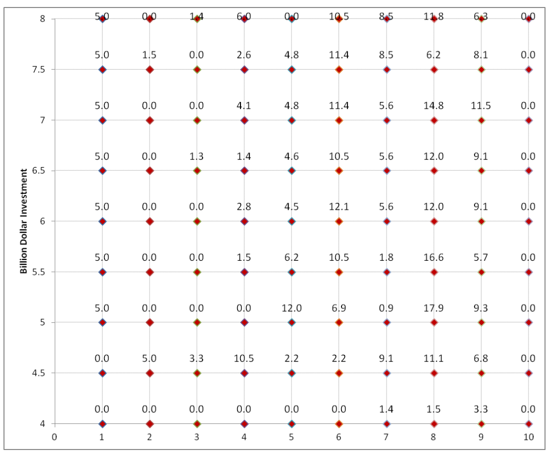
Figure 4.8: Efficient frontier for changing natural gas prices

4.4.2 Effect of Natural Gas Prices

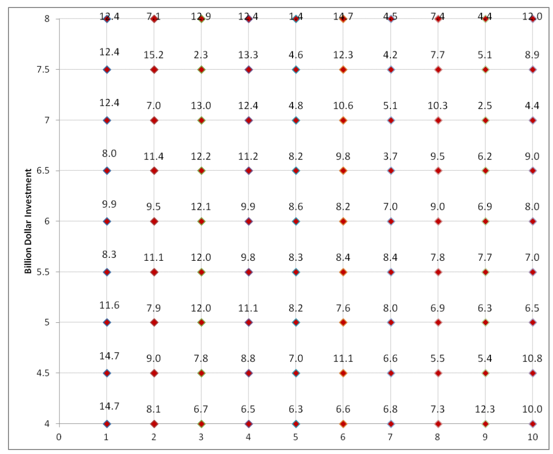
The most apparent effect of natural gas is observed on total cost over the time horizon. In order to see the price effect Figure 4.8 that shows the trade of between cost and emission with respect to natural gas price is included.

4.4.3 Effect of Investment Level

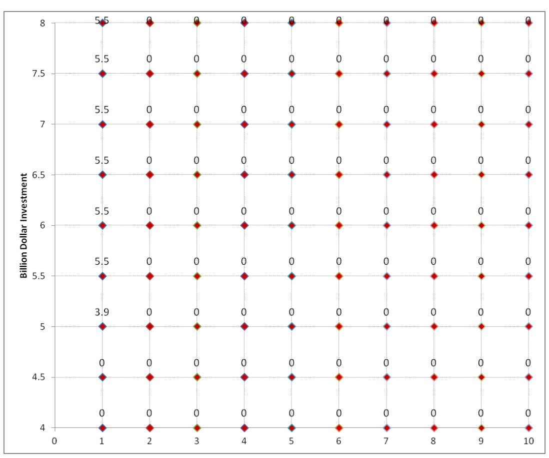
In order to see the effect of investment allocated to capacity expansion or plant conversion, converted plants, newly constructed wind, geothermal and hydro-power plants are analysed for different investment levels. Figure 4.9 gives the results of this analysis. The capacity addition or the converted coal plant capacity is introduced in sub-figures as data labels.



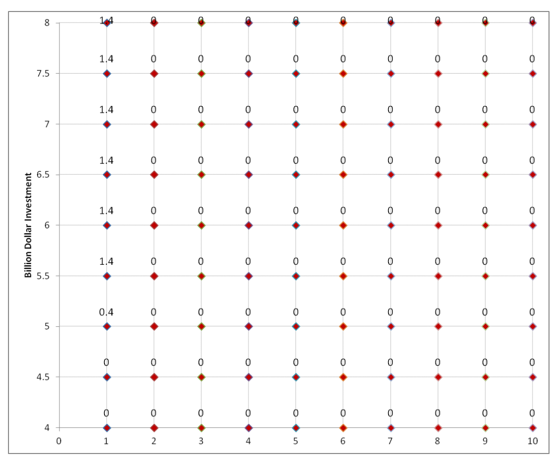
(a) Capacity of converted coal plants (GWh)



(b) Wind capacity addition (GWh)



(c) Hydro capacity addition (GWh)



(d) Geothermal capacity addition (GWh)

Figure 4.9: Capacity change of plant utilization for different investment levels with respect to time periods

Chapter 5

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

5.1 Conclusion

The requirements of the modern life make the energy most important value of our time. While increase in the population and economic growth rate push the energy demand up, the irresponsible consumption of goods and services and inadequate regulation of energy efficiency deepen the problem of satisfying this high demand. In this thesis, we tried to find an answer to this problem by considering measurable indicators of economical and environmental aspects. Therefore, it is crucial to keep in mind that the aspects, we could not take into consideration like social impacts of energy sources should have a say in energy planning of a region.

We included Tables 4.5 and 4.6 in results section in order to be able to make comparison with the targeted values of Vision 2023 which are presented on Tables 1.4 and 1.5 in Chapter 1. The results are consistent with targeted values in terms of hydro and wind energy utilization. Although 2023 targets predict solar energy to play role in electricity generation, the results are in line with our expectation because having a relatively lower efficiency factor and being the most expensive renewable power make solar utilization undesirable. However, unlike our expectation the results show that increasing the efficiency of solar power does not create a considerable difference unless the investment cost decrease. Besides, in order to drive the geothermal electricity generation up, the discovery of new geothermal sites is of first priority. There is an envisaged capacity of 2000 MW, but discovered geothermal locations have only around 450 MW capacity according to the data of MTA and YEGM.

The increase in the installed capacity which is shown in Figure **??** is in accordance with the intention of decreasing the GHG emissions and increasing the share of renewable source in total mix year by year. The reason why the capacity addition of hydro power is relatively low is that most of the economical and efficient capacity has already been established. Conforming to hydro power maps of YEGM, there is a capacity of 7931 GWh potential of which the feasibility studies are ongoing. These potential is not included as parameter in the implementation phase of our model because of the limitation of time period. Besides, the new hydro-power plants should not be established in agreement with only economic and emission-based objectives. In Turkey, there is a public resistance to hydro power plants due to the irresponsible utilization of the potential sources. There are a lot of people who are the suffering as a result of submergence of their towns under water because of the installation of hydro power plants. Improving the power utilization is our main goal but not in the expense of destroying people's living space. Therefore, social impacts should be evaluated systematically before a potential power location is labelled as feasible and during the phase of construction.

Sensitivity analysis on investment level reveals the required annual investment to be allocated for energy industry. According to the results presented on Figure 4.9, there will be no considerable difference over the time horizon in terms of renewable capacity and coal plant retrofit after the investment level is bigger than \$6 billion. If the annual investment is less than \$3.5 billion, then the possible power utilization will not be able to catch the demand in the following years and the dependency on imported electricity will be strengthened.

Considering the output of our model in terms of fossil fuel employment, despite the dependency on other countries, natural gas seems to continue its dominance in power sector. It is an expected result for us since natural gas is the field that our two objectives , minimum emission and minimum cost, meet on a common ground. Therefore, even if natural gas prices go up, our model does not abandon natural gas utilization. In that case, the cost parameter of natural gas will only have an effect on total cost not on the share of natural gas in total mix. This situation is presented on Figure 4.8 for the changing natural gas prices up to 13 $/MMBtu. Besides, recent developments in the natural gas industry have made the natural gas an economically attractive fuel. With the invention of shale gas which is the natural gas formed inside of the shale formations, natural gas prices fall down. The future frame promises the increase in natural gas utilization all over the world.

On the other hand, shifting the fuel of a coal plant requires a detailed and careful consideration. When strict goals about the GHG emission levels compels the abandonment of the coal burning, fuel switching will probably be the most preferable choice. This seems to be the most powerful driving force for converting coal plants to burn natural gas. However, in order to be eligible for the retrofitting process, the age and the condition of the plant are the key factors. In the scope of this thesis, we did not conduct a feasibility study to decide on the eligibility of the plants for conversion. The plants that are found suitable for conversion as a result of our optimization model should be evaluated in terms of economy and efficiency. In addition, transporting natural gas from supply point to the burners requires a careful attention regarding pipeline construction and electrical equipment and systems design.

5.2 Future Research Directions

In our study, we aimed to present a sustainable energy mix of Turkey's power generation system. The optimality criteria depends on the reduction of GHG emissions in addition to cost minimization. However, sustainability deals not only with economical and environmental issues, it has also a social condition. As a future work, we suggest to add a new objective function which accounts for the social impacts of capacity expansion. Public opinion can be effective to choose a location over the other one which seems optimal without the social considerations.

Our model can also be extended in terms of time step of analysis. Rather than using an annual base, time step can be reduced in a way that will allow to use different load blocks according to the degree of demand. In that case, the parameters for demand, electricity generation and imported electricity must be assigned separately for load blocks. This requirement calls for a great increase in the number of parameters and a highly complex model.

Another addition to our model can be the integration of transmission network costs. In order to be able to make this contribution, exact locations of renewable energy plants must be known and the length of required grid lines must be determined.

The most important requirement to improve the application of the model is a strong collaboration with government, policy makers, non-governmental organizations and public to obtain a more transparent data and make an accurate impact assessment.

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CURRICULUM VITAE

Aybike ALKAN was born in Manisa on January 22, 1989. She graduated from Gazi Anatolian High School in 2007. She received her B.S. degree in Chemical Engineering from Middle East Technical University (METU), Ankara, Turkey, in 2012. She received her M.S. degree under the supervision of Prof. Metin Turkay in Industrial Engineering from Koc University, Istanbul, Turkey in 2014. At the same time, she was a research and teaching assistant in Koc University. Her current research interests include optimization theory, power generation systems, capacity expansion planning and social impacts of energy technologies.