ERASMUS MUNDUS MASTERS IN COMPLEX SYSTEMS SCIENCE

Optimization of Energy Conversion Technologies in Turkey between 2010-2025

M1 Project

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ABSTRACT

Energy is an indicator of quality of life; it provides electricity, heat and transportation fuel. With the increasing demand of energy, modelling of energy systems have been started for different purposes such as: understanding of current and future markets, facilitating a better design of energy systems, understanding of interactions between energy and economy, and understanding of the potential implications to environmental quality. The proposed model is a simple version of the energy system as a flow chart in three different parts: primary energy suppliers, energy conversion technologies and final energy demand. The aim is to find the least cost set of technologies in Turkey that will meet the final demand between 2010-2025 by decreasing CO_2 emission. In order to implement this model, a mathematical programming method with a bottom-up approach has been used. According to the results, electricity demand is met by renewable energy sources (hydro, solar, geothermal and wind energy). The heating sector is run on solar-heat based energy systems. And finally, transportation fuel demand is either met with a coal-based hydrogen system or a mix of solar-hydrogen and natural gas-hydrogen system; depending on the restrictions on CO_2 emissions.

Contents

1 Introduction

Energy plays an important role in our lives; it provides electricity, heat and transportation fuel. Almost all the activites depend on energy; which makes energy an indicator of quality of life. There are some models developed in the literature for the quality of life as a function of energy consumption [1]. The energy industry of a country reflects the social and economic development of that country. Starting from 1980s, energy policies have became related with economic, social, security, environmental policies as well as the national interests [2].

Energy can be found in different forms, and these forms can be converted to each other. Primary energy sources are classified as renewable or non-renewable energy sources. Crude oil, hard coal or natural gas are examples to primary energy sources. If the sources are produced from primary sources, then it is called as secondary sources. Electricity and hydrogen are the examples of secondary resources. The renewable energy sources are produced from natural sources, and there is no shortage of these sources. Biomass, geothermal, wind, solar, hydro energy are examples of renewable energy. Non-renewable energy sources cannot be created once they are used. Fossil fuels (coal, oil and natural gas) and types of nuclear power such as uranium are the examples of non-renewable energy sources.

After the industrial revolution in 19th century, firstly coal and then oil started to be used as primary energy sources [3]. Currently, the vast majority of the energy demand is met by fossil fuels (see Figure 1.1). Fossil fuels causes CO_2 emissions and they have limited potential; it is expected that they will depleted within a few centuries. The high usage of fossil fuels indicates that the principles of sustainable energy is not supported. Sustainable energy depends on clean, environmentally friendly renewable energy sources.

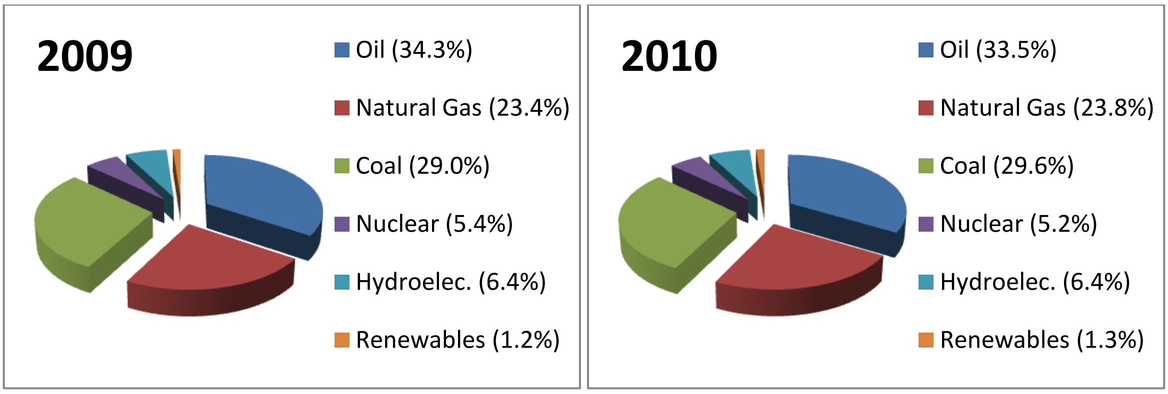


Figure 1.1. Comparison of world's total primary energy consumption between 2009 and 2010

Figure 1.1 illustrates the share of primary energy resources in the world; according to British Petrol's Statistical Review of World Energy 2011; in 2009 and 2010. In 2009, world's total primary energy consumption was around 11,365 million tons of equivalents(Mtoe); of which oil with 3909 Mtoe, natural gas with 2661 Mtoe, coal with 3306 Mtoe, nuclear energy with 614 Mtoe, hydroelectricity with 736 Mtoe and renewables with 137 Mtoe. In 2010, world's total primary energy consumption was around 12,002 Mtoe; of which oil with 4028 Mtoe, natural gas with 2858 Mtoe, coal with 3556 Mtoe, nuclear energy with 626 Mtoe, hydroelectricity with 776 Mtoe and renewables with 16 Mtoe.

World's primary energy consumption increased by 5.6%; the highest increase between two years since 1973 [4].

World's total energy demand increased by 40% since 1990 and it is expected to increase more than 50% for the next 15 years [5]. There is an increasing demand to energy like in Jevons paradox. Jevons paradox is named after William Jevons, who observed in the 19th century that an increase in the efficiency of using coal to produce energy tended to inrease consumption, rather than reduce it. Because, Jevons argued, the cheaper price of coal-produced energy encouraged people to find innovative ways to consume energy [6].

The increasing demand of energy started the modelling of energy systems. Energy modelling has different purposes such as; understanding of current and future markets, facilitating a better design of energy systems, understanding of interactions between energy and economy, and understanding of the potential implications to environmental quality [7]. Decision making processes become more reliable as the model reflects the real world more accurately. This paper focuses on the current energy conversion technologies and making predictions about the least cost set of technologies for the next 15 years.

In Section 2, the energy systems and their classifications are explained in detail. In Section 3, the model is presented with the explanations of parameters, decision variables, objective function and constraints. In Section 4, the facts about the energy in Turkey are given. In Section 5, the necessary data regarding the energy model is given. In Section 6, the results are presented with different scenarios based on sensitivity analaysis. In Section 7, conclusions and improvements which can be done as a future work are discussed.

2 Energy Systems

2.1 Energy Systems Modelling

An energy system consists of an integrated set of technical and economic activities operating within a complex societal framework, thus energy system-modelling should be related with other disciplines. Energy systems modelling is defined as the use of comprehensive computer based models applied to energy and climate policy issues [8]. Energy systems are modeled using different approaches: Theoretical and analytical. These models can be shaped with different disciplines such as engineering, economics, operations research and management science. In order to implement these models, there are also different techniques such as mathematical programming, staticstics and econometrics [7]. According to the Nordic Energy Perspectives, the benefits of using energy systems modelling may be summarized as the following [8]:

- The complex reality is transformed to a simpler model making it easier to analyze.
- The model may act as an efficient filter to evaluate consequences of certain policies. In reality, the analysis of “cause-effect chain” is difficult; however, in a model specific actions or measures can be directly related to their consequences by keeping that specific action unchanged.
- Modelling a complex system leads to a better understanding of that system; and better understanding of the system leads to a better decision-making.
- Models are also used for forecasting energy prices, and energy demand.
- Once a model is set up, it is easier to perform scenario analysis to see the difference in the objective function by changing the input values.
- Since energy systems are related with other disciplines, all the participants coming from different disciplines or business fields should agree on a certain view to describe the model.

2.2 Classification of Energy Models

According to Nicole van Beeck, there are nine classifications of energy models [9]. This classification is based on the main model distinctions in the literature. Two inspiring classification from literature had done by Hourcade and Grubb. Hourcade stated three ways to differentiate energy systems; purpose of the models, their structure and their external and internal assumptions [10]. On the other hand, Grubb differentiated six different cathegories including; top-down vs. bottom-up approach, time horizon, sectoral coverage, optimization and simulation techniques, level of aggregation and geographic coverage,trade and leakage [11]. All the energy models are simpler versions of the reality.

The nine dimensions to classify energy models are the following: (1) purposes of energy models, (2) the model stucture: internal assumptions and external assumptions, (3) the analytical approach, (4) the underlying methodology, (5) the mathematical approach, (6) geographical approach, (7) sectoral covarage, (8) the time horizon and (9) data requirements. These dimensions are not totally independent from each other. If the analytical approach of the model is bottom-up, then the assumptions regarding the model will be defined by the user; whereas if the model has a top-down approach, many of the assumptions will be mostly internal [9]. The detailed explanations are given as the following:

1. **General and specific purposes of energy models:** General purposes of the model are related with how the future is addressed. There are three groups of general purposes; to predict or forecast the future, to explore the future with scenario analysis and to look back from the future to the present, which is called as backcasting. On the other hand; models with specific purposes focus on models such as energy demand, energy supply, impact or appraisal [9].
2. **The model structure:** For each type of model, some internal and external assumptions has to be decided. External assumptions address to the user defined assumptions such as: population growth, economic growth, energy demand, energy supply, price and income elasticities of energy demand, existing tax system and tax recycling [10]. On the other hand, internal assumptions are embedded in the model structure. Hourcade defined four independent dimensions of internal assumptions: the degree of endogenization, the extent of description of the non-energy sector components of the economy, the extent of the description of energy end-uses, and the extent of the description of energy supply technologies [10].
3. **The analytical approach:** The analytical approach are either top-down or bottom-up approach. Top-down models use an "economic approach" whereas bottom-up models use an "engineering approach". Top-down models do not feature technological details of energy production and conversion, whereas bottom-up models reflects the detailed description of technologies. Top-down models are based on observed market behavior describing the interrelationship between labor, capital and natural resources such as energy; whereas bottom-up models are independent of observed market behavior. Furthermore, top-down models generally used for prediction purposes, while bottom-up models mainly used for exploring purposes [9].
4. **The underlying methodology:** In the literature the following methodologies used commonly: econometric, macro-economic, economic equilibrium, optimization, simulation, backcasting and multi-criteria models. In particle, the distinction of these methodologies is not that clear.
5. **The mathematical approach:** In order to implement energy models, there are different techniques such as linear programming, mixed integer programming and dynamic programming [9]. Linear programming is a branch of mathematical programming which aims to minimize or maximize the objective function with user-defined constraints [12]. Mixed integer programming is an extension of linear programming which allows formulating technical properties and relations. Finally, dynamic programming aims to divide the model into sub-models in order to find the optimal growth path.
6. **Geographical coverage:** In order to determine the structure of the model; the geographical coverage plays an important role. The models either focus on global, regional and national level; or on local and project level [9].
7. **Sectoral coverage:** Models can focus on just one sector, or include more sector. Single sectoral models provide information on a specific sector (energy sector), it does not focus on the interactions between sectors; which is called as multi-sectoral models. All bottom-up models are sectoral [9].
8. **The time horizon:** Time horizon classification is important becuase economic, social and environmental processes differ with time period. According to Grubb, a time period which is less than 5 years considered as short term, a time period between 3-15 years considered as medium term, and a time horizon more than 10 years is called as long term horizon [11].

9. **Data requirements:** All the models require certain type of data. Most of the models require quantitative, cardinal and monetary type of data. Some of the models require qualititative and ordinal data when data are not available or unreilable. Furthermore, data may be aggragated or disaggragated [9].

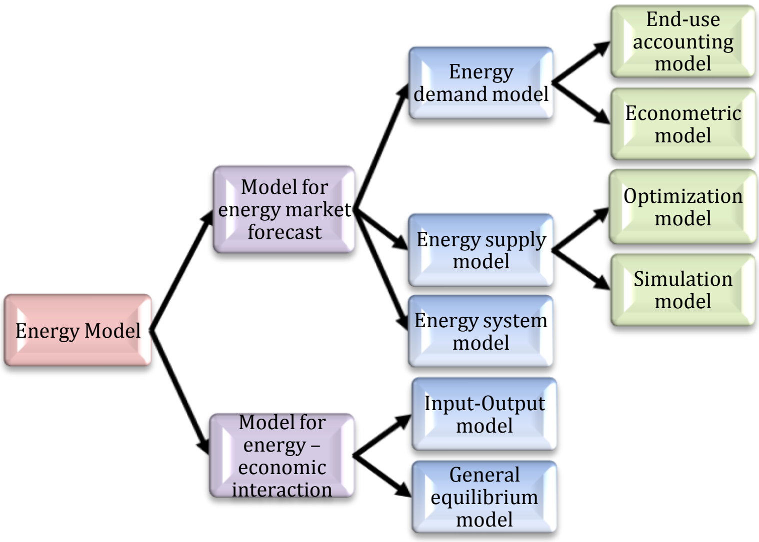


Figure 2.1. Classfication of energy models

2.3 Market Allocation Energy Systems

The most specific example of bottom-up model is the existing energy model which is called MARKAL (MARKet ALlocation). MARKAL is based on the principle of Reference Energy System (RES). **Reference Energy System** is a network representation of an energy system. It represents all the activities from the primary energy resources to end-use activities. All of these activities are connected to each other with a link in the network. The system also includes the input values such as the efficiency of the technologies, environmental impact and the cost coefficients related with the energy suppliers and technologies [13]. The network representation of a reference energy system can be seen in Figure 5.2 [14].

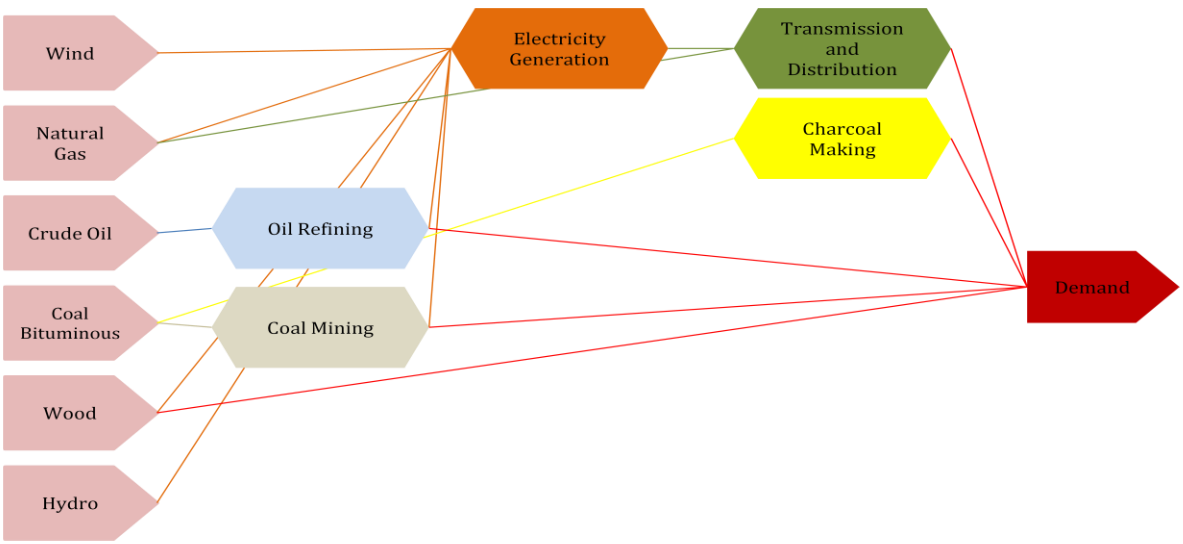


Figure 2.2. Reference Energy System diagram

MARKAL is a data-intensive, technologhy-rich energy system which initially developed by International Energy Agency (IEA). MARKAL models are in use in energy and environment planning sector since 1980s. MARKAL is a widely accepted model with implementation in more than 40 countries and by more than 80 institutions [15]. It is a detailed representation of energy sources, energy conversion technologies, end-use technologies and demand for energy services (see Figure 2.3). The energy technologies consists of production, transmission and use of energy, with associated information on the costs of these technologies [16]. The objective is to find a least cost set of technologies that will meet the energy demand for a specific time period with satisfying the user-defined constraints.

MARKAL model contributes national and local energy planning by giving detailed explanation of technologies and interactions between macro-economy and energy use to the energy policy makers and planners [15]. The answers to following energy and enviromental questions are found with the model: How to reach carbon dioxide reduction?, What is the effect of market-based instruments?, How to model technology dynamics and the impact of research and development? [15].

The proposed model (see Section 3) in this paper is a simplification version of MARKAL model. The comparison between MARKAL and proposed model is given in Table 2.1, regarding the nine classifications of energy systems.

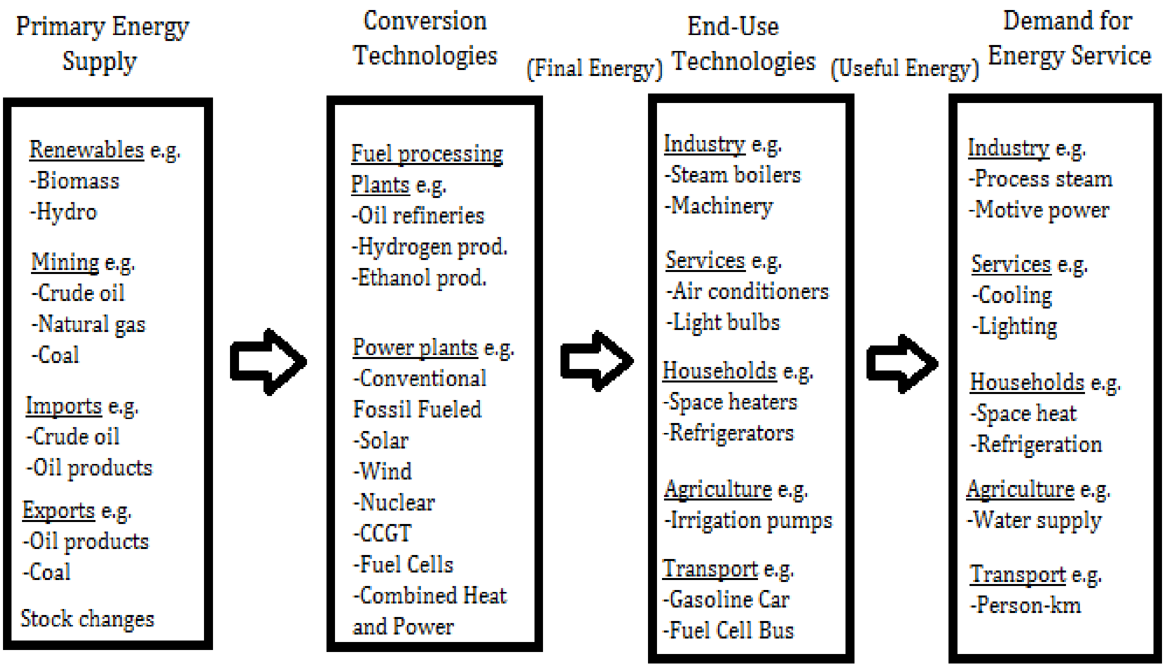


Figure 2.3. Illustration of MARKAL Energy Perspective [17]

		MARKAL	PROPOSED MODEL
1	**Purposes**	General: Exploring Specific: Energy supply with constraints. The objective includes target oriented integrated energy analysis and planning through a least cost approach	Specific: Energy supply with constraints. The objective includes target oriented integrated energy analysis and planning through a least cost approach
2	**Structure**	Low degree of endogenization, detailed description of end-uses and energy technologies possible.	Detailed description of suppliers, technologies and end-uses
3	**Analytical approach**	Bottom-up model	Bottom-up model
4	**Methodology**	Toolbox / Optimization	Optimization
5	**Mathematical approach**	Linear programming, dynamic programming	Linear programming
6	**Geographical approach**	Local, national	Local
7	**Sectoral Coverage**	Energy sector only	Energy sector only
8	**The time horizon**	Medium, long term	Medium, long term
9	**Data requirements**	Quantitative,monetary, disaggragated	See Section 5

Table 2.1. Comparison of proposed model with MARKAL model

3 Model Description

Experimenting with models involves less risk, requires less time and is less expensive according to experimenting with real situation [18]. As soon as the problem is defined, a mathematical model should be developed in order to use an optimization solution algorithm [19]. The general process in optimization modelling is the following: (1) decribe and understand the problem, (2) propose a solution, (3) update the optimal solution. The post solution analysis is crucial in order to control the problem; the structure of the model and parameters may vary with time [19].

The proposed model is a mathematical model which is solved by an optimization solution algorithm. Optimization problems are made up of three basic ingredients [19] : (1) objective function, (2) inputs, and (3) constraints (see Figure 3.1). In a mathematical model, the aim is to maximize or minimize some objective function subject to constraints. The values of decision variables that provide the mathematically-best output are referred to as the optimal solution for the model [18]. There are two kind of inputs: controllable (parameters) and uncontrollable(decision variables). Parameters are the fixed numbers defined by the user, they may vary with time; decision variables are found as a result of the model with the objective function. A variety of software packages are available of solving mathematical models such as GAMS, Xpres-MP [20]. Linear programming is a mathematical method for determining a way to achieve the best outcome in a given model; subject to linear equality and linear inequality.

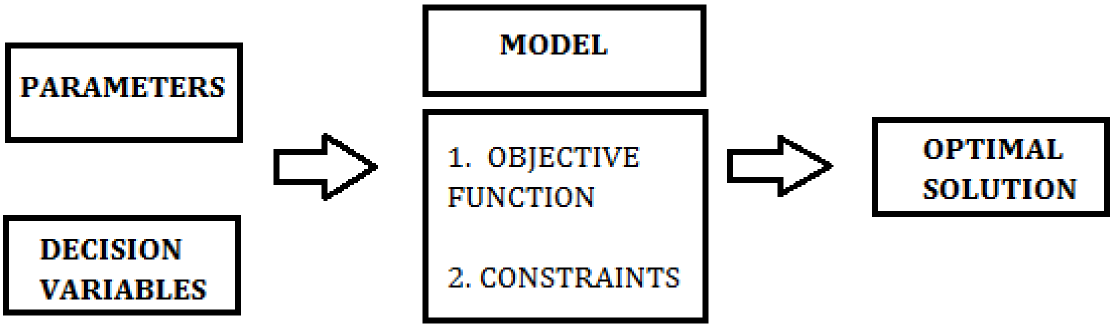


Figure 3.1. Simple structure of a mathematical model

3.1 Model Structure

The proposed model is composed of three different parts: primary energy suppliers, energy conversion technologies and final energy demand (see Figure 3.2). The U.S. Department of Energy divides energy sector into four groups: industrial, commerical, residential and transportation. According to the data provided by Enerdata, 37% of total energy of Turkey in 2009 is consumed for residential and services, 32% for industry, 20% for tansportation, 6% for agriculture, and 5% for non-energy use [21].

Three major types of energy are consumed by these four sectors: electricity, direct heat and transportation fuel. *Electricity* is used to provide light and power to homes, bussinesses and industry. *Direct heat* is used to provide heat to buildings and cook food. Finally, *transportation fuel* is used to provide power to vehicles [22].

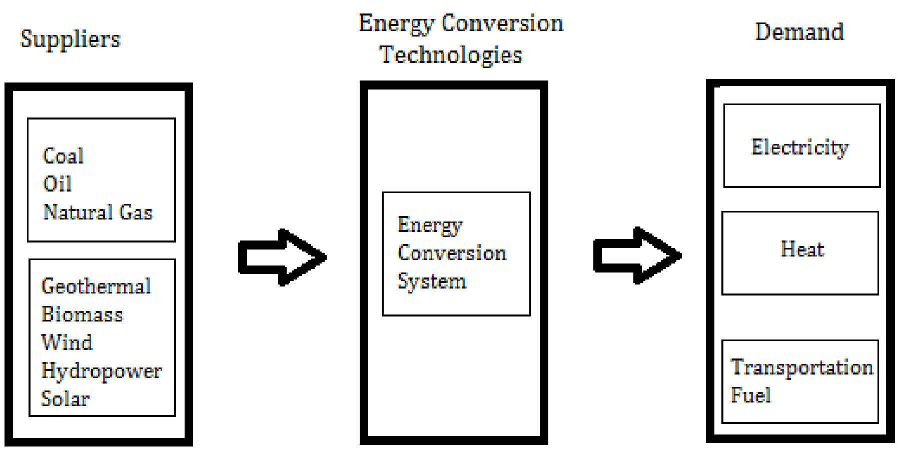


Figure 3.2. Model representation as a flow chart [23]

3.2 Sets, Parameters and Decision Variables

Sets

There are four different set of indices which form the model: Primary energy resources (*r*), energy conversion technologies (*te*), final energy demand (*d*) and time (*t*). The model is formed in order to reflect the reality between years 2010 and 2025. Each unit of time refers to five years; the inital time *t*=0 is 2010, *t*=1 refers to year 2015, and the same pattern goes until *t*=3 which is year 2025. Energy suppliers are formed with renewable and non-renewable energy resources. In Turkey, the current resources are coal (*r*=1), oil (*r*=2), natural gas (*r*=3), hydropower (*r*=4), wind (*r*=5), geothermal (*r*=6), biomass (*r*=7) and solar energy (*r*=8). A detailed description of these sources, including their economically feasible potential in Turkey will be explained in Section 5.1.

Energy conversion technologies are the relationship between suppliers and demands. In the proposed model, there are 21 different energy technologies. $te \in \{1,..8\}$ are the technologies produce electricity, $te \in \{9,..13\}$ are the technologies produce heat; and $te \in \{14,..21\}$ are the technologies produce transportation fuel. The difference in these technologies is the type of resource which is used. The current capacities of the technologies will be discussed in Section 5.2. Final energy demand is categorized with three major types of energy: electricity (*d*=1), heat (*d*=2), and transportation fuel (*d*=3). There are different algorithms used to forecast the energy demand in Turkey, the results of these algorithms will be given in Section 5.3.

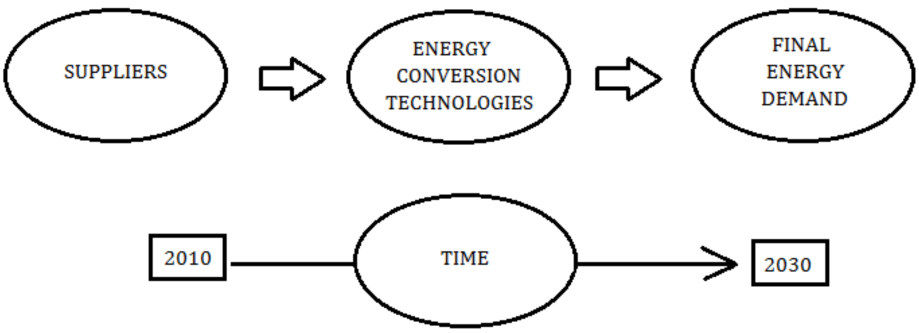


Figure 3.3. Illustration of sets in the proposed model

Parameters

Parameters are the fixed numbers entered by the user. The model parameters are subject to the energy suppliers (see Table 3.1), energy conversion technologies (see Table 3.2), final energy demand (see Table 3.3) or to the system itself (see Table 3.4).

	NOTATION	UNIT	EXPLANATION
marketPrice(*r*,*t*)	MP(*r*,*t*)	USD/GJ	Market price of the resources : *r*ϵ{1,..8}, *t* ϵ{1,.4}. There is no market price of renewable energies except biomass.
emissionFactor(*r*)	EF(*r*)	g/kWh	The CO_2 emission factor of the fossil fuels(coal,oil, natural gas) : *r* ϵ{1,..3}.
potential(*r*,*t*)	P(*r*,*t*)	GWh	The economically feasible potential of resources in Turkey : *r*ϵ{1,..8}, *t* ϵ{1,.4}.
carbonTax(te,t)	CT(t)	USD/tonC	The cost of CO2 emission (of fossil fuels) at time t : t ϵ{1,.4}.

Table 3.1. Notations, units, and explanations of the parameters related with energy suppliers

	NOTATION	UNIT	EXPLANATION
investmentCost(*te*,*t*)	IC(*te*,*t*)	USD/MW	Investment cost of the technologies : *te* ϵ{1,..21}, *t* ϵ{1,.4}. The maintenance cost is assumed to be 10% of the investment cost. The total cost related with technologies is defined as 1.1*investmentCost
conversionEfficiency(*te*)	CE(*te*)	-	Conversion efficiency of each technology: *te* ϵ{1,..21}. The conversion efficiency is the ratio of the useful output (final demand) to the input [24].
initialCapacity(*te*)	A(*te*)	MW	The current capacity of each technology *te* at time *t*=0 : *te* ϵ{1,..21}.
lifeSpan	l	-	Life span of technologies; is assumed to be 15 years.
decay	de	-	The decay of technologies in each time step.

Table 3.2. Notations, units, and explanations of the parameters related with energy technologies

	NOTATION	UNIT	EXPLANATION
energyDemand(*d*,*t*)	D(*d*,*t*)	GWh	The amount of final energy demand *d* at time *t* : *d* ϵ{1,..3}, *t* ϵ{1,.4}

Table 3.3. Notations, units, and explanations of the parameters related with energy demand

	NOTATION	UNIT	EXPLANATION
technologiesUsed(*r*,*te*)	RT(*r*,*te*)	-	Binary matrix. If resource *r* can be used in technology *te*, then the value is 1; otherwise 0 : *r*ϵ{1,..8}, *te* ϵ{1,.21}.
discountRate	dr	-	The discount rate in order to calculate the total cost.
timeSteps	s	-	The times steps of the system; which is defined as 3.

Table 3.4. Notations, units, and explanations of the parameters related with the system

Decision Variables

There are three decision variables which the model will find solutions. They are under control of the input values(parameters), contraints and the objective function of the model. The notations and the explanations of the variables are given in Table 3.5.

	NOTATION	UNIT	EXPLANATION
inputToTech(r,te,t)	x(r,te,t)	GWh	The amount of resource r that is converted to energy demand with technology te between time t-1 and t ; $r\epsilon\{1,..8\}$, $te\ \epsilon\{1,..21\}$, $t\ \epsilon\{1,.4\}$
investedTech(te,t)	y (te,t)	MW	The amount of invested technology te between time t-1 and t ; $te\ \epsilon\{1,..21\}$, $t\ \epsilon\{1,.4\}$
capacityTech(te,t)	z (te,t)	MW	The capacity of technology te at time t ; $te\ \epsilon\{1,..21\}$, $t\ \epsilon\{0,..4\}$. capacityTech(te,t=0) is defined by the user (which is the parameter called A(te))

Table 3.5. Notations and explanations of the decision variables

3.3 Objective Function

The objective of this model is to find the least cost set of technologies that will meet the energy demand in Turkey in the next 15 years by decreasing the $C0_2$ emission. The objective function to be minimised is defined as the total cost which consists of three parts: (1) Market price of the primary energy resources, (2) investment and maintenance cost for technologies, and (3) carbon tax of fossil fuels for CO_2 emission.

$$\mathrm{ResourceCost(t)} = \sum_{te\in \mathrm{TECH}} \sum_{r\in \mathrm{RESOURCES}} \mathrm{x(r,te,t)} \times \mathrm{MP(r,t)} \times \mathrm{RT(r,te)} \times \mathrm{c1}\ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{1}]$$

$$\mathrm{TechnologyCost(t)} = \sum_{te\in \mathrm{TECH}} 1.1 \times \mathrm{IC(te,t)} \times \mathrm{y(te,t)}\ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{2}]$$

$$\mathrm{CarbonTaxCost(t)} = \sum_{te\in \mathrm{TECH}} \sum_{r\in\{1,..3\}} \mathrm{x(r,te,t)} \times \mathrm{E(r)} \times \mathrm{CT(t)} \times \mathrm{RT(r,te)}\ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{3}]$$

$$\mathrm{Cost(t)} = \mathrm{ResourceCost(t)} + \mathrm{TechnologyCost(t)} + \mathrm{CarbonTaxCost(t)}\ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{4}]$$

$$\mathrm{TotalCost} = \sum_{t\in \mathrm{TIME}} \mathrm{s} \times \mathrm{Cost(t)} \times (1-\mathrm{dr})^{\mathrm{s}\times \mathrm{t}} \quad [\mathbf{5}]$$

Note that c1 is the constant ratio of GWh/GJ; which is equal to 3600. 1gigawatt-hour is an energy unit; and it is defined as the energy consumed by power consumption of 1 GW during 1 hour. 1 GWh = 3600 GJ [25].

3.4 Constraints

There are seven constraints to be satisfied in order to minimize the total cost which is defined in Section 3.3. The last constraint (7) is optional to the third part of the objective function (carbon tax of fossil fuels). While running the model, just one of these parts should be included. The detailed explanation of the constraints and their equations are given below:

(1) The energy produced at time *t* should be equal or bigger than the energy demand at time *t*.

$$\sum_{r \in \mathrm{RESOURCES}} \sum_{te \in \{1,..8\}} \mathrm{x(r,te,t) \times RT(r,te) \times CE(te) \geq D(1,t)}\ \ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{6}]$$

$$\sum_{r \in \mathrm{RESOURCES}} \sum_{te \in \{9,..13\}} \mathrm{x(r,te,t) \times RT(r,te) \times CE(te) \geq D(2,t)}\ \ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{7}]$$

$$\sum_{r \in \mathrm{RESOURCES}} \sum_{te \in \{14,..21\}} \mathrm{x(r,te,t) \times RT(r,te) \times CE(te) \geq D(3,t)}\ \ \forall\, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{8}]$$

Note that equation 6 holds for electiricity production, equation 7 holds for heat production and equation 8 holds for transportation fuel production.

(2) Initialization of capacity of each technology at *t*= 2010. (current time)

$$\mathrm{z(te,0) = A(te)}\ \ \forall\ \mathrm{te} \in \mathrm{TECH} \quad [\mathbf{9}]$$

(3) The energy produced in technology *te* should be equal or smaller than the capacity of technology *te*.

$$\sum_{r \in \mathrm{RESOURCES}} \mathrm{x(r,te,t) \times RT(r,te) \times CE(te) \leq z(te,t) \times c2}\ \ \forall\, \mathrm{t} \in \mathrm{TIME}, \mathrm{te} \in \mathrm{TECH} \quad [\mathbf{10}]$$

Note that c2 is the amount of energy produced in terms of GWh in 1 MW of energy conversion technology; which is approximately 6.132 GWH/ MW [26]. It is assumed that the energy conversion technologies run 70 % of the time.

(4) Calculation of the capacity of a technology *te* at time *t*+1 is dependent on the capacity of that technology at time *t*.

$$\mathrm{z(te,t) = z(te,t-1) \times (1-de) + y(te,t)}\ \ \forall\, \mathrm{t} \in \mathrm{TIME}, \mathrm{te} \in \mathrm{TECH} \quad [\mathbf{11}]$$

(5) Some of the resources have an upper limit.

$$\sum_{te \in \mathrm{TECH}} \mathrm{x(r,te,t) \times RT(r,te) \leq P(r,t)}\ \ \forall\, \mathrm{r} \in \mathrm{RESOURCES}, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{12}]$$

(6) All the decision variables should be equal or bigger than zero.

$$\mathrm{x(r,te,t) \geq 0}\ \forall\, \mathrm{r} \in \mathrm{RESOURCES}, \mathrm{te} \in \mathrm{TECH}, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{13}]$$

$$\mathrm{y(te,t), z(te,t) \geq 0}\ \forall\, \mathrm{te} \in \mathrm{TECH}, \mathrm{t} \in \mathrm{TIME} \quad [\mathbf{14,15}]$$

(7) *OPTIONAL:* The amount of CO_2 emissions in 2025 should be less than the 40% of the amount in 2010.

$$\sum_{te \in \mathrm{TECH}} \sum_{r \in \{1,..3\}} \mathrm{x(r,te,3) \times RT(r,te) \times E(r)} \leq \sum_{te \in \mathrm{TECH}} \sum_{r \in \{1,..3\}} \mathrm{x(r,te,1) \times RT(r,te) \times E(r) \times 0.4} \ [\mathbf{16}]$$

4 Turkey Energy Profile

According to the data provided by the Ministry of the Interior in 2010, the population of Turkey is 73,722,988 [27]. The annual incrase of the population in the last 3 years was around 1.46% [27]. The increasing population leads to an increasing energy consumption. Also, the location of Turkey makes it an important energy transit country between Asia and Europe; with a total area of 783,562 km^2. Moreover, Turkey has the 16th largest economy in the world, and 6th largest compared with EU countries in 2010 with GDP [28]. Also, according to the OECD, Turkey is expected to be the fastest growing economy of the OECD members during 2011-2017, with an annual average growth rate of 6.7% [29]. The energy sector in Turkey is one of the promising fields in the economy. Turkey's funding needs for the energy sector is the highest of the southern & eastern Mediterranean countries (see Figure 4.1). The needs of each energy sector are: electricity 56 billion dollar; gas 6 billion dollar; oil 4 billion dollar; and solid fuels 1 billion dollar [30].

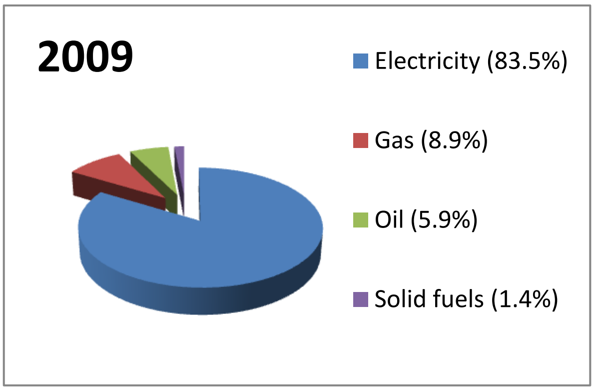


Figure 4.1. Turkey's funding needs for energy

Turkey consumed energy equivalent to 110.9 million tons of oil during 2010, with an increase of 9.8% since 2009 [4]. The fuel mix of primary energy supply is mostly formed by nonrenewable fossil fuels (see Figure 4.2). Fossil fuels contribute 90.3% of the total production; whereas renewable energy suppliers just contribute 9.7% of the total production [31]. A comparison of fuel mix of total energy consumption between world and Turkey is given in Figure 4.3 [32].

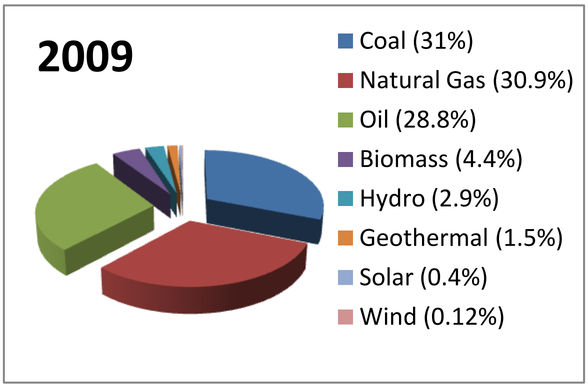
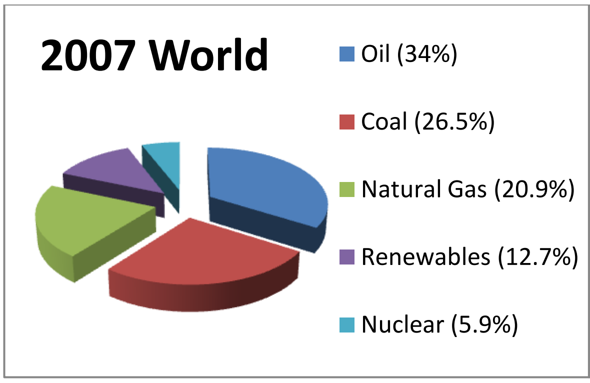


Figure 4.2. Turkey's primary energy supply



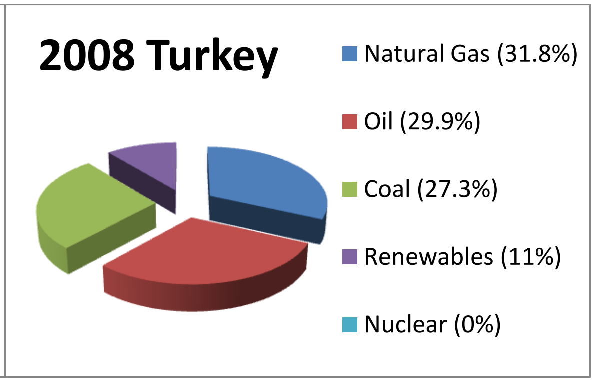


Figure 4.3. Comparison of fuel mix of total energy consumption between world & Turkey

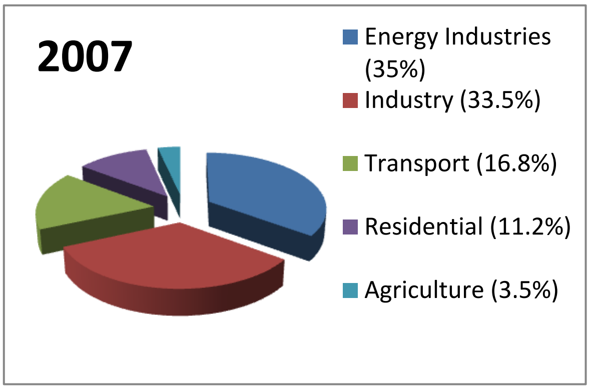


Figure 4.4. CO_2 emissions by sector: Turkey

Inspite of the fact that the energy consumption is increasing exponentially, the domestic energy production is not sufficient. According to the data given in 2009, just 30% of the total energy demand is met by domestic energy resources; the remaining 70% is imported from other countries. Currently 97% of natural gas demand, 93% of oil demand and 20% of coal demand is met by imports [33]. In 2007, it is estimated that 35% of CO_2 emissions occurred due to energy, 33.5% due to industry, 16.8% due to transportation, 11.2% due to residential and 3.5% due to agriculture (see Figure 4.4) [34]. The increase of CO_2 emission due to economical gowth and energy consumption in the past years is given in Figure 4.5. In 2020, it is expected that 40% of CO_2 emission will occur due to energy, 35% due to industry, 14% due to transportation and 11% due to other sectors [30].

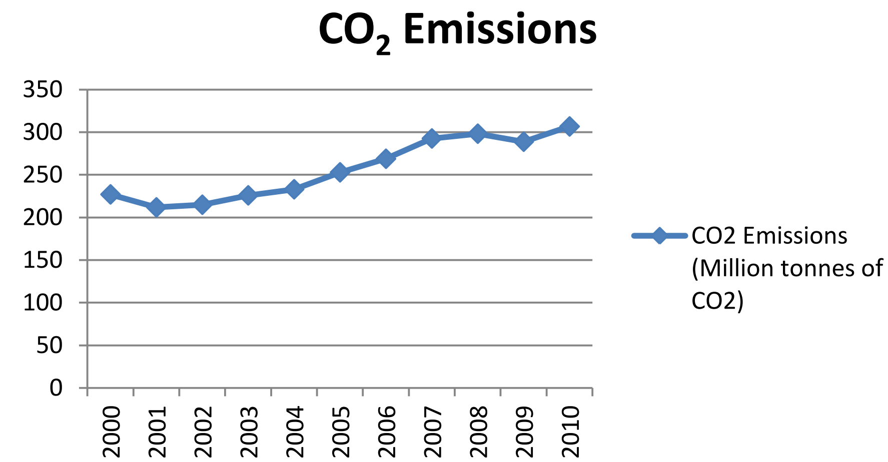


Figure 4.5. CO_2 emissions for Turkey [35]

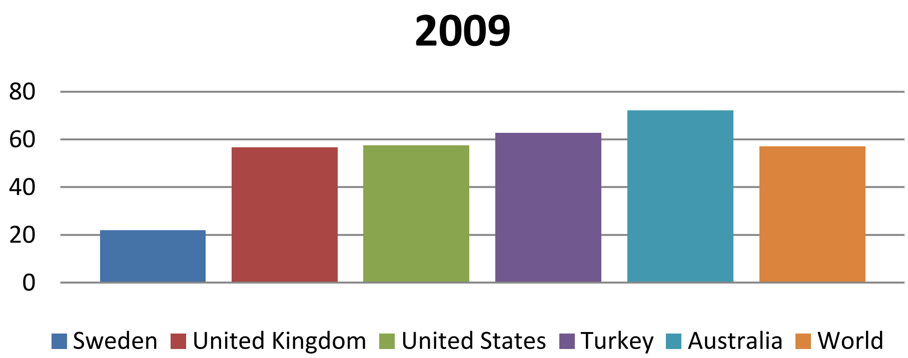


Figure 4.6. Comparison of CO_2 emissions/TPES [36]

Figure 4.6. shows the comparison of CO_2 emissions/TPES (total primary energy supply in terms of Terajoule) in several countries and world.

The CO_2 emission in Turkey was 307 million tonnes in 2010, and it is expected to increase. The incrase in the greenhouse gas emissions force Turkey to use more renewable energy sources. The percentage of each renewable energy used is given in Figure 4.7. Wood and biomass accounted 47% of the total renewable energy suppliers [31]. Turkey has a lot of renewable energy sources; such as solar energy, hydro power and geothermal energy (see Figure 4.8). However, lack of capital, high investment costs and technological issues does not allow Turkey to increase installed capacity of plants that uses renewable energy resources.

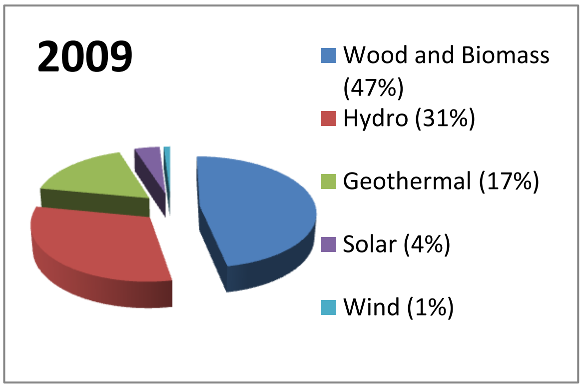


Figure 4.7. Turkey's renewable energy suppliers

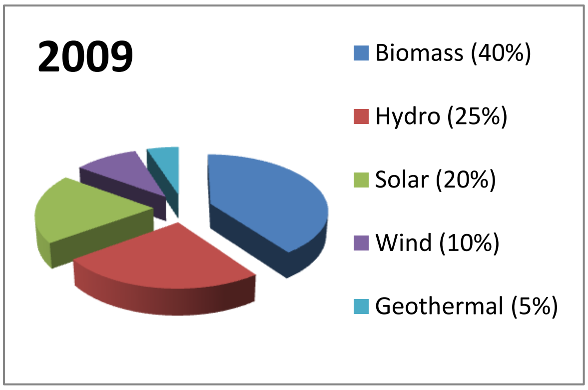


Figure 4.8. Turkey's economically feasible renewable energy potential [33]

Three major types of energy (electricity, heat and transportation fuel) are consumed by different sectors that can be seen in Figure 4.4. The percentage of electricity, heat and transportation fuel used for Turkey is given in Figure 4.5 [37]. The total energy production in Turkey in 2010 was around 210,2 billion kWh, and the energy consumption was 209,4 billion kWh. The Hydroelectric Plants Industry Businessmen's Association (HESİAD) states that Turkey's annual total energy demand in 2020 will be around 450 billlion kWh (1 billion Kwh = 1TWh). According to the report published by the Turkish Electricity Production Company (TEİAŞ), the electricity produced in Turkey in 2010 was composed 46% from natural gas, 25% from coal, 25% from hydroelectric plants and the rest through other liquid fuels and renewable energy sources [33]. Turkey is dependent on natural gas to a great extent in electricity generation.

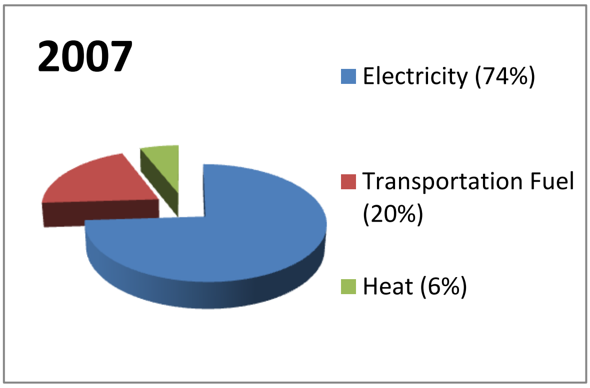


Figure 4.9. Types of energy used for Turkey

Since 2007, Turkey started and improved the energy efficieny applications with acceleration in several areas. According to the International Energy Agency (IEA), the energy efficiency applications include: (1) Decreasing the use of fossil fuels gradually, (2) applying sectoral energy efficiency standards and (3) increasing the use of biofuels [38]. These applications are important in order to decrease emissions. In the lights of these, Ministry of Energy and Natural Resources determinded the following four targets to be achieved by 2023: (1) To be able to make complete use of our potential of indigenous coal and hydraulic resources, (2) to make maximum use of renewable resouces, (3) to incorporate nuclear energy into electricity generation within the period until 2020, (4) to secure rapid and continous improvement in energy efficiency in a way that parallels to European Union countries [32].

5 Supply Potentials and Energy Conversion Technologies

Turkey does not have enough primary energy sources such as natural gas and oil. The largest energy source is coal. Almost 70% of the energy consumption is met by fossil fuels. The amount of fossil energy resources in Turkey can be seen in Table 5.1.

Sources	Apparent	Probable	Possible	Total
Hard coal (million tons)	428	449	249	1126
Lignite (million tons)	7339	626	110	8075
Asphaltite (million tons)	45	29	8	82
Bituminous schist (million tons)	555	1086	269	1641
Oil (million tons)	36	---	---	36
Natural gas (billion m^3)	8.8	---	---	8

Table 5.1. The amount of fossil energy resources in Turkey [30]

The huge usage of fossil fuels increases the search of alternative resources such as renewable energy sources. In fact Turkey has abundant reserves of renewable energy, such as hydro, solar, wind, biomass and geothermal energy. Turkey's economically feasible renewable energy potential exceed 495 TWh/year; which is almost 2.3 times of the current electricity consumption in Turkey (see Figure 5.1).

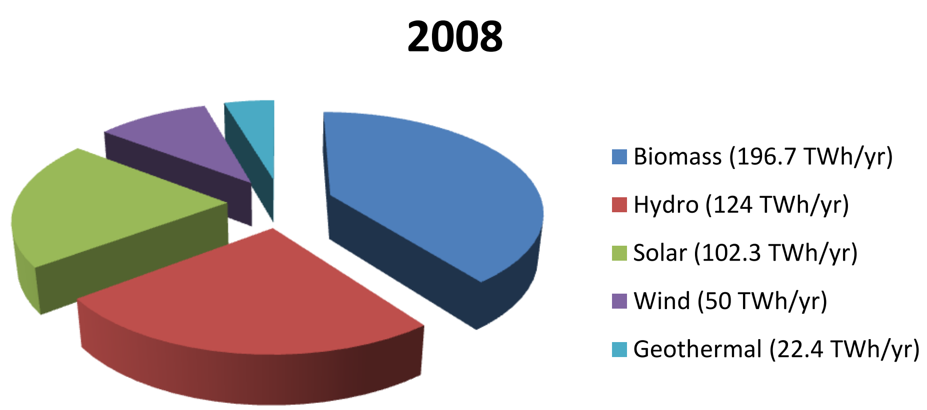


Figure 5.1. Turkey's economically feasible renewable energy potential [33]

5.1 Coal

Coal use in 2009 accounted for 31% of total primary energy supply, being the largest share among energy resources. Coal is a relatively cheap energy resource, it can be easily transported to the power station. In Turkey, there are high local lignite potential, diversity of important coal suppliers, and potential for high efficiency. These are the reasons why the coal share is the biggest; however, there is increased demand for imported coal, limited transportation capacity, low calorie of lignite

[39]. In addition to these problems, CO_2 emission is very high; 1 kWh of coal produces 1021 g of carbon [5].

In 2010, the coal consumption was 34.4 Mtoe (0.5% of world's total coal consumption), whereas the coal production was just 17.7 Mtoe (1% of the world's total coal production). Hence, 51% of the coal consumption is imported from other countries (see Figure 5.2). There is huge potential of coal (see Table 5.1). MENR aims to use the complete potential of indigenous coal [31].

Coal (Million tons)	Anthracite and Bituminus	Sub-bituminous and Lignite	Total	Share of Total (World)
Proved Reserves at end 2010	529	1814	2343	0.3%

Table 5.2. Proved reserves of coal at the end of 2010 [4]

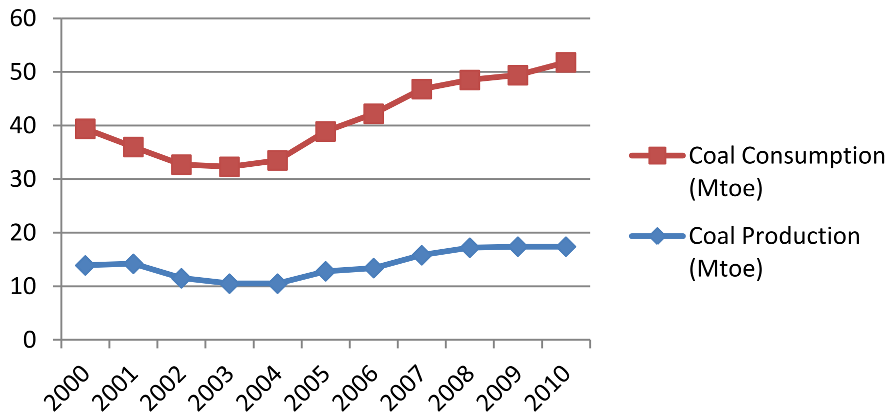


Figure 5.2. The amount of coal production and consumption between 2000-2010

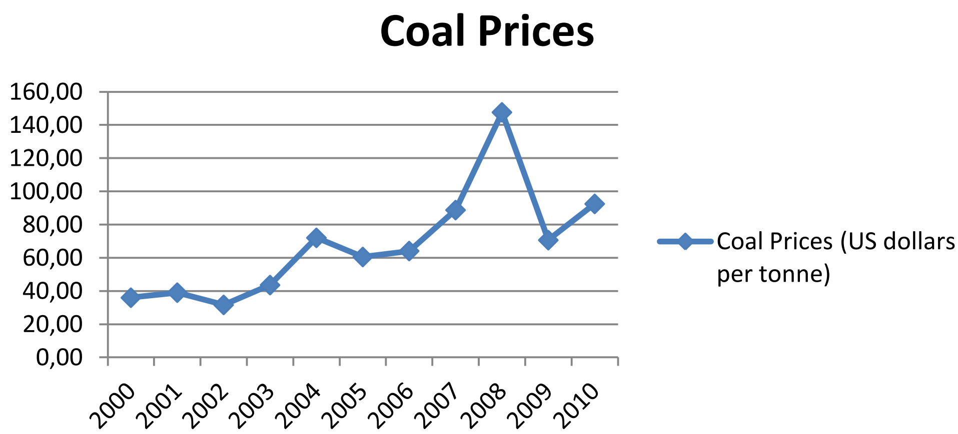


Figure 5.3. Coal prices between 2000-2010 [4]

5.2 Natural Gas

In 2009, natural gas accounted for 30.9% of total primary energy supply. Altough Turkey doesn't have sizeable reserves of natural gas, it is an important natural gas transit country. Turkey holds a strategic role between the world's second largest natural gas market (continental Europe), and the substrantial gas reserves of the Caspian Basin & the Middle East [40]. Natural gas has the least specific CO_2 emission among fossil fuels, 1 kWh of natural gas produces 355 g of carbon [5]. Natural gas plants have high conversion efficiencies and low investment costs (see Appendix 1). On the other hand, natural gas prices are unstable (see Figure 5.4) and using natural gas increases the dependecy to import and possibly supply problems [39].

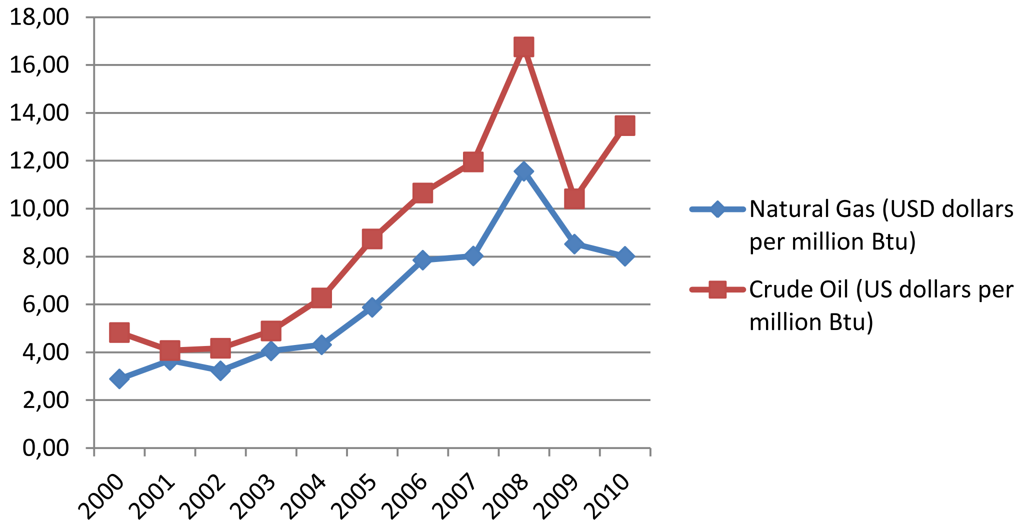


Figure 5.4. Natural gas and crude oil prices between 2000-2010 [4]

According to data given by CIA, natural gas production was 674 million cubic meters in 2010; whereas the natural gas consumption was 38.12 billion cubic meters [41]. Natural gas consumption in 2010 contributed 1.2% of the world's total natural gas consumption (see Figure 5.5).

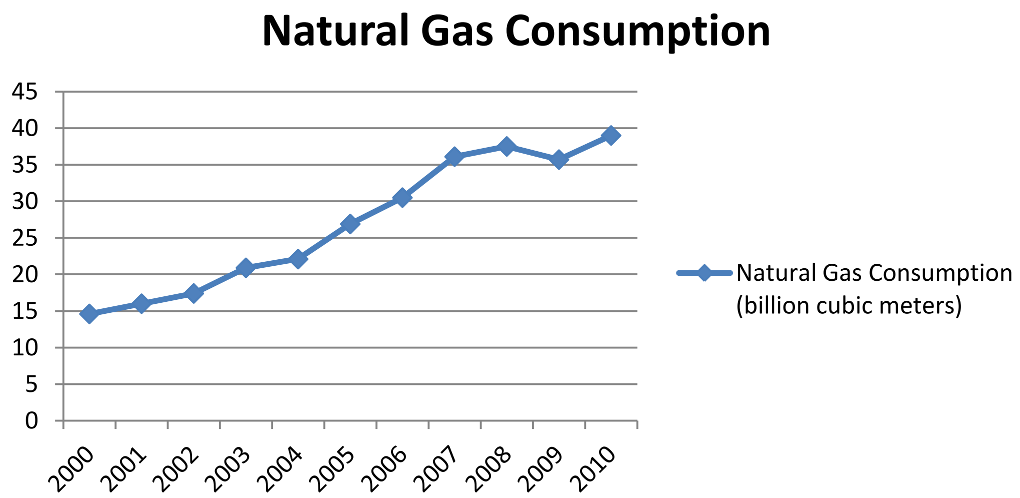


Figure 5.5. Natural gas consumption in Turkey between 2000-2010 [41]

The total natural gas exports and imports were 38,689 million cubic meters in 2010; where exports being 1.7% and imports being 98.3% of the total amount. Natural gas reserves in Turkey decline with time (see Figure 5.6).

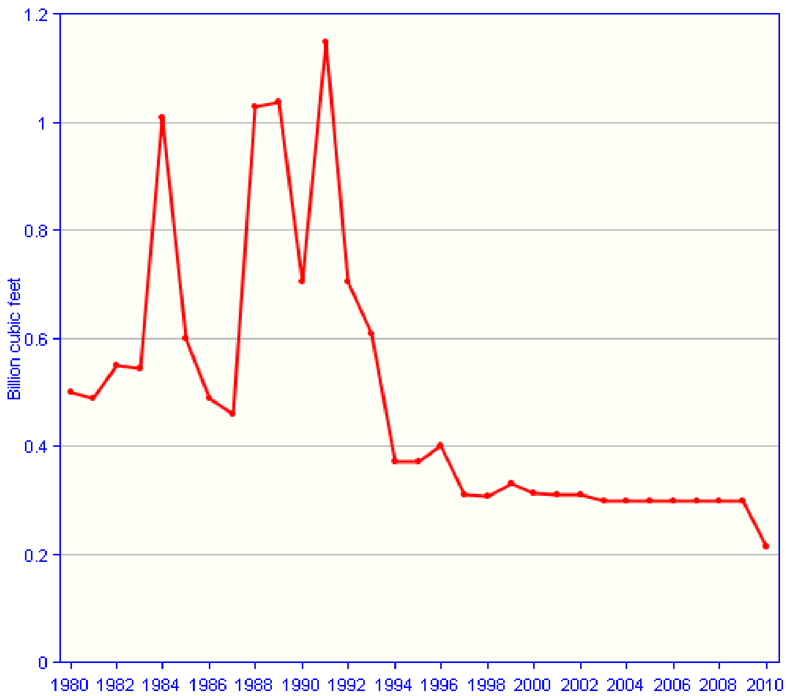


Figure 5.6. Natural gas reserves in Turkey [40]

5.3 Oil

Oil contributed 28.8% of total primary energy supply in 2009. Although Turkey is not a major oil producer, the location of the country makes an important oil transit country. 89.3% of Turkey's crude oil is imported mainly from Saudi Arabia, Iran, Iraq and Russia [4]. Using oil is advantageous because it can be widely and easily distributed over the world through rail and sea tankers, is easily combustible and large amount of energy can be generated. However, amount of oil will run out once the suppliers are used. Locating additional oil reserves are costly (see Appendix 1) and prices of oil are unstable (see Figure 5.4). The CO_2 emission is not high as coal; 1 kWh of oil produces 771 g of carbon [5].

Turkey's oil sector is mixed of state-owned, private and foreign companies. Oil exploration and production activities are dominated by the state-owned Turkish Petroleum Corporation (TPAO) which accounts for roughly 70% of Turkey's domestic oil production [39].

According to data published in 2010, the oil production was 55,110 barrels per day (bbl/day); and the oil consumption was 646,300 bbl/day [39]. Oil consumption in 2010 was 0.7% of world's total oil consumption [4]. The total amount of oil exports and imports (include both crude oil and oil) are 649,450 bbl/day; of this amount 10.6% is exported and 89.4% is imported. Proved oil reserves; proved reserves of crude oil; are 270.4 million bbl. Oil refinery capacities also decline like natural gas over years (see Figure 5.7).

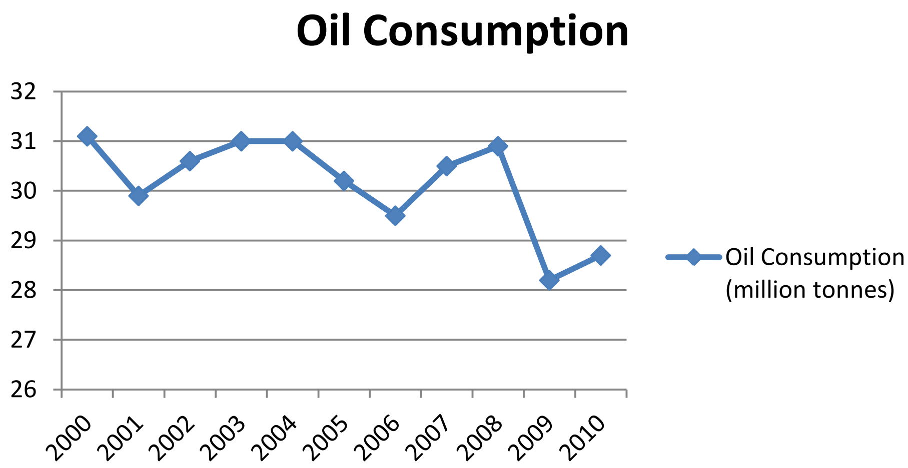


Figure 5.6. Oil consumption in Turkey between 2000-2010 [4]

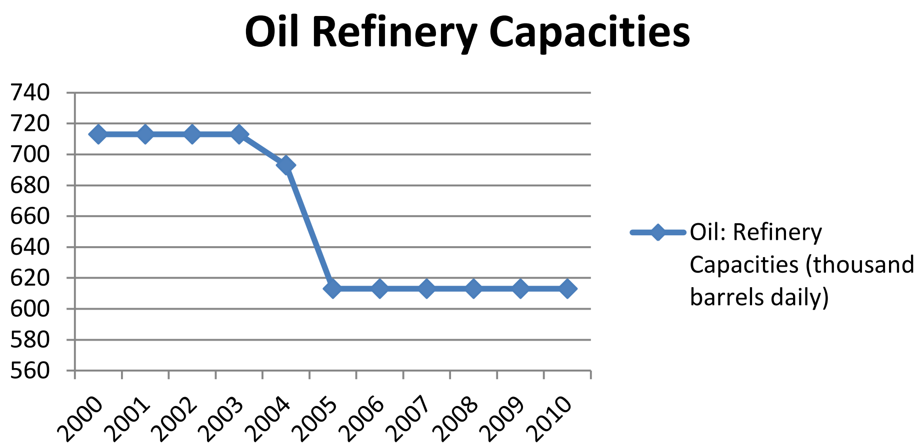


Figure 5.7. Oil refinery capacities in Turkey between 2000-2010 [4]

5.4 Biomass

Biomass use in 2009 was 4.4% of the total primary energy supply. Biomass is the major energy source in rural Turkey [42]. Biomass is carbon, hydrogen and oxygen based. Key biomass energy sources are garbage, wood, waste, landfill gases, and alcohol fuels. As an energy source, biomass can either be used directly, or converted into other energy products such as biofuel [43]. About 2/3 of current renewable energy production is obtained from bio energy. Bio energy is used to generate electricity, heating homes, providing process heat for industry and fuel vehicles.

The installed capacity in 2010 was 86.6 MW and electricity generated in these plants was 2,199 GWh/year [44]. Biofuel generation in Turkey was 10,000 ton in 2009 [31]. The annual biomass potential of Turkey is approximately 32 Mtoe. Total recoverable bioenergy is estimated to be 17 Mtoe [45]. Economically feasible biomass energy potential is 196.7 Twh/year.

5.5 Geothermal

Geothermal energy contribute 1.55% to the total energy supply. Geothermal energy is thermal energy generated and stored in the Earth [46]. Turkey is at the 2nd rank in all European Union countries and as the 7th in the world regarding its geothermal energy potential [47]. The potential is in "Alpine Himalayinic Belt". Fossil fuels will decline and geothermal energy will contribute in the replacement. The increase in the price of oil and gas make the geothermal energy resource more feasible.

During the last 10 years, Turkey increased the installed capacity of geothermal energy 130 MWt to 1177 MWt [48]. Installed geothermal power generation capacity in 2010 was 100 MW_e (see Figure 5.8). The total installed geothermal power forms 0.7% of the world's total geothermal capacity.

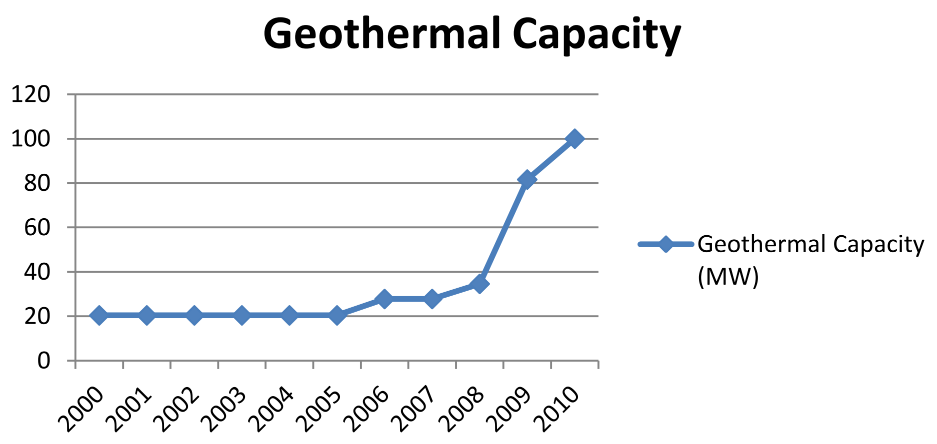


Figure 5.8. Cumulative installed geothermal power [4]

Direct use (district heating) installations are 795 MW_t. First district heating system was built in 1987. During 2001-2006, other 19 district systems were installed [49]. These show that geothermal energy will be a significant part of future energy supply. The overall geothermal energy potential is around 35,000 MW, where thermal energy is 31,500 MW_t and electrical energy is 4,500 MW_e. Economically feasible potential is 22.4 TWh/year. It is expected that geothermal energy will reach 6.3 Mtoe by 2020, accounting approximately 3% of the total national energy mix [50-52].

5.6 Hydropower

Hydropower contributed 2.9% of the total primary energy supply in 2009. For hydro energy Turkey is at 3rd rank in European Union countries; forming 1.2% total world potential [53]. Water resources are found in Southern and Eastern Black Sea.

During 2000-2008, the hydroelectricity installed capacity increased from 11,175 MW to 13,830 MW [44]. Total installed capacity in 2009 was 15,831 MW generating on average of 45.3 TWh/ year (see Figure 5.9). The share of hydroelectricity consumption in Turkey is 1.5% of the world's total consumption. Economically feasible hydro potential is 129.5 TWh/year. The gross theoretical small hydropower potential is 50 TWh/year; in which technical potential of 30 TWh/year and economical potential of 20 TWh/year. According to the governmental plan, it is expected that capacity of hyrdo power will reach 35,000 MW in 2020.

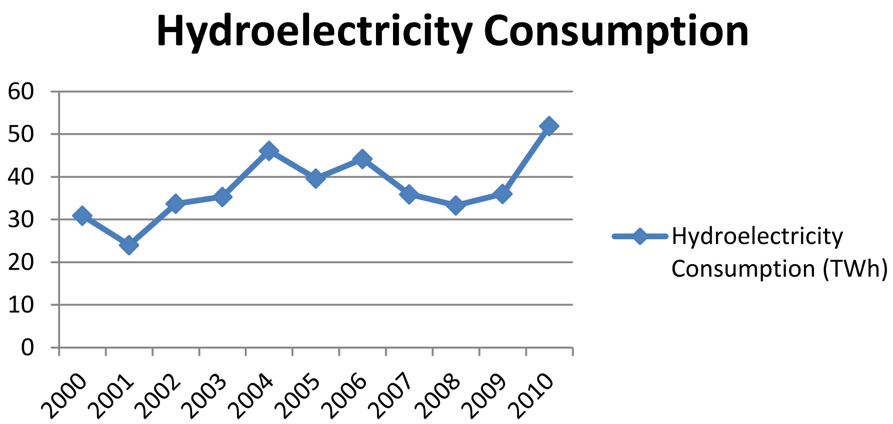


Figure 5.9. Hydroelectricity consumption between 2000-2010 [4]

5.7 Solar

Solar energy only contributed 0.4% to the total energy supply in 2009. Turkey is a promising country in solar energy potential regarding its geographical location; hence the potential in photovolatic market is very strong. Installed solar thermal capacity is 7.1 GW_t. Turkey is the 3rd largest producer of solar thermal power after China (84 GW_t) and Europe(15.5 GW_t) [54]. Total PV generation capacity is 6 MW_p (see Figure 5.10). The solar capacity in Turkey is 0.02% of the world's total solar capacity [4].

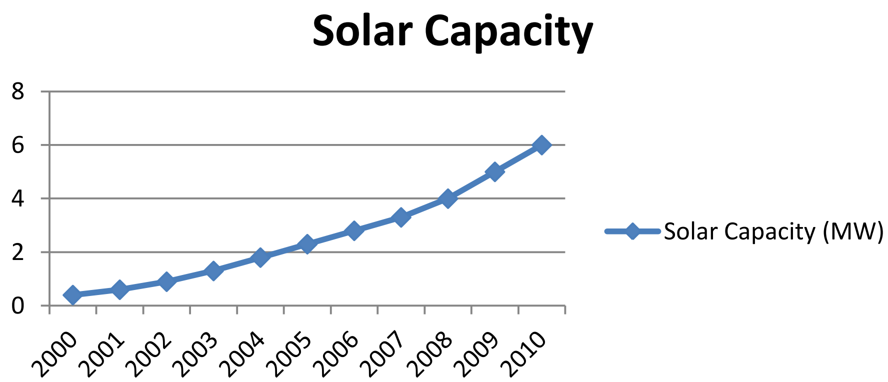


Figure 5.10. Cumulative installed photovoltaic power [4]

The annual average sunshine duration is 7.2 hours/day, while the average monthly total solar energy is 3.6 kWh/ m^2/day (see Table 5.3). The estimated total solar potential is 88 Mtoe/year, of which 40% can be used economically [55]. Economically feasible solar energy is 102.3 TWh/year, and potential is 380 TWh/year. Utilization of PV systems is very limited according to high installation costs. It is hoping that PV usage will increase in the future.

Months	Monthly Total Solar Energy (kWh/m^2-month)	Sunshine Duration (hours/month)
January	51.75	103
February	63.27	115
March	96.65	165

April	122.23	197
May	153.86	273
June	168.75	325
July	175.38	365
August	158.4	343
September	123.28	280
October	89.9	214
November	60.82	157
December	46.87	103
Total	1311	2640
Average	3.6 kWh/m²-day	7.2 hours/day

Table 5.3. The monthly average solar potential in Turkey

5.8 Wind

Wind energy use in 2009 only accounted 0.12% of the total primary energy supply. Wind energy is created when masses of air with differing temperatures switch places. Of the energy that reaches the earth from the sun, 1 to 2% is transformed to wind energy [56]. The use of wind energy is growing rapidly due to limited fossil fuels, environmental pollution, and global warming. It is one of the most widely used alternative sources of energy.

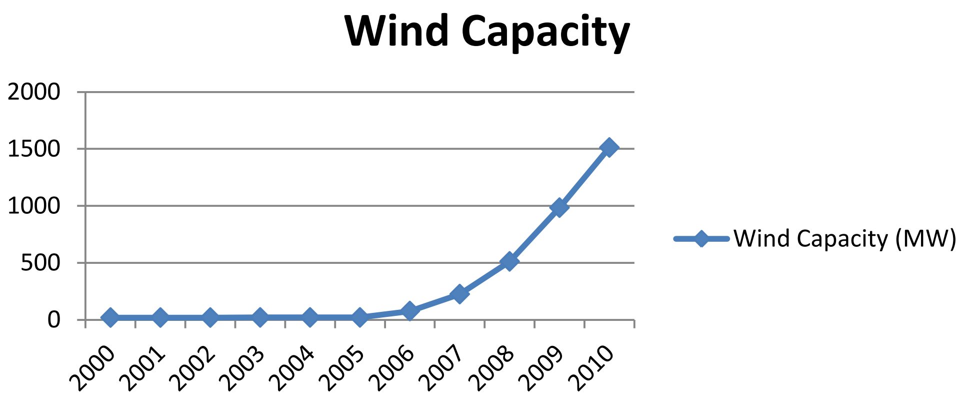


Figure 5.11. Cumulative installed wind turbine capacity [4]

For wind potential, Turkey is at the 3rd rank in European Union countries. Even, Turkey can meet all the electricity from wind energy [57]. Annual wind potential is around 160 TWh. However, Turkey has just 12 wind power plants. Installed capacity is 1512 MW (see Figure 5.11). The installed capacity is expected to reach 20,000 MW by 2023. Total technically available potential is 88,000 GW. Economically feasible potential is 11,000 MW [58,59]. Estimated wind potential is 48,000 MW.

5.9 Nuclear

Nuclear power is not included in this project, because there is no nuclear power in Turkey. In April 2006, the location of the first nuclear power plant has been decided. The power plant with the 1,800 MW capacity is scheduled to be built in 2014. Turkey is trying to build a nuclear power plant for more than 30 years, but the plans have been blocked by difficulties such as insufficient financing, legal issues, opposition from environmental and anti-nuclear groups [39].

6 Results

The solution of the model varies on chosen set of parameters. By changing the values of the parameters, we can understand their importance in terms of the measured effect to the objective function value. In order to apply different scenarios, four main categories of sensitivity analysis has been chosed. There are four different indicators for a model, which will be discussed furtherly for each sensitivity analysis: (1) objective function, (2) amount of used resources, (3) amount of installed capacities of technologies, and (4) the change of CO_2 emission over time.

6.1 A Scenario With no CO_2 Restrictions

Low Energy Demand

Under the assumption that there are no restrictions on CO_2 emissions, a mixture of coal, hydro and geothermal based energy system develops (see Figure 6.1). The transportation sector is run on coal based hydrogen. The heating sector is run on solar-heat based energy system.Inspite of the fact that solar heat system has a relatively higher investment cost at the begining, the conversion efficiency of this plant is very high. Finally, the electricity demand is just met with renewable energy source: pv, wind, hydro and geothermal energy (see Figure 6.2).

Total carbon emissions reach 170 million tonnes of CO_2 by 2025. Oil and natural gas consumption does not occur in this scenario, so just coal based CO_2 emission occurs. The CO_2 emission dependent on coal increases over time. The values of the emission at year 2015,2020 and 2025 given respectively as: 91, 124 and 170 million tonnes of CO_2.

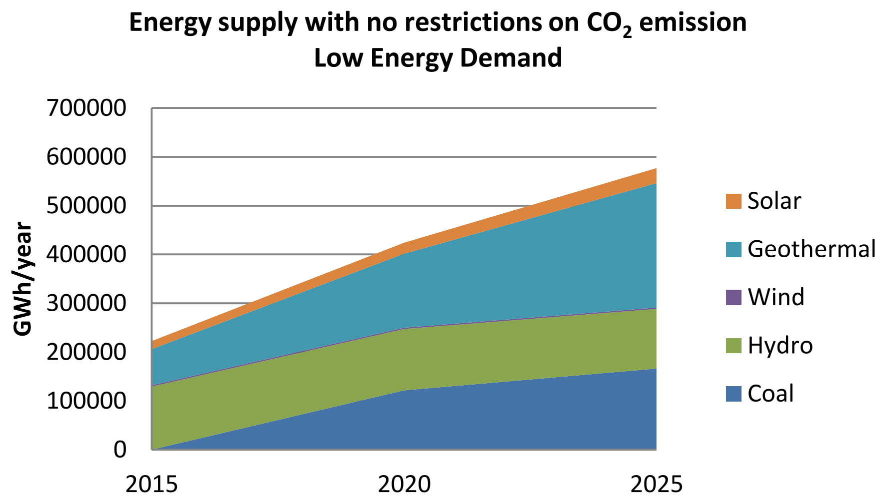


Figure 6.1. Energy supply with no restrictions on CO_2 emission

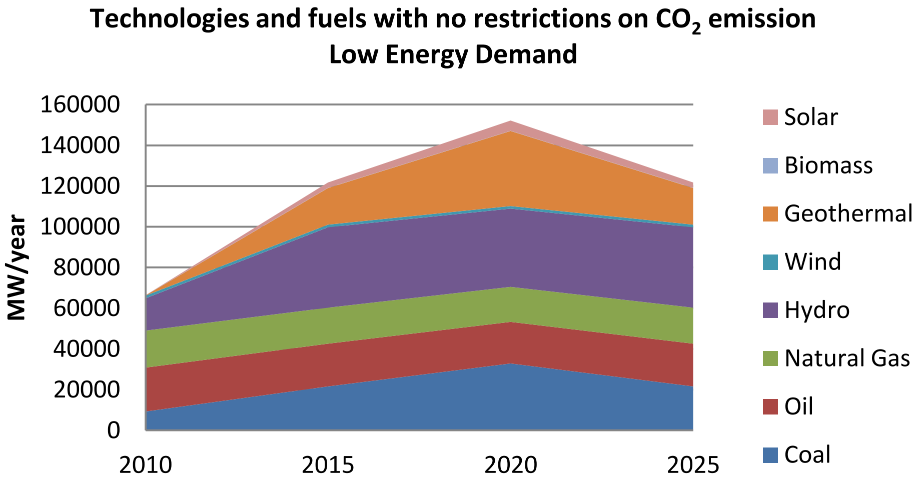


Figure 6.2. Installed capacities of technologies with no restrictions on CO_2 emission

High Energy Demand

In high energy demand scenario, the primary energy mix is again same; it is composed mainly from coal, hydropower and geothermal based energy sytem (see Figure 6.3). Since the transportation fuel demand is high in this case, the amount of used coal also increases. The reason of coal based hydrogen is preferred than coal based methanol is because of the conversion efficiency is higher for hydrogen. The heating sector is run on solar heat based energy system, with a higher amount of solar energy. Finally, the electricity demand is again met with renewable energy sources. In this case the amount of used wind energy is same, the hydropower is more and geothermal energy is less (see Figure 6.4).

Total carbon emissions with high energy demand senario reach 194 million tonnes of CO_2 by 2025; with a difference of 24 million tonnes of emission between low energy demand scenario. The market price of oil and natural gas is much more expensive from coal, that's why coal is preffered to satify the transportation fuel demand. The CO_2 emission dependent on coal increases over time. The values of the emission at 2015 and 2025 are calculated as 95 and 136 million tonnes of CO_2.

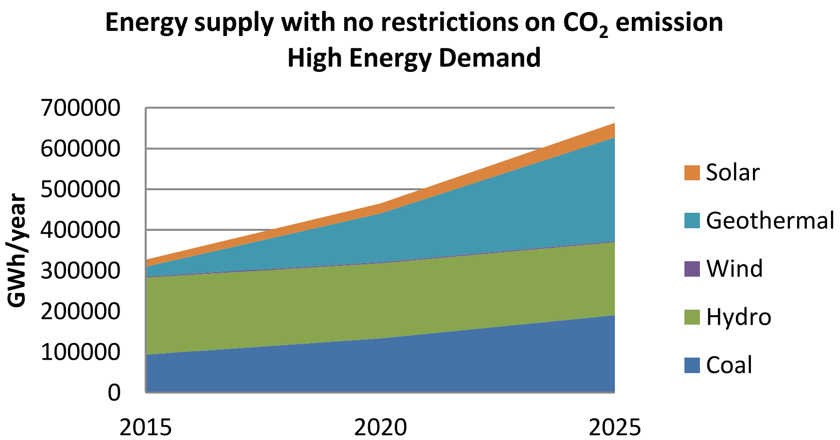


Figure 6.3. Energy supply with no restrictions on CO_2 emission

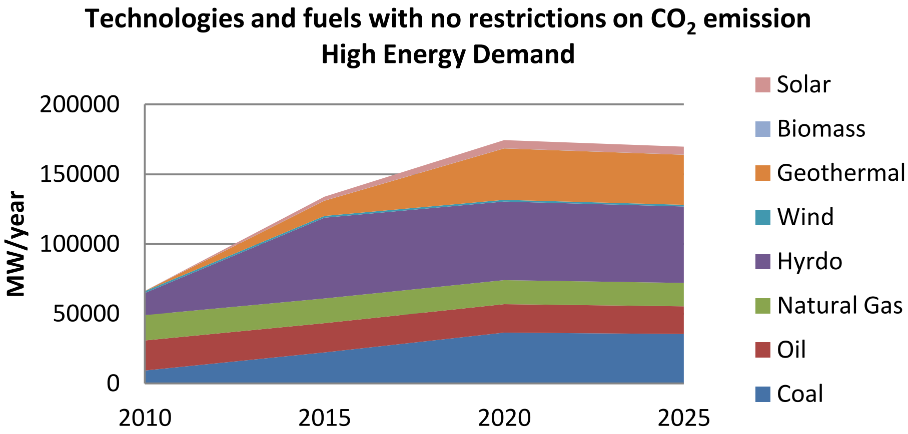


Figure 6.4. Installed capacities of technologies with no restrictions on CO_2 emission

6.2 Stablising Atmospheric CO_2 Concentration

Low Energy Demand

The purpose of this study is to look at the energy sector under CO_2 restrictions. In order to meet an atmospheric CO_2 stabilisation target of 100 million tonnes of CO_2, a change is needed in the mixture of primary energy supply and installed capacities of technologies (see Figure 6.5). In the previous scenario given in Section 6.1, there were no restrictions on CO_2 emission so that coal used to meet all the transportation fuel. However, in this scenario, during the period 2020-2025 the coal usage decreases and solar hydrogen and natural gas increases. The emission factor for natural gas is lowest among all fossil fuels. And solar hydrogen does not produce any carbondioxide. For the electricity demand, the mix of primary energy supply stays same for wind, hydro, solar and geothermal energy. Additionally, the heating sector is run on solar-heat based energy system (see Figure 6.6).

Total carbon emission with stablising atmospheric CO_2 concentration decreases to 70 million tonnes of CO_2 by 2015. This is mainly becuase of the reason coal based hydrogen changes into solar hydrogen and natural gas. The coal based CO_2 emissions for years 2015, 2020 and 2025 are 91, 124 and 44 million tonnes of CO_2. The natural gas based CO_2 emission occurs between years 2020-2025 with a total amount of 26 million tonnes of CO_2.

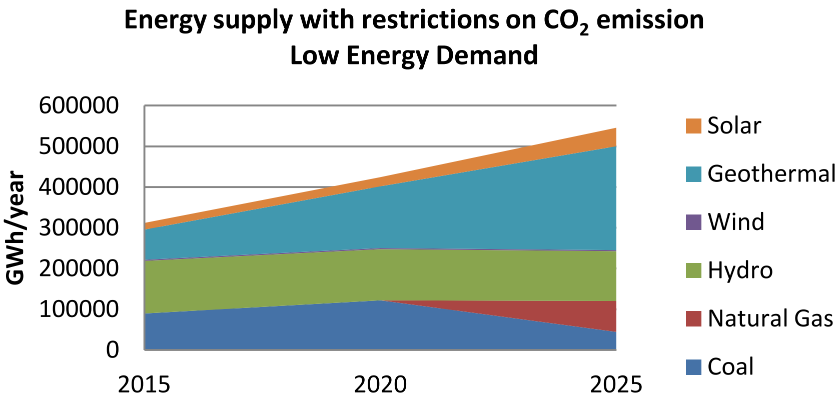


Figure 6.5. Energy supply with restrictions on CO_2 emission

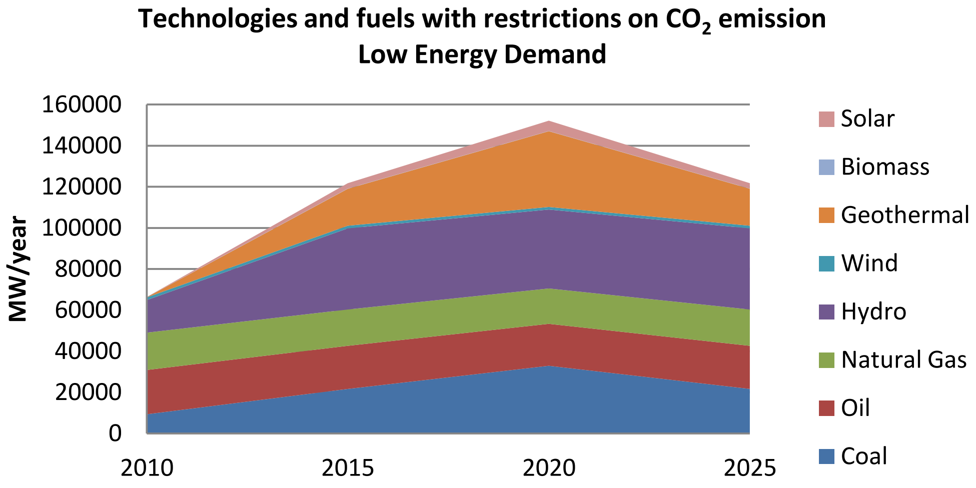


Figure 6.6. Installed capacities of technologies with restrictions on CO_2 emission

High Energy Demand

In high energy demand scenario, the primary energy mix again based on first hydropower, then geothermal energy and coal (see Figure 6.7). The transportation fuel is composed from coal based hydrogen between years 2010-2020, and a mix of solar-hydrogen and natural gas based hydrogen between years 2020-2025. This is because the restriction on CO_2 that the emission should be less in 2025. Heating is again based on solar-heating system. Electiricity energy primary supply mix is from renewable resources: hydropower, geothermal, solar and wind energy (see Figure 6.8).

According to Business As Usual (BUA) scenario with no CO_2 emission constraints, for the transportation fuel mix, coal based hydrogen consumption increases between 2010-2020 and then decreases between 2020-2025. The remaining prouduction is done with solar-hydrogen. Hence, the total consumption in 2025 is less, with an amount of 44 million tonnes of CO_2. The other difference occurs in the consumption of electricity. The use of hydropower increases whereas the geothermal energy consumption decreases.

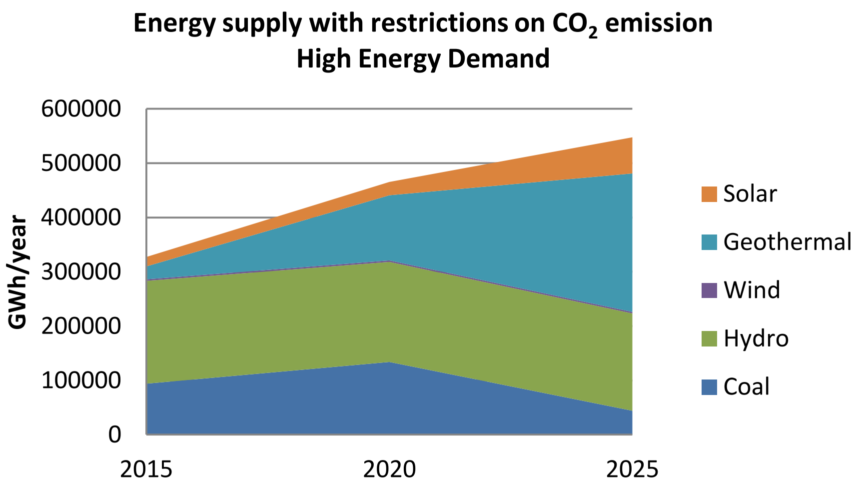


Figure 6.7. Energy supply with restrictions on CO_2 emission

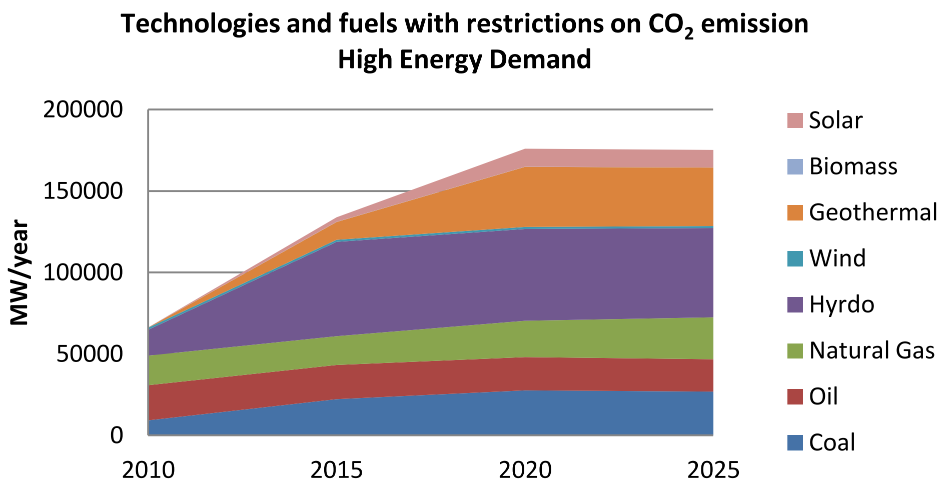


Figure 6.8. Installed capacities of technologies with restrictions on CO_2 emission

6.3 Sensitivity Analysis

In this section, three energy parameters are chosen to perform sensitivity analyses. The first one is the carbon tax, second one is the biomass price, and the last one is the market price of oil and natural gas. The least cost set of technologies and the total cost of the system vary depending on these different set of parameters. The detailed explanations for each scenario are given in Table 6.1.

PARAMETERS	SENARIO 1	SENARIO 2	SENARIO 3
1. Carbon tax	Carbon tax = 0	Carbon tax = 50$/tonC	Carbon tax ≥ 150$/tonC
2. Biomass price	Biomass price < Oil price	Biomass price = Oil price	Biomass price > Oil price
3. Oil and natural gas price	Market price increase 2.7% annually	Market price increases two time faster	Market price increases three time faster

Table 6.1. Explanations of the scenarios for each chosen parameter

Carbon tax=50$/tonC

We already analyzed the model where there is no carbon tax in the beginning; it is the Business-As-Usual (BAU) scenario where there is no restrictions on CO_2 emission. In this setting, the unit cost related with the fossil fuel increases, so the model aims to use less amount of fossil fuels (see Figure 6.9). For the electricity production, supply mix is the same as BAU; which depends just on renewable energy sources. The heating sector as well is just dependent on the solar-heat based energy system. The only difference is the supply mix for the transportation fuel demand. When there were no restrictions on CO_2 emissions, it was based on coal-hydrogen based system; however with this scenario the demand is produced by natural gas-hydrogen system between 2010-2015, and solar-hydrogen based system between 2015-2025 (see Figure 6.10). Total carbon emissions; which is 24 million tonnes of CO_2 is less in this scenario; which was 170 million tonnes of CO_2 in BAU. The emission is dependent on the natural gas consumption for the transportation fuel which happened between 2010-2015.

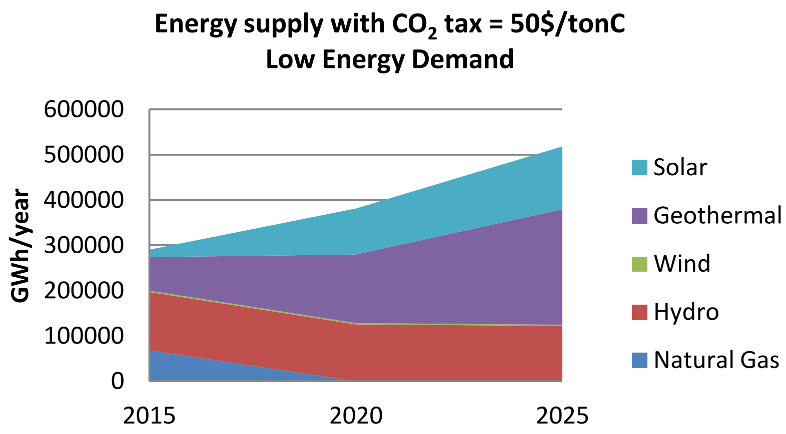


Figure 6.9. Energy supply with CO_2 tax = 50$/tonC

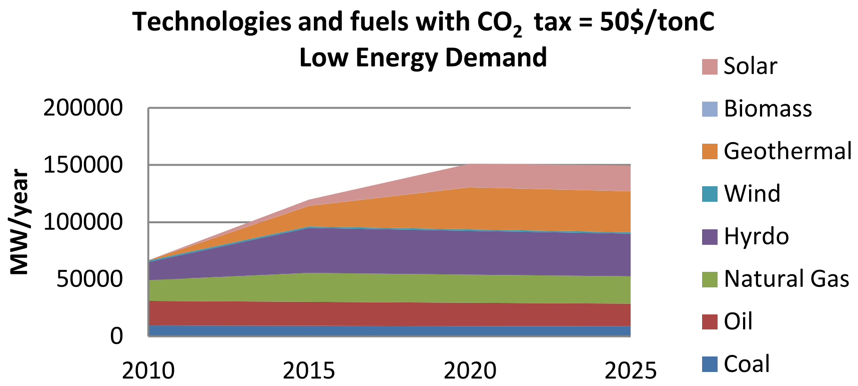


Figure 6.10. Installed capacities of technologies with CO_2 tax = 50$/tonC

Carbon tax ≥ 150$/tonC

When the carbon tax increases to 150$/tonC, the fossil fuel consumption becomes zero (see Figure 6.11). In this scenario the transportation fuel demand is met with solar-hydrogen based energy system. The primary energy mix for the demand of electricity and heat is the same when the carbon tax is 50$/tonC (see Figure 6.12). Hence, there is no CO_2 emission.

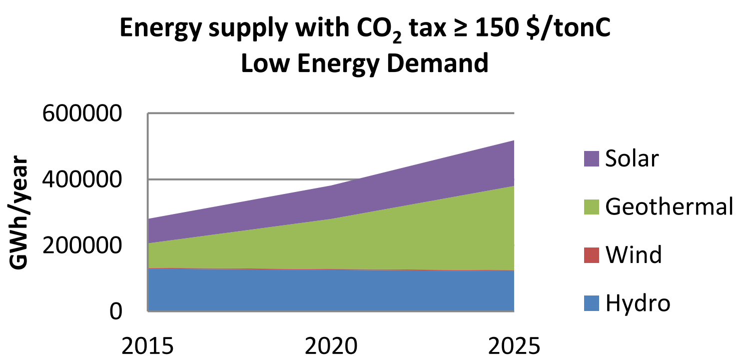


Figure 6.11. Energy supply with CO_2 tax ≥ 150 $/tonC

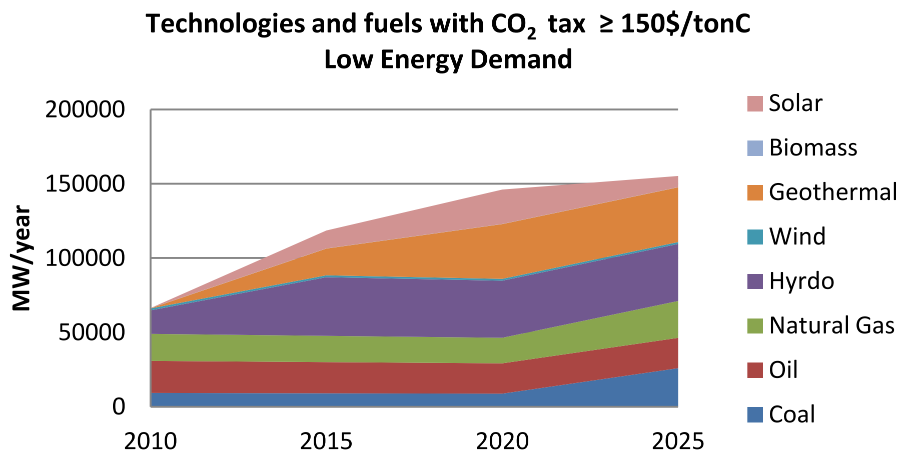


Figure 6.12. Installed capacities of technologies with CO_2 tax ≥ 150 $/tonC

Biomass,natural gas and oil costs

As stated in Table 6.1, different values of biomass cost were selected to perform analyses as well as the oil and natural gas market price. In neither of cases, there are differences on the total cost & the choices of fuel. All the scenarios lead to a same solution, which is the one explained with carbon tax ≥ 150$/tonC.

6.4 Cost Analysis

The objective function is defined as the total cost of the proposed energy system. The results are given below for each defined scenario.

	Description	Low energy demand	High energy demand
Scenario 1	No restrictions on CO_2 emission	11 bilion $	13 billion $
Scenario 2	Restrictions on CO_2 emission	17 bilion $	21 billion $

Table 6.2. Comparison of total cost varying the restriction on CO_2 emission

Table 6. 2 indicates the differences between the total costs for two scenarios where the difference is the restriction on CO_2 constraint. When there is no constraint, the model decides to use coal, which is a relatively cheap resource; however when there are restrictions model decided to use solar-hydrogen with a relatively higher market price and investment cost. The increase of the total cost in the 2nd scenario depends on these different amount of resources.

	Description	Low energy demand	High energy demand
Scenario 3	CO_2 tax = 0	11 bilion $	13 billion $
Scenario 4	CO_2 tax = 50$/tonC	40 bilion $	44 billion $
Scenario 5	CO_2 tax ≥ 150$/tonC	41 bilion $	46 billion $

Table 6.3. Comparison of total cost with varying CO_2 tax

Table 6.3. shows the differences between total cost when carbon tax is introduced to the system. When there is no tax and restrictions, even if there is a usage of fossil fuels, it does not reflect to the defined cost. That’s why in scenario 3 the total cost is very low according to scenarios 4 and 5. When carbon tax increases with the same amount of energy demand scenario, there is no fossil fuel consumption. So the increase is because of the usage of solar-hygrogen which has a relatively higher market price and investment cost according to the coal-based energy system.

7 Conclusion

The purpose of this paper is to construct a model of an energy system by using optimization and to implement this model by using Turkey as an example. The challenge in this process is to find the right values for the parameters. There are two major problems regarding the energy sector in Turkey; currently just 30% of the energy consumption met with domestic resources. And the contribution of renewable energy sources to energy production is 9.7%. Turkey currently is in the ongoing process on regulations in energy sector. Ministry of Energy and Resources seeks to increase domestic energy supply and energy efficiency by managing the following targets [31]. There are large coal reserves and Turkey is expected to increase their use. Remaining potential for hydro and wind power will be utilized. There are extensive plans for solar and geothermal energy, and nuclear power is aimed to be introduced to the energy sector in Turkey. The challenge in modelling is that finding the right parameters for the system.

The choosen methodology was to develop a local energy systems model. This is done by using a bottom-up approach optimization model. The model aims to minimise the total cost related with energy sector given the energy demand for the next 15 years. The only environmental concern is the concentration of CO_2 emission in the atmosphere. The solution of the problem is optimal and unique.

What are the main results and how these results should be interpreted?

- Electricity generation is based on renewable energy sources which are wind, solar, geothermal and hydropower energy. Turkey has lots of domestic coal reserves, and the usage of coal-based hydrgoen energy system is proposed to meet with the transportation fuel demand. Additionally, heat production is done with solar-heat enegy system.
- The CO_2 emission should be lower in order to increase the sustainability. Fossil fuels are expected to deplete in few decades, so more focus should be given to the renewable energy conversion technologies. Turkey has a huge potential for all renewable energy sources, so the usage of these resources should be utilized in order to have a sustainable energy and more clean environment.
- The model aims to reduce the total cost and increase the energy efficiency. The solution based on this model is solved with mathematical programming which gives an optimal solution. Sensitivity analyses with respect to different set of parameters show that the solution is model robust.

As a future work the following targets may be achieved:

- More sensitivity analyses depend on the different set of parameters can be done. Monte carlo simulation which is a problem solving technique used to approximate the probability of certain outcomes by running multiple trials using random can be done. In addition to this, shadow price of constraints can be found. It is the change in the objective value of the optimal solution by relaxing the constraint by une onit.
- Finally, more accurate analysis of the future possible technologies and the future energy demand prediction can be done. It should be pointed out that studies of future technologies and demands choices are highly uncertain, and the difference of these values may have a big effect on the result.

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APPENDIX 1. Conversion efficiencies and investment costs

Table A.1. The conversion efficiency and the cost of power plants

Resource	Conversion Efficiency	Investment Costs [USD/kW_e]
Coal	41%	1691
Oil	51%	955
Natural Gas	51%	795
Biomass	28%	2642
PV	n.a.	4700
Wind	n.a.	1692
Hydro	n.a.	1440

Table A.2. The conversion efficiency and the cost of heat plants

Resource	Conversion Efficiency	Investment Costs [USD/kW_{Th}]
Coal	75%	340
Oil	87%	248
Natural Gas	91%	118
Biomass	81%	480
Solar Heat	98%	980
Geothermal	100%	518

Table A.3. Energy conversion into hydrogen

Resource	Conversion Efficiency	Investment Costs [USD/kW_{H2}]
Coal	65%	1691
Oil	75%	955
Natural Gas	85%	495
Biomass	65%	2642
Solar Hydrogen	n.a.	5000

Table A.4. Energy conversion into methanol

Resource	Conversion Efficiency	Investment Costs [USD/kW_{MeOh}]
Coal	60%	1691
Natural Gas	70%	595
Biomass	60%	2642

Source: The estimates are based on the working document of “Commission of the European Communities”, which is called as “Energy Sources, Production Costs and Performance of Technologies for Power Generation, Heating and Transport”.