ANALYSIS OF CO_2 EMISSIONS RESULTING FROM ELECTRICITY SECTOR IN TURKEY BY USING BOĞAZİÇİ UNIVERSITY ENERGY MODELING SYSTEM (BUEMS) MODELING FRAMEWORK

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ABSTRACT

ANALYSIS OF CO_2 EMISSIONS RESULTING FROM ELECTRICITY SECTOR IN TURKEY BY USING BOĞAZİÇİ UNIVERSITY ENERGY MODELING SYSTEM (BUEMS) MODELING FRAMEWORK

Due to factors such as industrialization, increase in population and economic growth electricity demand has shown a significant increase at global scale. This increase has put forward discussions concerning electricity supply security, source diversification and clean electricity generation. Fossil based electricity generation featured the transition to clean generation in this sector. Particularly, towards the goal of the Paris Agreement, policy developments have gained momentum to reach carbon neutral electricity sector by 2050. These developments have been closely monitored by Turkey. The purpose of this thesis is to evaluate long-term results of the CO_2 emissions resulting from electricity sector in Turkey by using BUEMS model in line with latest available data and updated policy papers. Total electricity installed capacity, generation portfolio and increase in electricity demand were investigated. In the context of the thesis, a Base scenario was established. The response of the electricity sector under carbon tax and emission restrictions and their effect to CO_2 emissions were analyzed.

The results of the study showed that tax and emission targets played an important role for CO_2 emission reduction. In Base Scenario, Total CO_2 emissions exceeded 1,000 Million tons and electricity sector's contribution was almost 680 Million tons in the year 2057. Among all scenarios the highest decrease was obtained under Peak Emission Scenario. Total emissions reduced to 705 Million tons and emissions from electricity sector decreased by 61% compared to Base Scenario and fell to 244 Million tons in 2057 by means of renewables and nuclear penetration.

ÖZET

TÜRKİYE’DE ELEKTRİK ÜRETİMİ KAYNAKLI CO_2 EMİSYONLARININ BOĞAZİÇİ ÜNİVERSİTESİ ENERJİ MODELLEMESİ SİSTEMİ (BUEMS) KULLANILARAK ANALİZİ

Hızlı sanayileşme, artan nüfus ve ekonomik büyüme gibi faktörlerin etkisiyle küresel ölçekte elektrik talebi önemli ölçüde artış göstermiştir. Bu artış, elektrik arz güvenliği, kaynak çeşitliliği ve temiz elektrik üretimi gibi tartışmaları da beraberinde getirmiştir. Fosil yakıt bazlı elektrik üretimi kaynaklı sera gazı emisyonları bu sektördeki temiz üretime geçiş sürecini ön plana çıkarmıştır. Bu doğrultuda, özellikle Paris Anlaşması doğrultusunda en geç 2050 yılında karbon nötr bir elektrik üretim sistemi için politika çalışmaları hız kazanmıştır. Ülkemizde de söz konusu gelişmeler yakından takip edilmekte ve elektrik sektörünün geleceğine yönelik politikalar ve stratejiler belirlenmektedir. Tezin amacı, Boğaziçi Üniversitesi Enerji Modellemesi Sistemi (BUEMS) kullanılarak mevcut güncel veriler, kısa vadeli hedefler ve politika belgeleri doğrultusunda Türkiye’de elektrik sektörü kaynaklı CO_2 emisyonlarının uzun dönemli sonuçlarını ortaya koymaktır. Bu çerçevede, elektrik üretim kurulu gücü, üretimin kaynaklara göre dağılımı ve elektrik talebinde yaşanacak artış gibi unsurlar incelenmeye çalışılmıştır. 2057 yılına kadar Baz senaryo oluşturulmuş olup, karbon vergisi, emisyon kısıtlaması hedefleri altında elektrik sektörünün nasıl şekillendiği ve bunun CO_2 emisyonlarına olası etkileri senaryo bazlı analiz edilmiştir.

Çalışmanın sonuçları vergi ve emisyon kısıtı uygulamalarının CO_2 emisyonlarının azaltımında önemli rol oynadığını göstermiştir. Baz senaryo sonucunda toplam emisyon değeri 1,000 Milyon ton değerini aşmış, elektrik üretimi kaynaklı emisyonlar 2057 yılı için 687 Milyon ton değerine ulaşmıştır. Tüm senaryolar arasında en düşük emisyon değeri Pik Emisyon Senaryosu altında elde edilmiştir. Bu senaryo sonunda 2057 yılında toplam emisyon değeri 705 Milyon tona gerilerken elektrik üretimi kaynaklı emisyonlar, artan yenilenebilir ve nükleer kaynaklı üretimle, %61 oranında azalarak 244 Milyon tona kadar düşmüştür.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**	**Unit**
CO_2	Carbon Dioxide	Million Tons

Abbreviation	**Explanation**
AGE	Applied General Equilibrium Models
BUEMS	Boğaziçi University Energy Modeling Framework
BUENAS	Bottom- Up Energy Analysis System
CCS	Carbon Capture Storage
CEA	French Atomic Energy Agency
CGE	Computable General Equilibrium Model
CIMS	Canadian Integrated Modelling System
CO2	Carbon Dioxide
DICE	The Dynamic Integrated model of Climate and the Economy
DREAM	Dynamic Resource/Environment Applied Model
E3ME	The Energy-Environment-Economy Model for Europe
E3MG	The Energy-Environment-Economy Model of the Globe
EIA	US Energy Information Administration
ETM	Energy Technology Model
ETSAP	Energy Technology System Analysis Program
GDP	Gross Domestic Product
GEM-E3	General Equilibrium Model for Economy Energy Environment
GEMINI-E3	General Equilibrium Model of International–National-Interaction for Economy-Energy
GHG	Green House Gas
GREEN	The General Equilibrium Environmental Model
IAM	Integrated Assessment Models
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IPCC	International Panel on Climate Change
LEAP	The Long-range Energy Alternatives Planning
LP	Linear Programing

MAED	Model for Analysis of Energy Demand
MARKAL MACRO	Market Allocation Model Combined with a Macro Model
MARKAL MICRO	Market Allocation Model Combined with a Micro Model
MARKAL	Market Allocation
MENR	Ministry of Energy and Natural Resources
MESSAGE	Model for Energy Supply Systems and Their General Environment
MIDAS	Multinational Integrated Demand and Supply Model
MIND	Model of Investment and Technological Development
MURE	Mesures d'Utilisation Rationnelle de l'Energie
NEMS	National Energy Modeling System of USA
NEMS-RSDM	National Energy Modelling System – Residential Sector Demand Module
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
PAMS	Policy Analysis Modeling System
POLES	Prospective Outlook on Long-term Energy Systems
PRIMES	Price Induced Market Equlibrium System
REEPS	Residential End-Use Energy Planning System
RICE	Regional Integrated Model of Climate and the Economy
SCREEN	Hybrid Bottom-Up Computable General Equilibrium Model
TEİAŞ	Turkish Electricity Transmission Operator
TIMES	The Integrated MARKAL-EFOM System
TÜİK	Turkish Statistical Institute
WEM	World Energy Model
WITCH	The World Induced Technical Change Hybrid

1. INTRODUCTION

Starting from the early 2000’s, Turkey has accomplished rapid development in many fields particularly in country’s economy. Inevitably, this economic growth brought significant increase in energy consumption in every sector, therefore Turkey has given priority to diversify its energy sources and to develop new energy strategies. These strategies have been built on energy supply security, use of alternative energy sources, bringing domestic resources into economy, reliable energy markets and energy efficiency. Within this context several policies have been implemented.

As a result of these developments, in April 2017 Turkey put forward a key policy and The National Energy and Mining Policy was announced by Ministry of Energy and Natural Resources (MENR). The policy is based on three main pillars and substantially is aiming to enhance Turkey’s energy perspective by improving energy supply security, increasing the use of domestic energy resources and providing foreseeable energy market.

Recently published official documents, such as MENR Strategic Plan (2019-2023) and 11th Development Plan, are in line with this latest policy. From electricity sector point, the main target is to increase the share of domestic resources, particularly renewable and domestic coal, by reducing the share of imported resources to decrease energy related budget expenditure.

For that purpose, Turkey has made significant achievement in renewables in the past decade due to the contribution of strong supportive energy policies and favorable investment climate and thus; the share of renewables in electricity generation and total installed capacity reached 44% and 49% respectively by the end of 2019. Moreover, 10 GW solar and 10 GW wind additional capacity investments are planned between 2017-2017 mostly through Renewable Energy Zones.

Apart from renewables, nuclear power plant program will also provide source diversification in electricity generation and enhance decarbonization policies. By 2023 the first unit, 1.200 MW of Akkuyu Nuclear Power Plant (NPP), being 4.800 MW in total, will be operational. Turkey is planning to install three nuclear power plants in the upcoming period.

On the other hand, although there are short term projections in electricity sector in the abovementioned official documents, it is possible to comment that there is a need to conduct various long-term energy and related environmental effects, such as CO_2 emissions, projections for the

Turkish energy system. Particularly, after the signing of the Paris Agreement in 2015 during COP21 meetings in Paris, the current trend in the global electricity generation is to move towards more clean energy resources and to achieve net-zero emission targets in electricity generation without disrupting security of electricity supply. As of 2018 energy related CO_2 emissions represents 85.8% of total CO_2 emissions and energy sector emissions increased by 177% in 2018 compared to 1990 levels. Emissions stemming from electricity and heat production constitutes an important component in total emissions and in 2018 CO_2 emissions from electricity and heat production represents 41.4% of CO_2 emissions from fuel combustion which was 25.3% in 1990 (TÜİK, 2020). Hence, this trend requires strong future policy design for energy sector and realistic modelling tools for policy-makers.

Therefore, in this study Boğaziçi University Energy Modeling System (BUEMS) was used in order to provide long-term distribution of resource-based electricity generation, installed capacity and related CO_2 emissions. BUEMS is a bottom-up approach energy-economy-environment modelling framework under cost optimization. It was first proposed by Işık, (2016) and used to model Turkish energy system as a whole under different scenarios. However, there is a need to update of the model based on the latest policy developments and available data. The aim of this study is to make future projection of CO_2 emissions stemming from electricity generation under different scenarios by using the most accurate and available data.

2. LITERATURE REVIEW

Energy models are utilized to predict the future of energy demand and supply at global or country and region scale. In order to carry out these projections, energy models are using some assumptions such as the development of macro-economic activities, change in population, energy commodity prices and available current energy balance data. Their outputs are used to evaluate future energy policy, technology changes and new necessary investments. (Herbs et al., 2012). As a well - known fact, energy modeling issue has been introduced in the early 1970's due to oil crisis. Since then, numerous types of modeling approaches have been developed over time (Herbs et al., 2012).

From energy-economy perspective, there are two accepted modeling approaches for the numerical evaluation of energy policy: bottom-up models of the technologically detailed energy system and top-down models of the macro economy (Böhringer and Rutherford 2008, Grubb et al., 1993). However, there are major differences in terms of the modeling approach which are technologically based treatment of the energy system, and general description of the macro economy. The models that focus on solely details of the energy sector, by not considering the relation with the other parts of the economy, are classified as bottom-up models and they are detailed engineering-based models that includes considerable amount of energy technologies, commodities, process substitution and its improvements (Löschel, 2002). Contrary, top down models make assessment of the system from total economic variables and do not capture sectoral and technological details (Nakata, 2004). Detailed characteristics and conceptual differences were also provided by van Beeck, (1999).

Table 2.1. Characteristics of modeling approaches (van Beeck, 1999).

Top-down Models	**Bottom-up Models**
Use an economic perspective	Use an engineering method
No representation of technologies	High level of technological detail
Reflect available technologies adopted by the market	Reflect technical potential
Use aggregated data for estimation	Use disaggregated data for estimation
Based on observed market behavior	Independent of observed market behavior
Not consider the technically most efficient technologies available, thus underestimate potential for efficiency improvements	Not consider market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
Determine energy demand through aggregate economic indices, but vary in addressing energy supply	Represent supply technologies in high detail using disaggregated data, but vary in addressing energy consumption
Endogenize behavioral relationships	Assess costs of technological options directly
Assumes no discontinuities in historical trends	Interactions between energy sector and other sectors of the economy is not considered

Due to the fact that there are differences of the modeling concepts described above, various studies focused on combining bottom-up models with top-down models to create hybrid modeling systems (Böhringer and Rutherford 2006). Hourcade et al., (2006) defines an ideal hybrid model involving all of the important baic characteristics of the top-down models along with the most important characteristics of the bottom-up models and schematized all of these concepts on a three-dimensional zone.

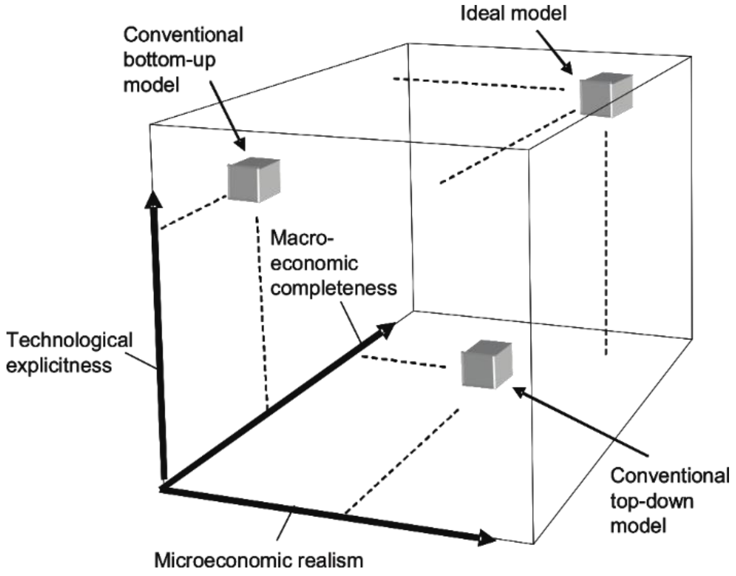


Figure 2.1. Three-dimensional assessment of energy-economy models (Hourcade et al., 2006).

In the next section, above-mentioned models will be evaluated in details as they are mostly used models in energy-economy modeling. Işık, (2016) gives an explanatory sub-classification of commonly used energy-economy model.

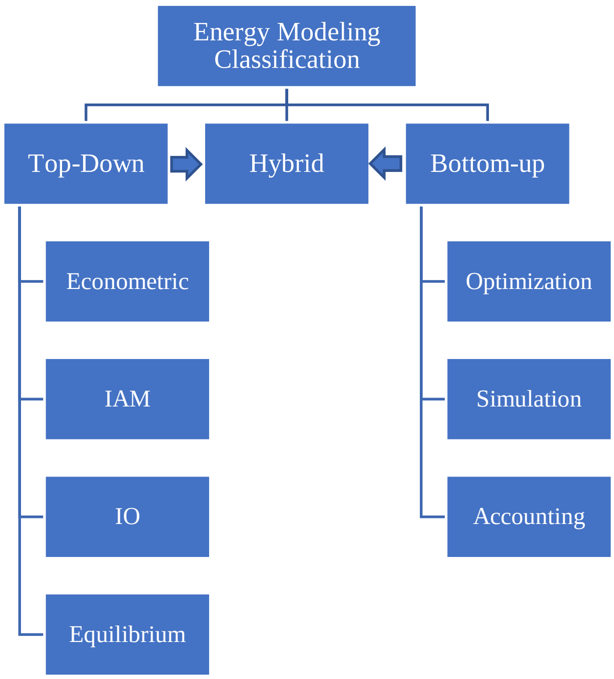


Figure 2.2. Energy model classification table (Işık, 2016).

2.1. Bottom-up Models

According to Herbs et al., (2012) the basic characteristic of a typical bottom-up energy model, compared to top-down energy models, is its high level of technological detail used to predict future energy balance. These are mostly unable to consider macroeconomic impacts of energy policies or associated investments and their costs which are extensively analyzed in top-down models. They generally work with the energy sector specifically, and utilize intensive representation energy supply and demand statistics (van Beeck, 1999).

According to Böhringer and Rutherford (2008) typical bottom-up energy models use cost minimization options of energy system to provide required demand value for the final energy under some technical limitations and policy restrictions such as emission restriction as in the case in many future energy planning.

Simulation, optimization, spreadsheet and accounting methods are mostly used to describe bottom-up models, however recently, some top-down models also use these approaches (Nakata, 2004., Mundaca et al., 2010., Müller et al., 2018). In the following section these concepts are detailed.

2.1.1. Optimization Models

These models are developed to optimize energy investment decisions through cost minimization (van. Beeck, 1997) and aim at minimizing the total system by using technologies and processes offering least-cost solutions.

MARKAL (MARket ALlocation) is one of the most applied bottom-up optimization, dynamic linear programming (LP) model developed by the Energy Technology Systems Analysis Programme (ETSAP), of the International Energy Agency (IEA). MARKAL family of models has multiplied to 77 institutions in 37 countries. MARKAL computes energy balances at all levels of an energy system: primary energy commodities, secondary resources, final total energy, based on intertemporal partial equilibrium on energy markets. The main goal of the model is to provide necessary energy services at minimum cost (Loulou et al., 2004). Energy carriers in MARKAL interconnect the conversion and consumption of energy so that this network includes all energy carriers involved with primary supplies, conversion and processing, and end-use demand for energy services (Seebregts et al., 2001). MARKAL is a data-driven model. The numerical results depend heavily upon the input assumptions. The input data can be classified as: i) technology categorization, ii) source of primary energy, iii) useful energy demands and iv) environmental constraints (Hamilton et al., 1992). MARKAL-MICRO, MARKAL-MACRO and MARKAL-ED are other MARKAL family models (Seebregts et al., 2001)

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program). In TIMES, similarly to MARKAL, the quantities and prices of the various commodities are in equilibrium, which means that the suppliers produce exactly the quantities demanded by the consumers in each period (Loulou et al., 2016). Similar to MARKAL, it has been widely used in energy modelling (Poncelet et al., 2014; McCollum et al., 2012). ETSAP also developed VEDA Front-End (VEDA_FE) and VEDA Back-End VEDA_BE) systems and integrated to TIMES for better handling input and output data.

MESSAGE is a dynamic linear programming model used for the optimization of energy supply and utilization which was developed by International Institute for Applied Systems Analysis (IIASA). The model is used to assess energy systems as a whole where energy demand is required to be met by a specific set of supply choices by minimizing of the total system costs like any other optimization models (Messner and Strubegger 1995). The model contains greater than 100 different energy extraction, conversion, transport, distribution and end-use technologies (Gritsevskyi and Nakicenovic 2000).

The PRIMES (Price-Induced Market Equilibrium System) energy system model is a development of the Energy-Economy-Environment Modelling Laboratory at National Technical University of Athens. It gives broad range of detailed estimations of energy demand, supply, prices and future technology investments, covering the entire energy system involving emissions. It focuses on prices as a means of balancing demand and supply simultaneously in several markets for energy and emissions and the model determines market equilibrium volumes. However, PRIMES is not a to-down model model and it cannot solve macroeconomic equilibrium analysis so that it needs to be combined with a macroeconomic model if necessary (E3MLAB, 2018).

2.1.2. Simulation Models

Simulation models attempt to make projections that does not follow a cost minimizing pattern unlike optimization types bottom up models (Herbs et al., 2012). These models try to repeat end-user behavior for technology choice by considering various variables such as revenue, energy supply security, energy policies, emissions and energy prices (Mundaca and Neij 2009). MIDAS and POLES (Prospective Outlook on Long-term Energy Systems) can be given as well-known simulation models. Besides, ELMOD based simulation was used by Bruninx et al., (2017) to investigate the potential influence of the nuclear power elimination in Germany and its neighboring countries. Other examples are “Residential End-Use Energy Planning System” (REEPS); World Energy Model (WEM) which was developed by OECD; Mesures d’Utilisation Rationnelle de l’Energie (MURE); and the National Energy Modelling System – Residential Sector Demand Module (NEMS-RSDM) (Mundaca and Neij 2009).

For instance, WEM, which is used by IEA to make long-term energy modeling for “World Energy Outlook”, is a simulation model utilized to replicate how energy markets function. It provides high degree energy projections at sectoral and regional level. It is made to analyze “global and regional energy prospects”, “environmental impact of energy use”, “effects of policy actions and technological changes” and “modern energy access prospects. The model is highly data intensive and its outputs are energy balance based on fuel, investment requirements and its cost assumptions, CO_2 emissions and prices (IEA, 2019).

2.1.3. Accounting Models

Accounting models are designed to account for the physical flows of energy. Accounting models require users to determine and enter outcomes rather than identifying them in energy system (Munduca and Neij 2009). Accounting models are generally preferred when sectoral approaches are needed (Bhattacharyya and Timilsina 2009).

(LEAP) The Long-range Energy Alternatives Planning which was developed by Stockholm Environment Institute at Boston is a flexible modeling environment that addresses at various geographical levels (cities, state, country, region or global) covering both the demand and supply sides of the energy. From demand perspective it does not optimize or simulate but make analysis of possible market shares (Bhattacharyya and Timilsina 2009). The model is not available to model the influences of energy choices on macroeconomic policy level. It is widely accepted tool for modelling and several researchers utilized to project general energy balance and emissions for various regions (Park et al., 2013; Heaps et al., 2009;).

Bottom- Up Energy Analysis System (BUENAS); Model for Analysis of Energy Demand (MAED); and the Policy Analysis Modelling System (PAMS) are other examples of widely used accounting type of models.

2.2. Top-down Models

As described by Grubb et al., (1993) economic studies use top-down models, which analyze aggregated behavior of the macro economy, whereas bottom-up models are technology rich and considers disaggregated approaches and investigate energy sector in a vast data driven way. Contrary to bottom-up modeling, these models consider a total view of the economy to project related energy balance (Herbs et al., 2012).

These models do not deal with high level of technology of energy sector. Energy and other sectors are mostly represented in a total way by means of production functions (Böhringer and Rutherford 2006). In top-down model concept energy is an input like every other sector of the economy, thus top-down energy system models aim to analyze the inter-sectoral connections which are not considered in a bottom-up model. Modeling such interconnections makes able the modeler to better analyze the influence of the energy on other sectors of the economy (Subramarian et al., 2018).

Various types of top-down model concepts are available. Some examples can be given as the econometric models, computable general equilibrium models and input-output models(I/O).

2.2.1. Input-Output (I/O) Models

Input–output types of model is first developed by Professor Wassily Leontief in the late 1930s. Miller and Blair, (2009) broadly analyzed this type of model. The basic knowledge used in input–output analysis is the flows of products from each industrial sector, as producer, to each of the other sectors, as consumer. This information is contained in an inter-industry transactions table, consisting of linear equations, in which the rows of table describe the distribution of a producer’s output throughout the economy and the columns describe the composition of inputs required by a particular industry to produce its output (Miller and Blair 2009). In other words, the output of an economic sector can be the input of another one, thus analyzing these input-output connections between different economic sectors enabling to study the sectoral relationships (Subramarian et al., 2018).

The tables that are used in this model approach, are detailed for the industrial and service sectors and are generally used via their economic indicators such as employment per value added to derive changes in economic structure resulting from economic or energy policies in short-term projections. The data in the tables do not change over time so that this model can be used for short term projections which disregard technological development (Catenazzi, 2009).

It is also widely used in energy economy estimation approach. For instance, Sasai, (2010) considers dynamic econometric model based on I/O table is the most suitable method for forecasting the amount of CO_2 emission caused by economic activities based on three assumptions. First, the CO_2 emission is closely linked with industrial production, second, the amount of CO_2 emission depends on the consumption of each energy source used in industry and finally, evolution of industrial structure corresponding to economic growth should be properly included (Sasai, 2010).

In another example Nathani, (2006) used a calculus, based on input-output analysis, to capture the use of material goods at the different levels of the economy and to calculate the induced output and energy consumption in Germany by using the data of the 2000. The author concluded that in case additional data is included into the input-output model, the scope of analysis can be further extended to environmental and social policy indicators (Nathani, 2006). The model was also used to forecast carbon footprint in Asia-Pacific Integrated Model (Ichisigu et al., 2019)

I/O models are used by US Bureau of Economic Analysis as well to show production relationships among industries and commodities and input-output data are updated each year and provide information on 71 industry categories.

2.2.2. Computable General Equilibrium (CGE) Models

These types of models generally assume that all markets are in perfect equilibrium. After policy intervention the equilibrium is conserved through price regulation which cannot be changed by ıther variables (Herbs et al., 2012). CGE models typically simulate markets for factors of products, and foreign exchange, with equations that specify supply and demand behavior (Nakata, 2004).

The models employ the three conditions of general equilibrium which are market clearance, zero profit and income balance (Kat, 2011). They have a detailed set of equations defining several sectors of the economy by means of aggregated production functions and consumers´ utility functions (Ortiz and Markandya, 2009).

Although energy-economy policy modeling has been dominated by CGE models in top-down modeling approach, it does not provide, as in the case of other top-down models in general, the technological flexibility (Hourcade, 2006). However, according to Nam et al., (2010) two of the major advantages of CGE are that the model's ability to describe economic dynamics (savings and investment) and resource reallocation implications of lost labor, leisure, and additional demands by allowing to create multiple scenarios.

A well-known CGE model is GEM-E3 (General Equilibrium Model for Economy Energy Environment). It is a dynamic multi-sectoral general equilibrium model that links the economy with the environment and the energy system (Capros et al., 1996b). The model includes all simultaneously interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agent's behavior. The model is dynamic, recursive over time, driven by accumulation of capital and equipment (E3M, 2011). Capros et al., (1996b) used the model to introduce carbon tax at EU level and its effect on GDP.

GEMINI-E3 (General Equilibrium Model of International–National-Interaction for Economy-Energy) is a typical CGE model developed by in cooperation between French Ministry of Equipment, Transportation and Housing and CEA (French Atomic Energy Agency) it has been used to understand carbon tax on the welfare of countries which are Parties to Kyoto Protocol and developing countries (Bernard and Vielle 2003).

GREEN (The **G**ene**R**al **E**quilibrium **EN**vironmental Model) was developed by the OECD Secretariat in order to assess the economic impacts of imposing limits on carbon emissions (OECD, 1994). It is a recursive-dynamic global CGE model, which means that each period of the model is solved as a single period model with a special focus on energy production and consumption (Nakata, 2004; OECD,1994). In the model, global economic activity is divided into twelve regions and economic activity is initially divided into eight sectors, with seven energy backstop substitutes introduced in later years. The model underlines the relationship between consumption of fossil fuels, energy production and use and CO_2 emissions (Burniaux et al., 1992).

DREAM (Dynamic Resource/Environment Applied Model) which was developed for Norwegian economy with environmental outputs is also a typical example of CGE model. In this model there is an interlink between environment and economy, which means that economy produces emissions to the environment and in return, the environment affects the productivity of economy and welfare of society. According to the model, reduced air quality, noise and traffic accidents trigger labor productivity and shows that growth in GDP is not totally equivalent of welfare due to the negative effect of environmental pollutions on welfare. Model also tries to investigate how taxes and subsidies can improve welfare in an economy where GDP and consumption are in temporarily decrease (Vennemo, 1995).

RICE (Regional Integrated model of Climate and the Economy) model is a dynamic multi-region general equilibrium model of climate and economy and integrates economic activity with GHG emissions and climate change. The model divides the world economy into 10 regions and each is endowed with initial capital stock, population and technology. Population and technology growth are given exogenously to model while capital is determined by the flow of consumption in time. It is worked under three different strategies which are: market policy, cooperative policy and non-cooperative policy options as described by (Nordhaus and Yang 1997)

2.2.3. Econometric Models

These models consist of econometrically estimated equations without equilibrium assumptions. Macro econometric models can provide a lot of economic detail, but they provide little structural detail and for that reason it is considered that they are well designed for short-run or medium-run evaluation and forecasting (Löschel, 2002). Herbs et al., (2012) pointed out as major disadvantage of econometric model as since they are heavily dependent of excessive macro-economic data, in the case of multi-country analyses where data for some countries might not be available, it can require rough guesses and method of estimations which can disrupt credibility and adequacy of the model outputs.

E3ME (The Energy-Environment-Economy Model for Europe), uses econometric methods on time series and cross-section data, which incorporate input-output tables to represent intermediate demand. It has been used by Barker, (1999) to reduce CO_2 emissions by 10% in 11 Member States of EU by applying excise duties.

E3MG (The Energy-Environment-Economy Model of the Globe) is an advanced version of E3ME. It has been developed to include an energy technology model (ETM), representing 26 energy technologies, mainly for electricity generation. This hybrid model treats technological change as endogenous in the macro economy. The purpose of the model is described as to simulate the economics of a transition to low-carbon societies across the globe by the year 2100 and taking into account that energy and transport are two main sources of GHG emissions the model aims at analyzing these sectors explicitly (Köhler et al., 2006).

2.2.4. Integrated Assessment Models (IAMs)

Kelly and Kolstad (1998) explain basically the IAM's as the models combining the scientific and economic aspects of the climate change. Weyant et al., (1996) stresses that IAMs can in serve three purposes which are i) to assess potential responses to climate change, ii) to compare costs of responses prevention and iii) to compare the relative effectiveness of the responses. Advantages of the use of IAMs in energy-environment modelling are the integrated analysis of the interactions between the environmental impacts and the social response; the development of forecasts for to prevent environmental impacts and finally the improvement of the communication process between policy makers and scientists (Davies and Simonovic 2011). They are also criticized being limited by weaknesses in underlying knowledge and for efficient modelling and simulation (Davies and Simonovic 2010). On the other hand, Ackerman et al., (2009) discussed that IAMs may be good solution for short term financial analysis and they constitute risk over-estimate the climate mitigation cost.

ANEMI (An Integrated System Dynamics Model for Analyzing Behavior of the Social-Energy-Economic-Climatic System) is a horizontally integrated IAM model, which means that it focuses on linkages between climate change and other physical and socio-economic issues. The model is composed of eight individual, horizontally-integrated components such as climate, carbon cycle, economy, land-use, population etc. and each sector represents a system dynamics model, ie., main goal is to make basic connections within a system instead of making future projections, which is coupled to other sectors through feedback connections (Davies and Simonovic 2010).

DICE (The Dynamic Integrated model of Climate and the Economy) has major similarities with RICE model with some differences. For instance, the modeling structure for population, economy-wide technological change, labor inputs, investment, and the capital stock are identical and DICE represents the globally aggregated magnitudes, while RICE considers each of these variables separately for each region (Nordhaus and Boyer 2000). In order to increase future consumption, the agents tend to invest in education, technology and capital and it aggregates the one single output in emissions, capital stock and technology. Global aggregates are estimated from the data of 71 countries representing 94% of world GHG emissions and 86%of population (Ortiz and Markandya 2009). In both models, accumulation of GHG is considered as negative capital so that any emission reduction is viewed as lowering this negative capital (Nordhaus and Boyer 2000).

WITCH (The World Induced Technical Change Hybrid) is a global model, divided into 12 macro-regions (Bosetti et al., 2007) model is top-down model that includes an energy input character working as bottom-up model so that it has a hybrid specification. It has an integrated climate module and climate damage reduces gross input through the cost of natural resources and CCS technologies (Ortiz and Markandya 2009). The model considers interdependencies and spillovers across 12 regions of the world. It has two features which are endogenous technical change and game-theoretic setup. First, carbon mitigation technologies can be integrated into model through R&D and public investment strategies. Second, the model allows the modeler to produce two different solutions being cooperative (globally optimal solution) or non-cooperative (decentralized) for each region. Therefore, from cooperative point of view a global emission reduction policy can be obtained (Bosetti et al., 2007).

MIND (Model of INvestment and Technological Development) is an IAM coupled with endogenous technical change similar to WITCH. It aims to improve endogenous technical change by adding separate R&D sectors for energy and labor efficiency, by differentiating the physical capital stock in energy and by allowing making a comparison between climate mitigation options. The Model calculates the impact of investments in different mitigation options on the overall macroeconomic costs of climate protection measured in terms of welfare losses (Edenhofer et al., 2005). The authors find out that addition of technological change can reduce the costs of climate policies and different mitigation policies have different effect on mitigation cost. For instance, improving energy efficiency is not cost effective solution in long term so that fossil fuels have to be substituted by renewable energy sources because for a cheaper option. Moreover, according to output pf the model, CCS option can also be considered for a late transition from fossil fuels to renewables (Edenhofer et al., 2005).

2.3. Hybrid Models

In the upper sections, the advantages and disadvantages of top-down and bottom-up models are discussed. To sum up, top-down models provides high degree of macroeconomic completeness with the lack of technology detail whereas bottom-up approach provides high degree of technological details and low level of macroeconomic completeness (Herbs et al., 2012).

To overcome the weakness and disadvantages of these two approaches in energy economy and environment modelling, modelers tend to combine them. For instance, some bottom-up model users have added macroeconomic feedbacks in their model while top-down researchers have added technological change modules in energy supply in their models (Hourcade et al.,2006). This combination can be done through combining two existing large top-down and bottom-up model (soft link), which is complex and difficult to handle mathematically, or through one single model having bottom-up and top-down features (hard link) (Böhringer and Rutherford 2006). Some of the hybrid modelling examples are provided below;

Kumbaroğlu and Madlener (2001) used SCREEN model, the hybrid computable general equilibrium model which integrates the technological detail of a bottom-up model with the merits of a top-down general equilibrium approach. The authors have analyzed two alternative scenarios for the development of the electricity sector and the macro-economy of Switzerland by introducing business as usual scenario and linearly increasing carbon tax on fossil fuels to achieve carbon reduction goals.

NEMS (National Energy Modelling System) is an energy-economic equilibrium model used by US Energy Information Administration (EIA) to project the energy, economic, environmental, and security impacts on the United States of alternative energy policies and different assumptions about energy markets (US EIA, Morrow et al.,2010). It combines optimization, simulation (for each demand sector) and accounting components that provide a general equilibrium system (Mundaca et al., 2010).

MARKAL-MACRO is good example of combination of detailed engineering model and a long term macroeconomic growth model. It is designed for estimating the costs and analyzing the technologies proposed for reducing environmental risks such as global climate change or regional air pollution based on US data. It allows to analyze indirect effect of emission reduction policies on aggregate level of economic activity and energy demands (Manne and Wene 1992).

CIMS (Canadian Integrated Modelling System) was basically designed as a predecessor to the NEMS model described above. CIMS contains three modules which are energy supply, energy demand and macro-economy. The model iterates between the macro-economy, energy balance modules in each time interval until equilibrium among each other has been sustained. CIMS contains a high level of technological detail in each of its sectoral sub-models however it lacks future technologies. The model also requires exogenous data entry about estimation of macroeconomic activity in every sub-sector. (Bataille et al., 2009).

3. RECENT STUDIES ON TURKISH ENERGY AND EMISSION MODELLING

In this section recent studies on energy-economy-environment modelling in Turkey will be investigated based on types of models used and general results.

Kat, (2011) proposed multi-sector energy-economy-environment model for Turkey based on concepts of Manne, (1977) and Güven, (1994). By using a hybrid model the author tries to reflect realism, macroeconomic completeness and technological explicitness by eliminating differences between bottom-up and top-down model.

The aim to create such a model to integrate sectoral details into a macroeconomic model and to evaluate the effects of policies on environment specifically on GHG emissions under non-abatement, abatement, price scenarios and under emission quota sets until year 2030. In the study the main purpose was not to address energy problems of Turkey but to demonstrate the capability of the model methodologically (Kat, 2011).

Dal, (2017), investigated the optimization of Turkish electricity generation between 2015-2035. In this study first; CO_2 emissions were analyzed till 2035 in case electricity demand is met by taking into account external costs under various scenarios. Second, based on these scenarios the most cost effective electricity generation option, which will meet the demand, was analyzed. The author compared models LEAP, MARKAL and TIMES. In the study ANSWER-TIMES was selected due to the fact that the model allows the modeler to enter technologically detailed data and user-friendly interface of the program.

Işık, (2016) studied and proposed Boğaziçi University Energy Modeling System (BUEMS) modelling framework as large scale bottom-up energy-economy-environment modeling framework representing Turkish energy sector as a new modelling program. The model attempts to obtain an optimizing solution to the described problem by applying linear programming methodology. For the validation, the results of the model were subject to comparison with TIMES model based on the output of the each scenario. In the study, the author analyzed the Turkish energy system under Business as Usual, tax scenarios and emission bounds.

Günel, (2017) used BUEMS and BUEMS-MACRO models for bottom up and top down analysis of the Turkish energy system. The author compared the results of the Base scenario, tax scenarios and emission restriction scenarios for the energy supply levels. It has been concluded that model invested more on renewables when tax and emission scenarios were applied and as a result lower CO_2 emissions values were obtained. For the Base scenario it has been found that in both BUEMS and BUEMS-MACRO, coal is the main energy source, not only for primary energy supply but electricity generation as well, due its relatively cheap price throughout the modeling timeline.

4. BUEMS MODELLING FRAMEWORK

Boğaziçi University Energy Modeling System (BUEMS) is a bottom-up structured modelling system that is designed to reflect Turkish energy system in detailed way. BUEMS is developed as a linear optimization model. Basically, the model predicts energy supply levels, CO_2 emission levels, energy technologies and investments in Turkey.

The model includes all the phases of the value chain form extraction of primary energy resources, processing with conversion technologies and consumption of the energy by end use energy sectors by offering a modeling system that facilitates the creation of the model structure requiring a minimum level of data. The Model allows the user to create energy scenarios as realistic as possible by utilizing minimum data requirement (Işık, 2016).

The base year in BUEMS is 2012 and the model is capable of making predictions until 2057 through 5-year intervals and the modeler is able to modify time horizon by respecting interval period. BUEMS is developed using General Algebraic Modeling System (GAMS) as programming language. The main objective of BUEMS is to minimize the total system cost as to meet energy demand by supply technologies. At the same time, a set of constraints must be satisfied over pre-defined planning horizon. These constraints specify energy balance relationship, capacities, activities, demand satisfaction constraints, emission level limitations and other technical limitations.

4.1. Structure of the BUEMS Model

There are two main elements in the model, namely technologies and commodities. The commodities are converted or generated by technologies. In BUEMS, total number of 209 energy carriers are defined such as coal, hydrogen, wind, natural gas and petroleum.

There are 3 different ways of introducing a commodity to the system. These are renewables, import and extraction (mining). Commodities are to be utilized solely for non-electric energy purpose through process technologies or conversion technologies use them as energy carriers with the purpose of generating power. Following this procedure, they become as useful energy and are ready to be used by demand devices.

A technology is defined as a complex mechanism that is used for transformation of one commodity type into another. Transformation operation can be handled by either processing, converting or transmitting the energy. BUEMS contains three types of technologies in its structure. These are supply technologies, conversion technologies and demand technologies. Detailed explanation of each technology type is as follows.

4.2. Supply Technologies

These technologies provide primary energy sources to the modeling system. There are three possible paths for establishment of energy sources to the system such as domestic supply, import and export. Domestic supply technologies can be divided into two sub-categories, namely extraction(mining) technologies and renewable energy resources.

BUEMS contains a total number of 108 energy resources in its format. The energy sources mainly consist of solid and liquid (conventional) fuels and renewables. Resources including coal, natural gas, oil, heavy fuel oil, light fuel oil, jet fuel and kerosene form the conventional resources in total. On the other hand, wind, solar, hydroelectric, geothermal energy compose the renewables. BUEMS also defines hydrogen and nuclear power as energy source. The related parameters are as follows.

- supply cost,
- maximum available capacity,
- lower and upper bounds
- decay/growth rates

Every supply technology has an associated cost with itself. It must be highlighted that commodity price of the conventional constitutes significant proportion of the objective function. Lower and upper bounds restrict supply levels for each period. On the other hand, cumulative supply bounds restrict the total supply for each technology through whole planning horizon. Decay/ growth rates indicate the decrease and increase in the capacity, respectively.

Foregoing parameters are defined in the model as follows.

bound_s_upper(s,t) : upper bound on the capacity of a supply technology
bound_s_lower(s,t) : lower bound on the capacity of a supply technology

bound_s_fix(s,t) : fix bound on the capacity of a supply technology

cum(m,cm) : supply cumulative capacity

decayr(m,t) : decay rate of a supply technology

growthr(m,t) : growth rate of a supply technology

scost(m,t) : supply cost

envsep(m,t) : emission factor for supply technologies at period t

4.3. Energy Conversion Technologies

These technologies convert one commodity into another type. From this perspective, they can be referred as intermediate technologies. BUEMS has three subcategories related with energy conversion technologies. These are electricity generation technologies, LTH generation technologies, process technologies. The decisions related with conversion technologies in the model are new investment level, capacity level and activity level.

The parameters related with energy conversion technologies are given below.

Table 4.1. Energy conversion technology parameters (Modified from Günel, 2017).

af (m,t)	annual availability factor of the technology m at period t
baseload(e,t)	the highest percentage of the baseload power plants in total electricity generation
bound_p_fix(m,t), bound_p_upper(m,t)	annual fix and upper bounds on the capacity of a technology at period t
bound_k_lower(m,t), bound_k_fix(m,t), bound_k_upper(m,t)	annual lower, fix and upper bounds on the activity of a process technology at period t
bound_c_lower(m,t), bound_c_fix(m,t), bound_c_upper(m,t)	annual lower, fix and upper bounds on the activity of a conversion technology at period t
bounds(b,t)	annual bounds on scenario constraints at period t
ibond(m,t), ibondfx(m,t), ibondlo(m,t)	annual lower, fix and upper bounds on the investment of the technology m at period t
capunit(m,t)	unit conversion factor between capacity and activity of the technology m at period t
decay(m,t)	maximum capacity decay rate of the technology m between consecutive periods
growth(m,t)	maximum capacity growth rate of the technology m between consecutive periods
invcost(m,t)	investment cost per unit of new capacity addition of the technology m at period t
edistinv(m,t)	unit investment cost for electricity distribution system of electricity generation technology at period t
etraninv(m,t)	unit investment cost for electricity transmission system of electricity generation technology at period t
dtraninv(m,t)	unit investment cost for LTH transmission system of LTH generation technology at period t

dtranom(m,t)	unit O&M cost for LTH transmission system of LTH generation technology at period t
etranom(m,t)	unit O&M cost for electricity transmission system of electricity generation technology at period t
edistom(m,t)	unit O&M cost for electricity distribution system of electricity generation technology at period t
ereserv(e,t)	peak reserve factor for electricity generation
hreserv(e,t)	peak reserve factor for LTH generation
fixom(m,t)	fixed operation and maintenance cost per unit capacity of the technology m at period t
varom(m,t)	variable operation and maintenance cost per unit activity of the technology m at period t
inpent	level of input requirement per unit of technology activity
outent	level of output generation per unit of technology activity
limit(m,t)	activity limitation on a multiple output technology
refinhlm(e,t)	“refinery parameter 1” for activity limitation on a multiple output technology
refinstd(e,t)	“refinery parameter 2” for activity limitation on a multiple output technology
cokeprod(e,t)	level of coke production of the technology e
life(m,l)	useful lifetime of the technology m
peakcon(m,t)	the fraction of the technology m’s capacity that should be credited towards the peaking requirement at period t
qhr_d(m,t)	fraction of the year "day share"
qhr_n(m,t)	fraction of the year "night share"
qhr_w(m,t)	fraction of the year "winter share"
qhr_s(m,t)	fraction of the year "summer share"
resid(m,t)	residual capacity that was invested prior to the start of the planning horizon
teent(e,t)	transmission efficiency of electricity
envact(m,t)	emission factor for process technologies at period t
cumem(v,cme)	cumulative emission level of emission type v
envcost(v,t)	emission cost per unit emission

4.4. Demand Technologies

Demand technologies are also called as demand devices. Basically, they are responsible of transforming energy carriers into the final energy demand. Demand technologies are divided into 5 basic elements. These are household, service, industry and transportation. It should be noted that useful energy demand should be added exogenously by the modeler into the BUEMS system (Işık, 2016).

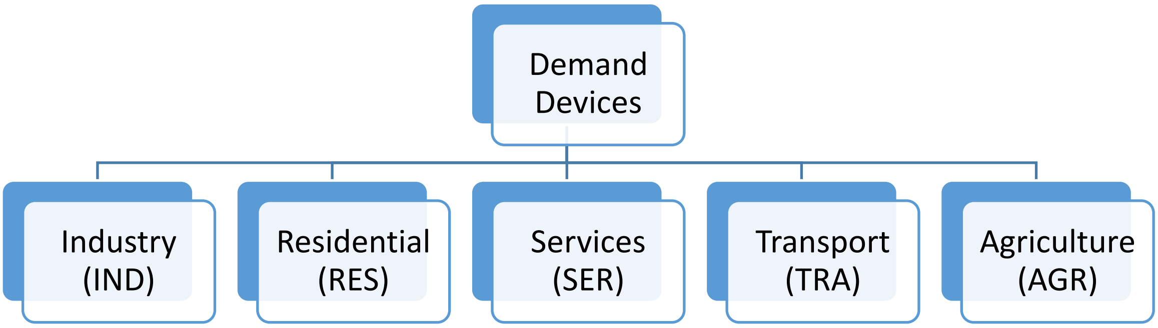


Figure 4.1. Demand technologies in BUEMS.

Demand technologies have investment and capacity level variables in common with conversion technologies. However, they do not have activity level variable since the activity level of a specific demand device is proportional to its capacity level. In BUEMS, this ratio is defined as "capacity utilization factor" indicating the proportion of capacity that is active in a particular period. On the other hand, a unit conversion factor is utilized, which is defined as **"capunit"** in BUEMS model, in case of a need for unit adjustment between capacity and activity levels.

Demand devices also have another distinct parameter which specifies the efficiency rate. It is defined as "**eff(m,t)"** in the model. Basically, efficiency rate gives the input/output ratio of a demand technology.

4.5. Sets, Parameters and Variables

In this section, the sets, parameters and variables of BUEMS will be explained in detail. Firstly, the Table below shows the abbreviations and descriptions of model sets. This is essential to have solid understanding about BUEMS.

Table 4.2. Model Sets.

•t: periods	•s(m): supply (resource) technologies
•y: years	•smn(m): extraction (mining) resource technologies
•e: energy carriers (source)	•sim(m): import resource technologies
•m: all technologies	•sex(m): export resource technologies
•v: emission type	•srn(m): renewable resource technologies
•l: technology life	•s_c(m): coal resources
•p(m):process-conversion-demand technologies	•sim_c(m): import coal resources
•k(m): process technologies	•smn_c(m): domestic coal resources
•c(m): conversion technologies	•d(m): all demand technologies

BUEMS contains two types of variables namely optimization variables and accounting variables. Accounting variables are only used for reporting and accounting purposes. They have no functionality for optimization process.

Optimization variables are as follows.

- Supply variables
- Capacity variables
- Activity variables
- Investment variables
- Emission variables
- Discounted cost variable

Supply levels are defined as "**r_tsep**" in the model. It is the only decision variable related with supply technologies. Regarding for energy conversion technologies, there are three decision variables. For each period, activity, capacity and investment of energy conversion technologies are predicted and they are defined as "**r_act**", "**r_cap**" and "**r_inv**", respectively. Similarly, demand technologies have also investment and capacity variables. However, as it was mentioned earlier, they do not have activity level variables. Lastly, the emission level of each technology is predicted for each period. It is represented as "**r_em**" in the model.

Detailed explanations of optimization variables are as shown below.

r_tsep (m,t) : the supply level of technology m in period t. The unit is PJ for all supply technologies.

r_cap (m,t) : installed capacity level of technology m in period t. The unit is PJ for all technologies.

r_act (m,t) : activity level of technology m in period t. The unit is PJ for energy conversion technologies.

r_inv(m,t) : investment level of technology m in period t. It indicated the level of new capacity addition. The units of investment level vary among technologies. For instance, it is GW for electricity conversion technologies, billion vehicle-kilometer per year for transportation

r_em (v,t) : the value of CO_2 as greenhouse gas for emission type during t. The unit is million tons of CO_2.

4.6. Objective Function

BUEMS aims to decrease the total system by using least cost options. The cost of the systems is calculated as summing up discounted annual cost occurred in each period.

$$totcost = \sum_{t} disanntcost(t) \tag{4.1}$$

where;

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

Briefly, total discounted annual cost of a period is the sum over all of the costs resulting from the consumption and usage of model elements (fuel consumptions, technologies, demand segments, environmental variables, etc.) (Işık, 2017).

In order to obtain disanntcost(t) undiscounted annually adjusted total system cost is used.

$$undanntcost\ (t) = undannsupply(t) + undanninv(t) + undannother(t) + undannenv(t) \tag{4.2}$$

where;

- undanntcost(t): undiscounted annual total system cost at period t
- undannsupcost(t): undiscounted annual total supply cost at period t
- undanninv(t): undiscounted annual total investment cost at period t
- undannothcost(t): undiscounted annual total other cost at period t
- undannenvcost(t): undiscounted annual total environmental cost at period t

Undiscounted annually system cost for each period is calculated as summing up annual supply, annual investment, annual fixed, annual variable and annual environmental cost of each period.

$$
\begin{aligned}
&undanntcost(t) \\
&\quad = \sum_{m}(scost(m,t) \times r\_tsep(m,t)) \\
&\quad + \sum_{m}(edistom(m,t) \times r\_act(m,t)) + \sum_{m}(etranom(m,t) \times r\_act(m,t)) \\
&\quad + \sum_{m}(dtarnom(m,t) \times r\_act(m,t)) \\
&\quad + \sum_{m}\sum_{t}^{t}(costinv(m,u) \times r\_inv(m,u)) \\
&\quad + \sum_{m}(fixom(m,t) \times r\_cap(m,t)) \\
&\quad + \sum_{m \in k \cup c}(varom(m,t) \times r\_act(m,t)) \\
&\quad + \sum_{m \in d}(capunit(m,t) \times cf(m,t) \times varom(m,t)) \times r\_cap(m,t)/eff(m,t)) \\
&\quad + \sum_{v}(envcost(v,t) \times r\_em(v,t))
\end{aligned}
\tag{4.3}
$$

This equation refers to detailed calculation of undanntcost(t) in which the first four sum equation refers to supply cost and the rest are detailed version of undanninv(t), undannothcost(t) and undannenvcost(t) respectively. Investment cost is distributed evenly through capital recovery factor (crf) (Işık,2016). In order to calculate the annualize form of the above equation investment cost is multiplied by defined below;

$$
costinv(m,t) = crf(m) \times invcost(m,t) + edistinv(m,t) + etrainv(m,t) + drainv(m,t) \tag{4.4}
$$

where;

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

$$
crf(p) = \frac{discount(p)}{1 - (1 + discount(p))^{-life(p)}} \tag{4.5}
$$

where,

- crf(p)***:*** capital recovery factor of technology p

- discount(p): discount rate of technology p
- life(p): lifetime of technology p

Multiplying period discount factor ((pdf(t)) with “undanntcost” gives discounted annual total system cost. It is defined as “disanntcost” in the model. General calculation is given below by mathematical expression:

$$\begin{aligned} disanntcost(t) \\ &= \sum_{m} (pdf(t) \times scost(m,t) \times r\_tsep(m,t)) \\ &+ \sum_{m} (pdf(t) \times edistom(m,t) \times r\_act(m,t)) \\ &+ \sum_{m} (pdf(t) \times etranom(m,t) \times r\_act(m,t)) \\ &+ \sum_{m} (pdf(t) \times dtranom(m,t) \times r\_act(m,t)) \\ &+ \sum_{m} (priinv(t) \times r\_inv(m,t)) \\ &+ \sum_{m} (pdf(t) \times fixom(m,t) \times r\_cap(m,t)) \\ &+ \sum_{m \in k \cup c} (pdf(t) \times varom(m,t) \times r\_act(m,t)) \\ &+ \sum_{m \in d} (pdf(t) \times capunit(m,t) \times cf(m,t) \times varom(m,t)) \times r\_cap(m,t) \\ &/eff(m,t)) + \sum_{m} (pdf(t) \times envcost(v,t) \times r\_em(v,t)) \qquad (4.6) \end{aligned}$$

where;

- disanntcost(t): discounted annual total system cost
- pdf(t): period discount factor
- priinv(m,t): periodic discount factor for the investment

As it was stated earlier, the main aim of BUEMS is to decrease the total cost which consists of sum of the total discounted annual system costs of each period.

In the following sections, each cost type that contributes to the total system cost will be explained in detail.

4.6.1. Total Annual Supply Cost

Supply cost covers all costs occurred during the supply of energy sources into the system. It also includes the cost regarding distribution and transmission of the electricity generation. Extraction, renewable and import supply technologies increase the cost whereas export technologies are considered as revenues.

The calculation of the total undiscounted annual supply cost is as follows:

$$
\begin{aligned}
undannsupcost(t) &= \sum_{m \in s} (scost(m,t) \times r\_tsep(m,t)) \\
&+ \sum_{ce \in s} (edistom(m,t) \times outent(m,t) \times r\_act(m,t)) \\
&+ \sum_{ce \in s} (etranom(m,t) \times outent(m,t) \times r\_act(m,t)) + \sum_{ch \in s} (dtranom(m,t) \\
&\times outent(m,t) \times r\_act(m,t)) + \qquad (4.7)
\end{aligned}
$$

where;

- undannsupcost(t): total undiscounted annual supply cost at period t
- scost(m,t): unit supply cost of technology m at period t
- r_tsep(m,t): supply level of technology m at period t
- outent(m,t): level of output generation per unit activity of technology m at period t
- edistom(m,t) : unit operational cost of electricity distribution at period t
- etranom(m,t) : unit operational cost of electricity transmission at period t
- dtranom(m,t) : unit operational cost of LTH transmission at period t

4.6.2. Other Cost

These variables consist of all fixed and variable operation and maintenance (O&M) costs. Capacity levels are used for calculating fixed O&M whereas variable O&M costs are calculated based on technology activity levels. As it was previously stated, demand technologies do not have activity level variables. Their activity level is obtained by capacity utilization factor.

$$undother(t) = \sum_{m \in k \cup c \cup d} fixom(m,t) \times r\_cap(m,t) + \sum_{m \in k \cup c} varom(m,t) \times r\_act(m,t) + \sum_{m \in d} capunit(m,t) \times cf(m,t) \times varom(m,t)) \times r\_cap(m,t)/eff(m,t)) \quad (4.8)$$

where;

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

Similar to the previous discounted cost calculations, the total discounted annual other cost is calculated by multiplying the periodic discount factor with undiscounted total other cost.

$$disother(t) = pridf(t) \times undother(t) \quad (4.9)$$

4.6.3. Environmental Cost

During energy production, conversion, transmission and consumption activities, CO_2 and other chemical gases are emitted to the environment. In BUEMS, a unit penalty cost is assigned due to the emission level of the systems. The environmental cost is calculated as follows.

$$undannenv(t) = \sum_{v} envcost(v,t) \times r\_em(v,t) \quad (4.10)$$

where;

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

The total discounted annual environmental cost is determined by multiplying periodic discount factor with undiscounted annual total environmental cost.

$$\mathrm{disannenv(t)=pridf(t)\times undannenv(t)} \tag{4.11}$$

4.7. Equations and Constraints

BUEMS aims to minimize the total annualized system cost. At the same time, the model must satisfy a set of constraints. In the model, the constraints can be considered as multi-dimensional. In other words, the constraints reflect the wide range of real-life applications in the context of energy, economy and environment.

4.7.1. Energy Balance Constraints

This constraint guarantees that the total supply level of a specific energy source is, any case, greater than or equal to the total value. It can be easily understood that energy balance constraint set is individually defined for each energy source. Extraction (mining) and import technologies in supply technologies and generation part of conversion technologies form the total supply level and it is located at the left part of the equations. On the other hand, export technologies, demand technologies and consumption level of energy conversion technologies constitute the right-hand side of the formula.

For this purpose, **"outent (m,t)"** is placed on the left hand side whereas **"inpent (m,t)"** parameter is utilized on the right part of the formula.

$$\sum_{m\in s} r\_tsep(m,t) + \sum_{m\in k\cup c} r\_act(m,t) \times outent(m,t) \geq \sum_{m\in s} inpent(m,t) \times r\_tsep(m,t)$$
$$+ \sum_{m\in k\cup c} inpent(m,t) \times r\_act(m,t)$$
$$+ \sum_{m\in d} inpent(m,t) \times capunit(m,t) \times cf(m,t) \times r\_cap(m,t)/eff(m,t) \quad (4.12)$$

where;

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

4.7.2. Demand Satisfaction Constraints

This set of restrictions are responsible to guarantee that, in any case, demand is met with the existing system capacity. Briefly, the total activity levels of end-use technologies are higher than or equal to the specific demand requirement. As described above, this constraint is defined for each demand technology separately.

$$\sum_{m\in d} (outent(dm)(m,t) \times capunit(m,t) \times cf(m,t) \times r\_cap(m,t) = demand(dm,t) \quad (4.13)$$

where;

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

4.7.3. Capacity Transfer Constraints

Available capacity of a technology m at period t is composed of two parts. First part is the capacities that are installed in previous periods and still in operation. The other part is the investments that are made at current and previous periods prior to modelling horizon. Within the planning horizon for a specified time period t, total available capacity of each technology p is calculated by capacity transfer constraints. Model considers all investments made before and on that period and the technology having technical life are added to the total capacity (Işık,2016). It is important to underline that capacity of a technology is no longer available if the lifetime of an investment is terminated.

$$t' = t - life(m,l)/nyrsper \tag{4.14}$$

where;

- l: lifetime of technology
- nyrsper : number of years at a period
- t-t': available investments of technology m at period t

Therefore, the equation below calculates the total available capacity of any technology m at period t.

$$r\_cap(m,t) = resid(m,t) + \sum_{x=t'}^{t} r\_inv(m,x) \tag{4.15}$$

where;

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

4.7.4. Activity-Capacity Relation Constraints

These constraints ensure that the activity level of energy conversion technologies always remains below or equal to its available maximum capacity of that period. It is solely applicable for energy conversion technologies due to the fact that demand technologies do not have activity level variables. This activity-capacity relation is satisfied with the following expression in the model.

$$r\_act(m,t) \leq capunit(m,t) \times af(m,t) \times r\_cap(m,t) \tag{4.16}$$

where;

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

4.7.5. Cumulative Supply Limit

This constraint type is only suitable for supply technologies ensuring that cumulative supply level is equal or greater than the total supply level of each supply technology. Cumulative supply restriction expressed in the model as following.

$$\sum_{t}(nyrsper \times r\_tsep(m,t)) \leq cum(s,cm) \tag{4.17}$$

where;

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

4.7.6. Activity Limit

Some process technologies such as refinery sector generate multiple outputs. In BUEMS, this type of flexible technologies is defined as **f(m)**. This constraint is responsible of setting the total generation of such technologies to a specific proportion of the total technology activity.

$$\text{limit}(m,t) \times r\_act(m,t) = \sum_{e}(r\_act(m,t) \times outent(m,e,t)) \tag{4.18}$$

where;

- limit(m,t): fraction for activity limitation of multiple output technology m at period t
- outent(m,e,t): level of energy source e generation per unit activity of technology m at period t
- f(m): flexible process technologies producing multiple commodities

4.7.7. Periodic Limitations

This group of constraints is responsible of limitation and to apply restrictions of the supply, capacity, activity and investment levels of any technologies.

$$r\_x(m,t) \leq bound\_x\_upper(m,t)$$

$$r\_x(m,t) = bound\_x\_fix(m,t)$$

$$r\_x(m,t) \geq bound\_x\_lower(m,t) \tag{4.19}$$

where;

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

4.7.8. Baseload Constraint

There are two constraints in the electricity sector and one of which is baseload constraint. The purpose of that constraint is to prevent base-load power plants, nuclear and conventional fossil fuels, damaged by demand fluctuations at night time, since these plants are not flexible for operational changes. Therefore, it provides that some part of the electricity demand is met by these type of plants.

The equations that describes this constraint in mathematical formula is as follows;

$$\sum_{m \in ce} (outelc(m,t) \times qhr\_n(m,t) \times r\_act(m,t) \times baseload(e,t)) \geq \sum_{m \in ce \cap cbs\_e} qhr\_n(m,t) \times outelc(m,t) \times r\_act(m,t)) \tag{4.20}$$

Where;

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

4.7.9. Peak Load Constraints

This constraint ensures that electricity demand is satisfied in each period. For this purpose, electricity production capacity of each period is arranged greater than the total demand by using reserve capacity.

$$\sum_{m\in s} teent(e,t)\times peakcon(m,t)\times r\_tsep(m,t)) + \sum_{m\in ce} teent(e,t)\times peakcon(m,t)\times outelc(m,t)\times capunit(m,t)\times af(m,t) \times r\_cap(m,t)) \geq \sum_{m\in s} inpelc(m,t)\times r\_tsep(m,t) + \sum_{m\in k} inpelc(m,t)\times r\_act(m,t) + \sum_{m\in c} inpelc(m,t)\times r\_act(m,t) + \sum_{m\in d} inpelc(m,t)\times capunit(m,t)\times cf(m,t)\times r\_cap(m,t)/eff(m,t)\times (1 + ereserve(e,v)) \qquad (4.21)$$

where;

- ce: electricity generation technology
- teent(e,t): transmission efficiency of electricity at period t
- peakcon(m,t): peak contribution parameter
- outelc(m,t): electricity generation level per unit activity of technology m at period t
- inpelc(m,t): electricity demand level per unit activity of technology m at period t
- ereserv(e,t) : electricity reserve capacity fraction for electricity generation technology at period t

4.7.10. Periodic Emission Constraints

In BUEMS, emission level for each period can be restricted with period emission constraint. As stated in sections above, in terms of emissions the model uses CO2 only as greenhouse gas. Therefore, the total level of emissions released by supply, conversion and demand technologies are calculated according to following formulation:

$$\sum_{s}(envsep(s,t) \times r\_tsep(s,t)) = r\_em(v,t) \tag{4.22}$$

where;

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

$$\sum_{s}(envact(m,t) \times r\_act(m,t)) = r\_em(v,t) \tag{4.23}$$

where;

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

$$\sum_{s}(envact(m,t) \times capunit(m,t) \times cf(m,t) \times r\_cap(m,t)) = r\_em(v,t) \tag{4.24}$$

Hence, the level of total emission for each period is calculated as follows.

$$totemis = \sum_{v} r\_em(v,t) \tag{4.25}$$

where;

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

In case that total emissions are required to keep in some specific value; it is given into model exogenously by the modeler.

$$totemis \leq bounds(b,t) \tag{4.26}$$

where;

- bounds(b,t) : scenario constraints

4.7.11. Cumulative Emission Limit

This constraint ensures that the total emission level released during planning horizon is less than or equal to a specific level. This level is also given to the model exogenously.

$$\sum_{t} nyrsper \times r\_em(v,t)) \leq cumem(v,cme) \tag{4.27}$$

where;

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

4.7.12. Decay/Growth Constraints

Supply level of any supply technology can be limited based on decay and growth constraint.

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

$$r\_tsep(s,t+1) \leq r\_tsep(s,t) \times (growthr(s,t+1)^{nyrsper} \tag{4.28}$$

where;

- decayr(s,t): decay rate of a supply technology between consecutive periods
- growthr(s,t): growth rate of a supply technology between consecutive periods

Apart from supply levels, activity and capacity of any technologies can be limited as well with the same mathematical point of view by using $r\_cap(m,t+1)$ for capacity and $r\_act(m,t+1)$ for activity of technologies.

5. OVERVIEW OF TURKISH ELECTRICITY SECTOR

In Turkey, the concept of the energy sector has been started to change by the announcement of The National Energy and Mining Policy in April 2017 by Ministry of Energy and Natural Resources (MENR). The policy is based on three main pillars and substantially is aiming to enhance Turkey's energy perspective by improving energy supply security, increasing the use of domestic energy resources and providing foreseeable energy market. In order to meet increasing energy demand and to reduce energy imports, the increase of the use of domestic resources become essential from energy supply security and economic perspective.

An important perspective of this policy is the use of domestic resources, being domestic coal and renewables, instead of imported resources as imported hard coal and natural gas. For instance, less than 1% of the consumed natural gas in 2019 was produced domestically (EPDK, 2019) and Turkey was among 10 biggest coal importer countries in 2018 (IEA, 2020a). Therefore, considerable investments were made to renewables during the last decade driven by a favorable investment climate, increase energy demand growth and supportive governmental policies.

One of the primary supportive policy for this high renewable penetration is the feed-in-tariff mechanism. Under the Renewable Energy Support Mechanism (YEKDEM), Turkey provides feed-in-tariffs ranging between 7.3-10.3 $cent/kWh depending on the type of the renewable power plants. New feed-in-tariff values, were also announced in January 2021 by Presidential Decree. Additional support is also provided if plant components are locally manufactured in Turkey.

Besides, By the Renewable Energy Resources Zone (REZ) model until now, 2,000 MW wind and 2,000 MW of solar competitions have been completed in the year 2017, 2019 and 2021.Moreover, applications for the small-scale REZ tender are planned to be applied throughout 2021 and 2022.

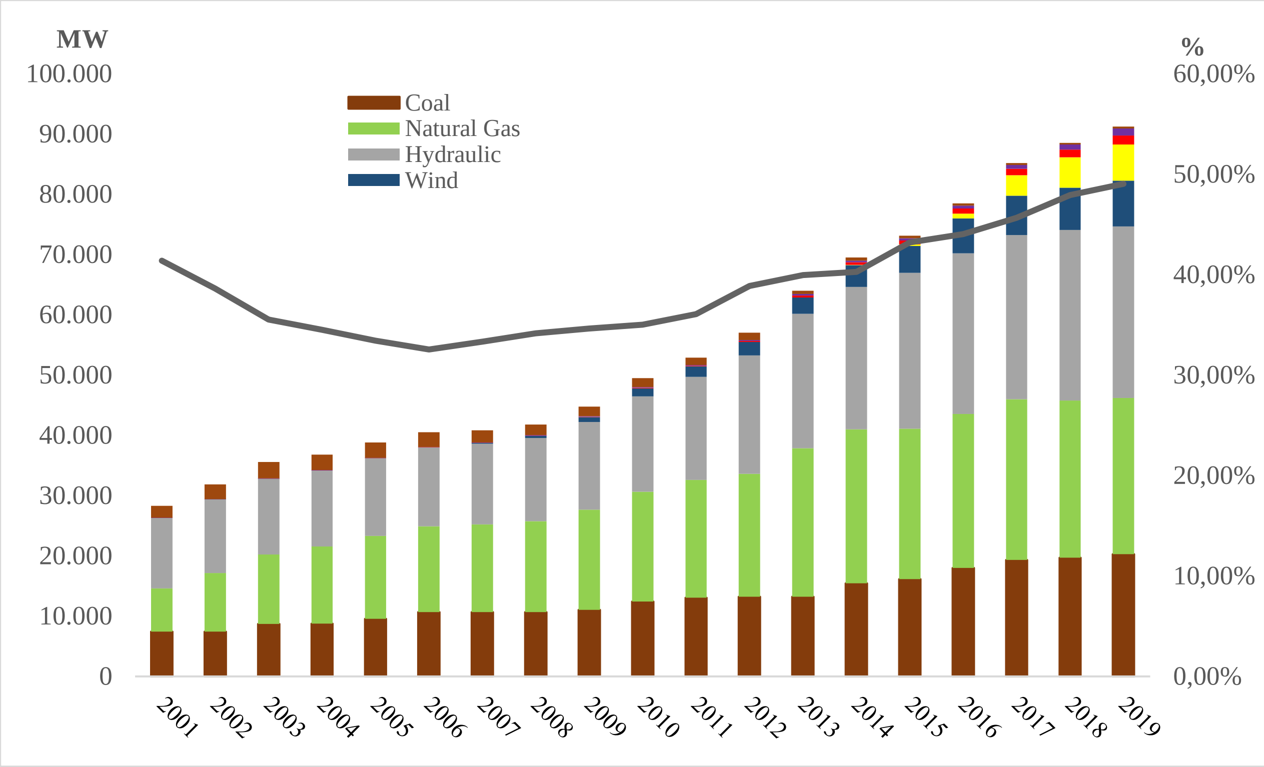


Figure 5.1. Electricity installed capacity development in Turkey.

From the Figure 5.1 it can be observed that total installed almost tripled between 2001-2019 and exceeded 90.000 MW at the end of 2019 due to strong economic development and rising energy demand. Another important achievement is that the share of renewables in installed capacity is greater than half of the total installed capacity (50,2%). With the contribution of government policies starting from the year 2014 the first solar capacities integrated into the system. Moreover, there has been an important increase in both hydraulic and wind capacity and their capacities reached to approximately 28,5 GW and 7,5 GW respectively. By 2023 it is planned that first nuclear unit of 1.200 MW (totally 4.800 MW) will be available and by 2026 the whole 4 units will start generating electricity. Addition of the nuclear energy to Turkish electricity fleet will provide an important flexibility to electricity system and contribution to decarbonization policy.

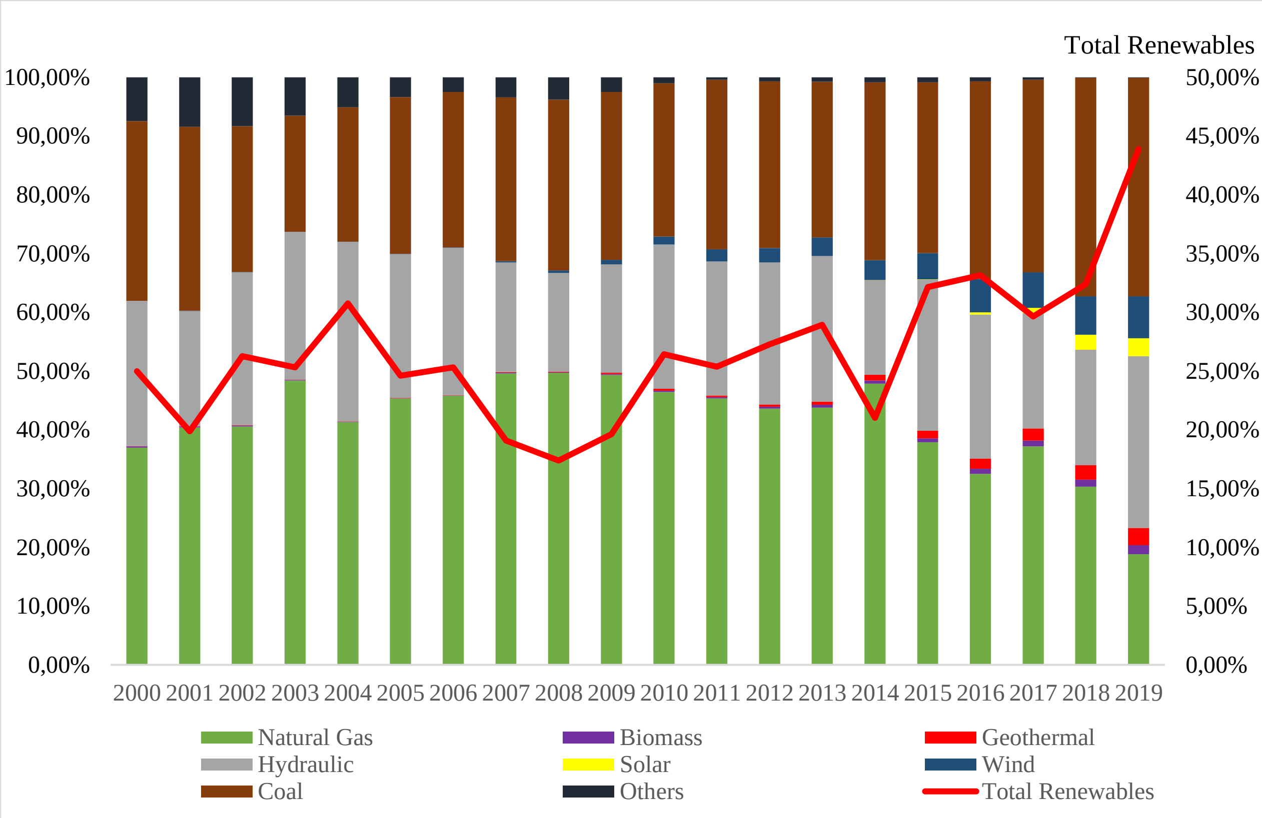


Figure 5.2. Electricity generation development by resource in Turkey.

As can be seen from the Figure 5.2 parallel to installed capacity development, share of renewables reached almost 45% at the end of 2019 with the contribution of hydro, wind and solar respectively. Electricity generation exceeded 300 TWh in 2019 and reached to 303,9 TWh corresponding to in an increase by almost 145% compared to year 2000. In 2019 hydro-based generation rose to 29,2% due to favorable climate conditions. Solar and wind generation reached also their maximum levels in 2019 by 2,5% and 7,1% respectively. Solar based generation started in 2014 as 0.017 TWh and rose to 9,25 TWh at the end of 2019. As explained above, coal-based generation also reached to approximately 37% led by both increase in imported and domestic coal-based production. Generation from natural gas decreased to 18,8% which was 47,8% in 2014, in accordance with the policy that foresees the reduction of imported natural gas in electricity generation.

In Turkey currently, there is a need to conduct various long term energy and energy-related CO_2 emission projections. Currently, the only example that can be given for a long terms CO_2 emission scenario is the Turkey’s Intended National Determined Contribution (INDC), which is subject to revision, to UNFCCC in which by 2030 it is forecasted that total greenhouse gas emission would be 929 Mtons of CO_2eq, corresponding to 21% decrease compared to Business as Usual Scenario. It is possible to mention about short-term projections found in 11th Development Plan and Strategic Plan

(2019-2023) of the MENR. The only long-term projection is the electricity demand projection that covers next 20 years stemming from Electricity Market Law as an obligatory duty.

From future perspective, it is planned to add 10 GW of solar and 10 GW of wind capacity between 2017-2027. All of these policies made significant contribution to growth in renewables, especially in electricity generation, in the last decade. According to recent studies it has been showed that Turkey has 37 GW onshore and 11 GW offshore technical potential (MENR, 2020). The Tables below shows the short term installed capacity of domestic resources and generation targets.

Table 5.1. Short term targets in MENR strategic plan (2019-2023).

Technology/Years	**2019**	**2020**	**2021**	**2022**	**2023**
Solar Capacity (MW)	5.750	7.000	7.750	8.500	10.000
Wind Capacity (MW)	7.663	8.883	9.633	10.633	11.883
Hydro Capacity (MW)	29.748	31.148	31.688	31.688	32.037
Geothermal and Biomass Capacity (MW)	2.678	2.717	2.772	2.828	2.884
Domestic Coal Capacity (MW)	10.664	10.664	10.664	11.464	14.664

Table 5.2. Energy-related targets in 11^{th} development plan (2019-2023).

Targets	**2023**
Primary Energy Demand (BTEP)	174.279
Electricity Demand (TWh)	375,8
Primary Energy Demand Per Capita (TEP/capita)	2,01
Electrical Energy Demand Per Capita (kWh/capita)	4.324
Share of Natural Gas in the Total Electricity Generation (%)	20,7
Share of Renewables in the Total Electricity Generation (%)	38,8
Electrical Energy Production by Domestic Resources (TWh)	219,5
Installed Electrical Power (MW)	109.474

According to the Tables 5.1. and Table 5.2. above, the total installed capacity is expected to reach almost 108 GW by 2023. The electricity generation from renewables will reach to 38.8%. On the other hand, this target is already achieved, since in the year 2019 the share of renewables in total generation was 45%. However, this target should be tracked due to the fact that in 2019 the high share of renewables was a result of high hydraulic penetration in line with favorable meteorological conditions. Therefore, potential reduction in the hydro generation should be offset with other renewable capacity additions.

These tables summarize the short-term targets in Turkey. The main purpose is to boost renewables and increase the share of domestic resources in energy portfolio. It is also planned that the first nuclear unit (1.2 GW) of Akkuyu Nuclear Power Plant will be available by 2023. Thus, another important progress will be made towards more decarbonized electricity sector.

6. CALIBRATION OF THE MODEL

As in all model studies the main aim for calibration is to draw a better picture of the current situation of the energy sector. As discussed in the above sections, BUEMS is able to make projections throughout the years 2012-2057. Moreover, as in the case of bottom-up modelling approach, it requires technological details on the energy sector.

In order to reflect current energy profile model was calibrated for the years 2012 and 2017 with the updated energy data. For that purpose, latest energy balance tables, electricity installed capacity data and fuel supply levels were obtained from official sources.

6.1. Calibration of the Supply

In order to calibrate supply module, energy balance tables, which was published by MENR, were used. In the model, 2012 supply values were already entered and they were validated with the latest updated data. For the year 2017, the coal and natural gas supply levels are as follows. It should be noted that in balance tables the values were ton of oil equivalent and they were converted to PJ for the entry to model.

Table 6.1. Coal supply levels 2017.

Coal Supply Levels (PJ)	**2017**
Domestic	
Lignite	577,4
Hard Coal	30,2
Asphaltite	23,2
Imported	
Hard Coal	1.019,3
Coke	21,1
Total Coal	**1.671,2**

According to the Table above, in the year 2017 the total coal supply is 1.671,2 PJ. It can be observed that domestic lignite is dominant fuel among coal types. Imported coal and asphaltite are used for electricity generation and industry while domestic coal is used for residential heating as well as electricity generation.

For the same year natural gas supply is 1.942,8 PJ excluding stock changes. Less than 1% of the natural gas supply was produced domestically. More than half (51,93%) of the total natural gas supply was imported from Russia followed by Iran, Azerbaijan, Algeria, Nigeria and from spot market. The Table below shows the amount of imported natural gas supply by country (EMRA, 2018).

Table 6.2. Imported natural gas supply levels by country 2017.

Imported Natural Gas Supply 2017	**(PJ)**
Russia	1009
Iran	325,3
Azerbaijan	230,1
Algeria	162,3
Nigeria	73,1
LNG	143

In order to better reflect sectoral energy supply, sectoral supply by energy resources was calibrated according to the Table below by using 2017 Energy Balance Table.

Table 6.3. Sectoral energy resource supply levels.

Industry		**Residential**		**Commercial and Services**		**Transport**		**Agriculture**	
Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ
Hard Coal	166,3	Hard Coal	102,3	Hard Coal	97,9	Petroleum Products	1162,1	Petroleum Products	122,9
Lignite	73,9	Lignite	39,9	Lignite	14,2	Natural Gas	18,2	Natural Gas	4,0
Asphaltite	0	Asphaltite	0,5	Electricity	252,7	Bioenergy and Waste	5,2	Geothermal	25,4
Coke	142,8	Coke	0	Other Heat	1,4	Electricity	4,6	Electricity	24,4
Cokegas	17	Cokegas	0	Geothermal	19,8				
Natural Gas	378,6	Natural Gas	466,8	Natural Gas	128,7				
Petroleum Products	179,7	Petroleum Products	10,2	Petroleum Products	36,8				
Electricity	412,7	Electricity	195,3						
Other Heat	94	Bio-waste	85,4						
Solar	12,3	Geothermal	32,5						
		Solar	22,9						
Total	**1477,3**	**Total**	**955,8**	**Total**	**551,5**	**Total**	**1190,1**	**Total**	**176,7**

6.2. Calibration of the Installed Capacity

In order to calibrate the installed capacity, the data from MENR was used. As explained in the above section, installed capacity of Turkey exceeded 90 GW as of 2019. Total renewable capacity almost reached to 50%, due to contribution of hydro followed by wind, solar and geothermal respectively. Total capacity of domestic resources, including renewables and domestic coal rose to 61,45% which was 52,4% in 2010.

For the calibration of the year 2017, following table was used.

Table 6.4. Installed electricity capacity and electricity generation by resources 2017.

INSTALLED CAPACITY (MW)	**2017**
Natural Gas	26.639
Imported Coal	8.794
Domestic Coal	10.555
Hydro	27.273
Biomass and Waste Heat	634
Geothermal	1.064
Wind	6.516
Solar	3.421
Other	304
TOTAL	85.200

ELECTRICITY GENERATION BY SOURCES (PJ)	**2017**
Lignite	146,5
Hard Coal	11,8
Asphaltite	8,6
Imported Coal	184
Natural Gas	397,7
Hydraulic	209,5
Wind	64,4
Solar	10,4
Geothermal	22,1
Biomass	10,7
Other	4,3
TOTAL	**1070**

Installed capacity and electricity generation data were adjusted according to Table above. On the other hand, in the Base scenario installed capacity targets in the MENR Strategic Plan (2019-2023) were entered into the model. Total maximum available wind capacity of 48 GW (11 GW offshore and 37 GW) was also fixed as a constraint in the model so that maximum wind capacity cannot exceed 48 GW any year between 2012-2057 in any scenario.

Moreover, nuclear capacity was also considered in the scenario modelling. First unit of Akkuyu NPP will be operation by 2023. It is also planned that whole NPP with 4.8 GW capacity will be operational gradually between 2023-2026. Therefore, in the model by 2027, 4.8 GW of nuclear capacity was added. On the other hand, it has been assumed that second NPP of 4.8 GW will be also operational by 2037 so that total nuclear capacity will be 9.6 GW between 2037-2057 in all scenarios.

6.3. Calibration of the Demand

The demand module of the BUEMS is analyzed under five categories being industry, residential, agriculture, transport and services. For the calibration of the end use demand of these sectors, Energy Balance Table of 2017 was used as given in the section above. In the Energy Table Balance 2017 service and commercial sector are covered together so that for the service sector in the model service sector is considered as sum of service and commercial sector.

The table below shows the end use demand of the abovementioned sectors.

Table 6.5. End use demand of the sectors by supply resources.

Industry		**Residential**		**Commercial and Services**		**Transport**		**Agriculture**	
Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ	Energy Sources	PJ
Hard Coal	166,3	Hard Coal	102,3	Hard Coal	97,9	Petroleum Products	1162,1	Petroleum Products	122,9
Lignite	73,9	Lignite	39,9	Lignite	14,2	Natural Gas	18,2	Natural Gas	4,0
Asphaltite	0	Asphaltite	0,5	Electricity	252,7	Bioenergy and Waste	5,2	Geothermal	25,4
Coke	142,8	Coke	0	Other Heat	1,4	Electricity	4,6	Electricity	24,4
Cokegas	17	Cokegas	0	Geothermal	19,8				
Natural Gas	378,6	Natural Gas	466,8	Natural Gas	128,7				
Petroleum Products	179,7	Petroleum Products	10,2	Petroleum Products	36,8				
Electricity	412,7	Electricity	195,3						
Other Heat	94	Bio-waste	85,4						
Solar	12,3	Geothermal	32,5						
		Solar	22,9						
Total	**1477,3**	**Total**	**955,8**	**Total**	**551,5**	**Total**	**1190,1**	**Total**	**176,7**

According to 2017 data, 6083,6 PJ of total energy supplied in Turkey. The highest sector consuming is industry sector with approximately 1478 PJ followed by transport and residential sector.

Total coal supply is 1656 PJ, natural gas supply is 1855 PJ; petroleum products is 619 PJ; crude oil supply is 1235 PJ respectively.

For the future projections of the end-use sectoral demand, sub-sectoral statistical data and GDP growth rate forecasts are used from relevant institutions as well as expert views.

7. SCENARIOS AND RESULTS

Before establishing a scenario, the model was calibrated by using 2012 and 2017 supply data by using updated energy balance tables and TEİAŞ installed capacity values. Demand data was updated by using Turkish sectoral activity data based on expert views.

7.1. Base (Strategic Plan) Scenario

In the base scenario the latest Strategic Plan of the Ministry of Energy and Natural Resources (MENR) (2019-2023) was taken into account.

Renewable and coal installed capacity targets were entered into model for the year 2023.

Table 7.1. MENR strategic plan targets.

Domestic Coal Installed Capacity	**Year 2023 Target (GW)**
Solar Installed Capacity	10
Wind Installed Capacity	11.8
Hydraulic Installed Capacity	32
Geothermal and Biomass Installed Capacity	2.8
Domestic Coal Installed Capacity	14.6

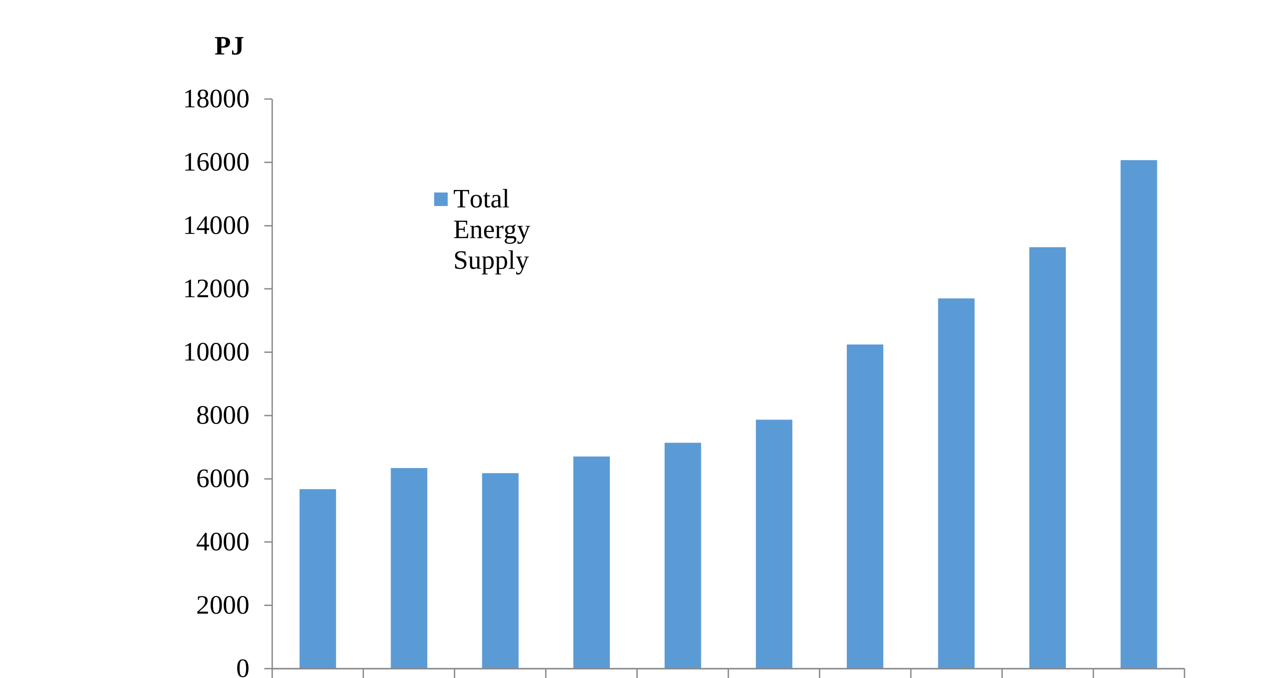
It has been also assumed that in 2023 4 GW of first nuclear plant will be fully operational and second plant having also 4 GW of capacity will be operational by 2037.

The maximum available onshore wind installed capacity was adjusted to 37 GW and hydraulic capacity was adjusted to 39 GW.

Under these assumptions the results of the base scenario are as follows;

7.1.1. Demand Technologies

As indicated above demand technologies are sub-grouped as agriculture, industry, residential, transport and services. Below, the results of each subgroup and total primary energy supply are given;



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Total Energy Supply	5669	6342	6181	6707	7140	7862	10243	11698	13321	16067

Figure 7.1. Primary energy supply in Base scenario.

According to the base scenario the total primary energy supply of Turkey reaches to 16067 PJ which was 5669 PJ in 2012. This corresponds to an increase of almost %200 in primary energy supply. This results are in consistency with the study made by Günel, (2017) for the year 2052. On the other Işık, (2016) found that for the year 2052 the energy supply would exceed 25000 PJ according to BUEMS Base scenario.

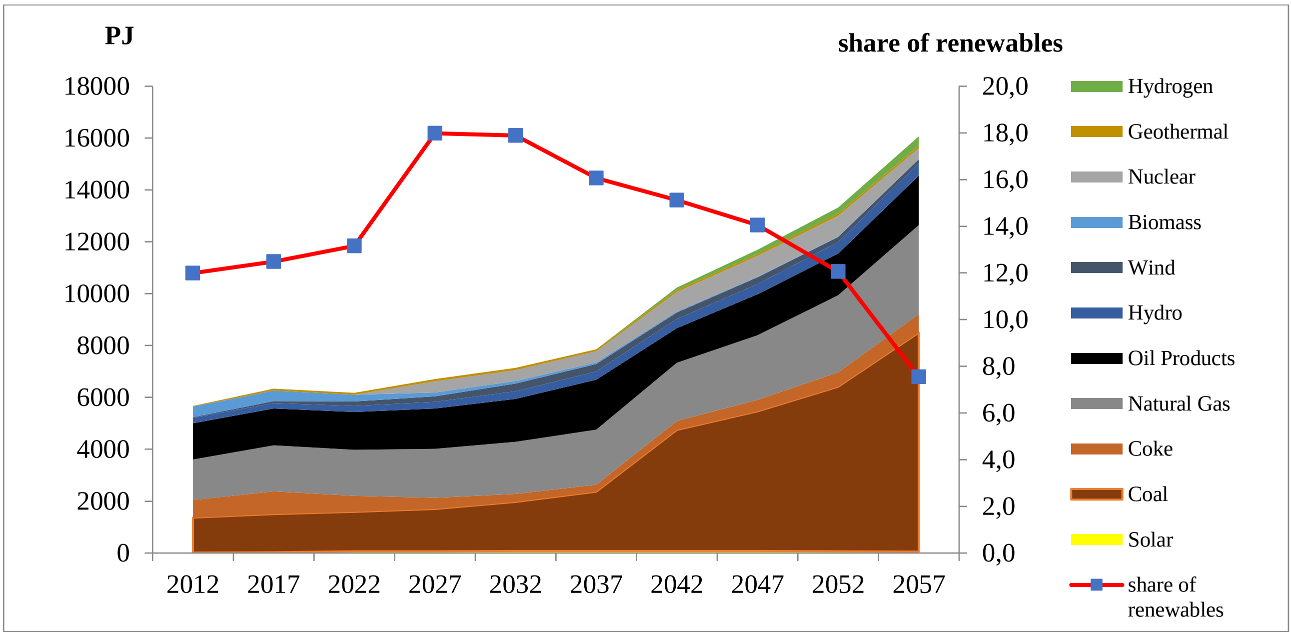


Figure 7.2. Primary energy supply by fuel in Base scenario.

In figure above, the distribution of fuels used for primary energy supply between 2012 and 2057 can be seen. According to data above the significant increase is observed in total coal supply. Coal supply increases from 1339 PJ from 2012 to 8435 PJ in 2057. Natural gas supply increases from 1564 PJ to 3436 PJ in the same period. Therefore, the share of renewables decreases from 16.9% to 7.5% during the same period. Starting from 2027 a penetration of nuclear supply is observed. The share of nuclear supply in 2057 is approximately 2.5% stemming from electricity generation. Another important penetration is the use hydrogen between 2042-2057. In this period model tends to invest in hydrogen which will be used in transport sector in respective years.

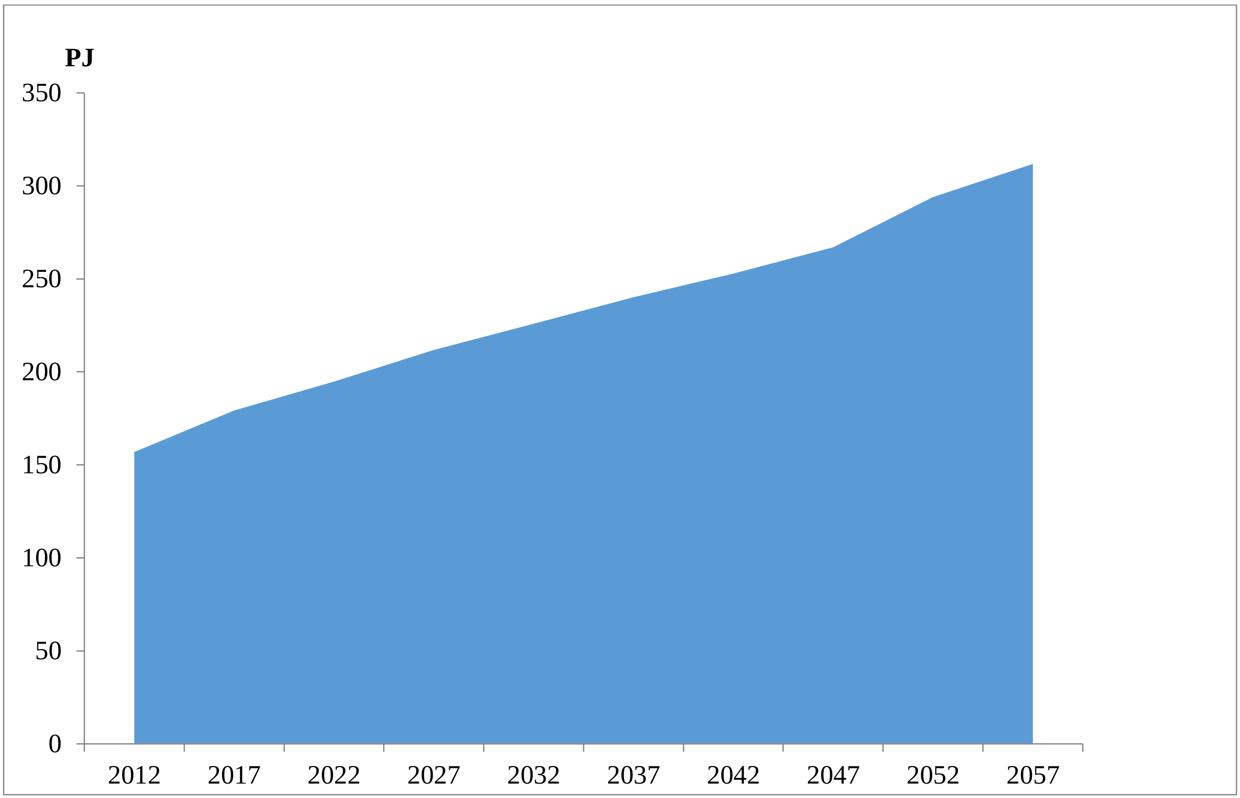


Figure 7.3. Agriculture sector energy demand in Base scenario.

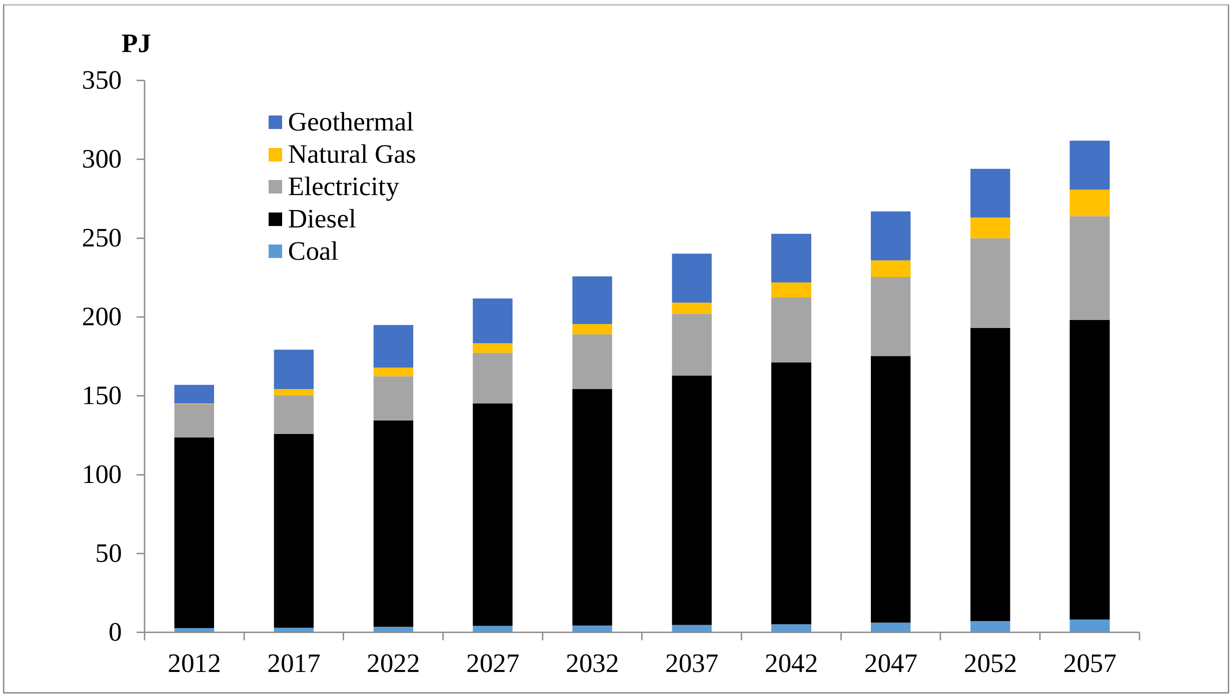


Figure 7.4. Agriculture sector energy demand by fuel type in Base scenario.

In the base scenario the total energy demand of agriculture sector increases from 157 PJ to almost 312 PJ in between 2012-2057 driven by considerable amount of increase in diesel consumption followed by electricity as indicated in the figures above. It is possible to see that coal consumption in agriculture sector is negligible. Although there is a slight increase in the use of geothermal and natural gas, the sector is dominated by diesel and electricity as primary fuel.

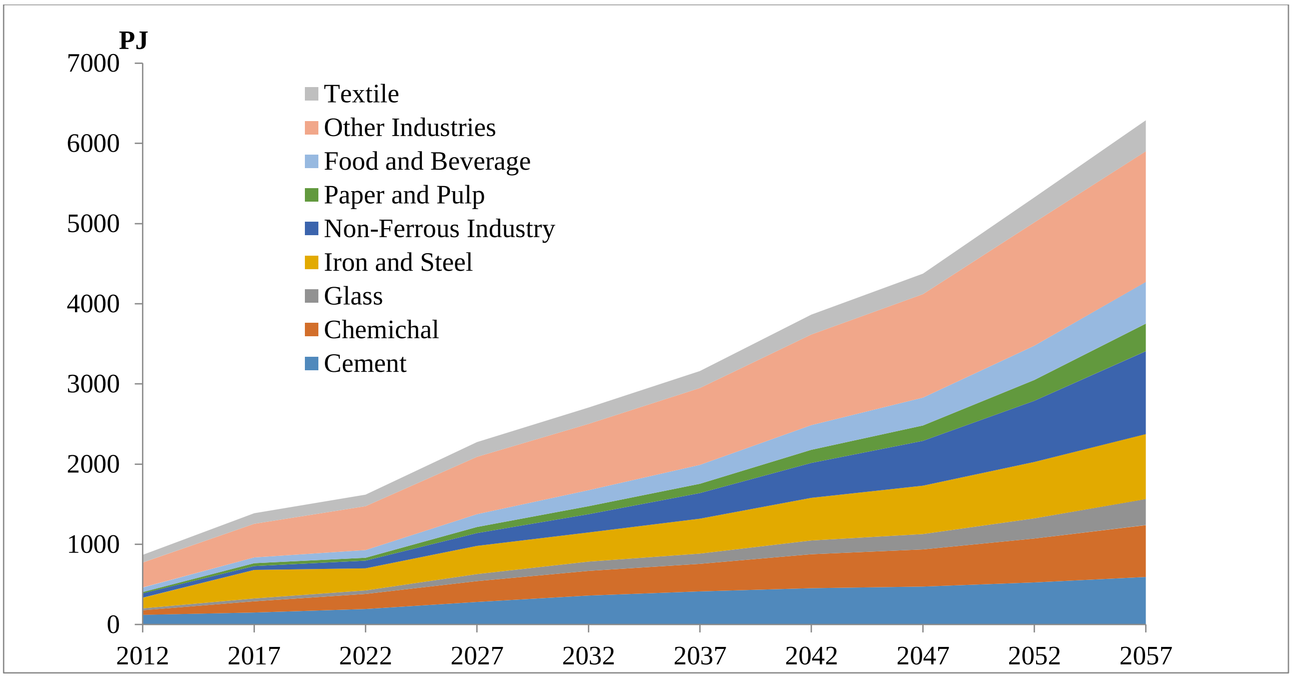
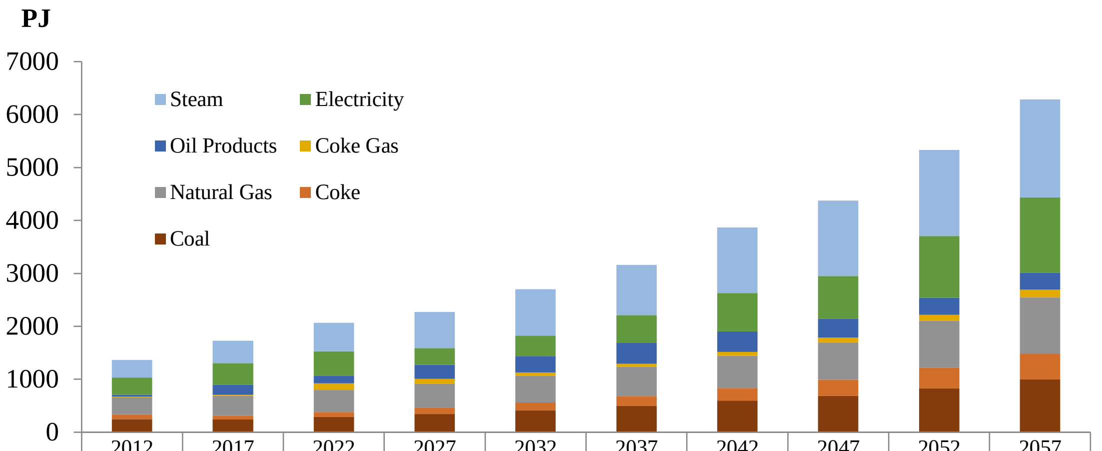


Figure 7.5. Industry sector energy demand in Base scenario.



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Steam	330,4	421,7	538,3	687	876,8	950,6	1236,5	1426,3	1621,7	1852,6
Electricity	324	412,7	459,3	312,3	384,3	526,7	723,6	806	1166,4	1426
Oil Products	39,8	185	148	268,5	313	392	391	356	321	316
Coke Gas	13,3	17	126,8	88,7	62,1	54,7	69,8	89,1	113,8	145,2
Natural Gas	319	378,6	416,4	458,1	503,9	554,3	609,7	704,1	890,5	1061,3
Coke	87,7	70,1	89,5	114,2	145,8	186,1	237,5	303,2	387	493,9
Coal	248,8	240,2	288,2	345,8	415	498	597	689,8	827,7	993,3

Figure 7.6. Industry sector fuel consumption in Base scenario.

The total industrial energy demand rises from 868 PJ in 2012 to 6288 PJ at the end of 2057. Considerable amount of rise in the demand was observed in non-ferrous and iron and steel industry from 52.8 PJ to 1032 PJ and from 133.3 PJ to 811 PJ respectively. Other industries including automobile, refineries, engineering etc., show the highest amount of increase from 310.6 PJ to 1629 PJ. From fuel demand perspective, steam demand rises from 330.4 PJ to 1853 PJ. Besides, coal, coke and natural gas demand is also in stable growth till 2057. Coal demand increases to almost 1000 PJ at the end of modeling period from 248.8 PJ. Similarly, natural gas consumption exceeds 1000 PJ and reaches to 1061 PJ in the year 2057 which was 319 PJ in the year 2012.

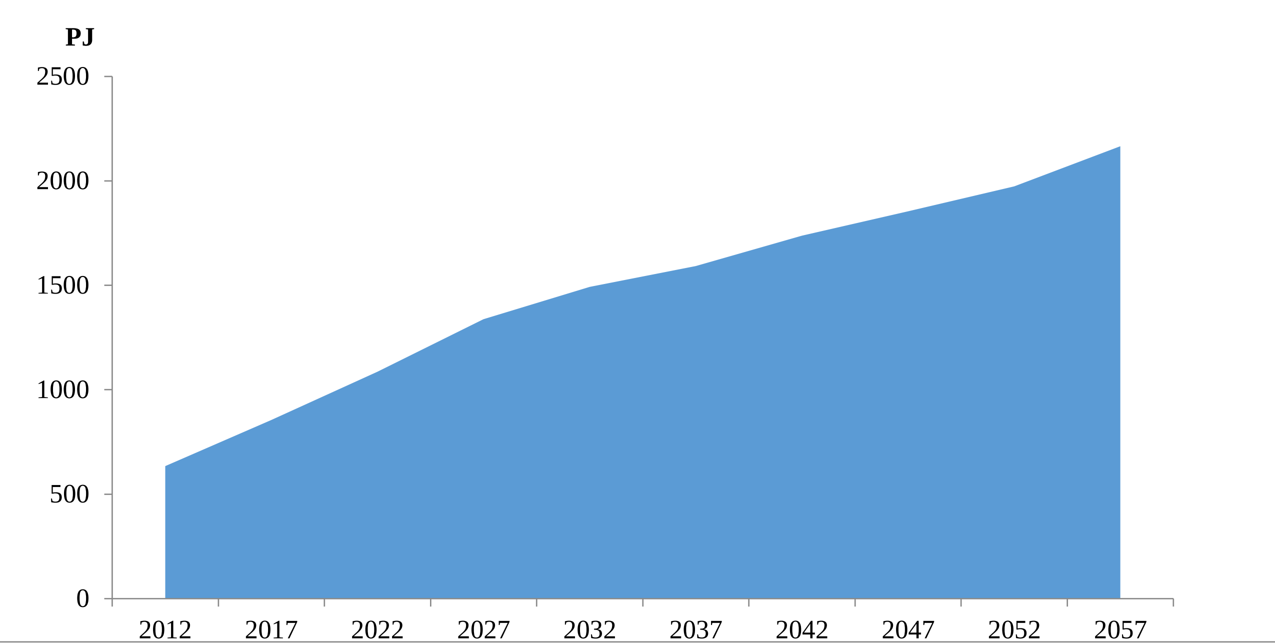
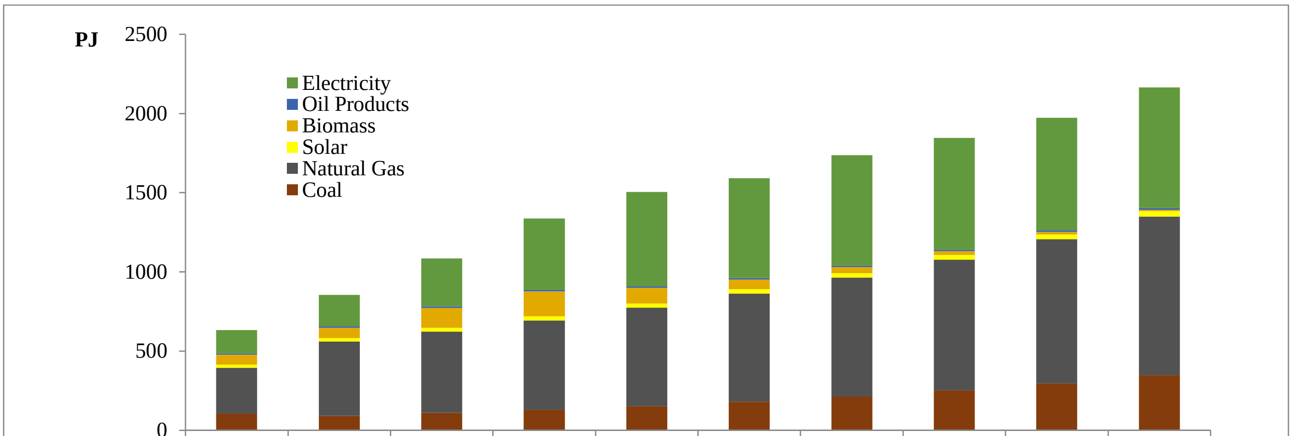


Figure 7.7. Residential sector energy demand in Base scenario.



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Electricity	148	197,4	303,4	449,9	595	628,9	696,3	703	711,4	762,6
Oil Products	9,1	10,6	10,6	10,6	10,6	10,6	10,6	10,6	10,6	10,6
Biomass	62	65	125	158,5	98,4	61,1	37,9	23,5	14,6	9
Solar	20,9	22,5	23,7	24,9	26,1	27,4	28,8	30,2	31,7	33,3
Natural Gas	287	466,7	513,4	564,8	621,3	683,4	751,7	826,9	909,6	1000,6
Coal	107	93	109,7	129,4	152,8	180,3	212,7	251	296,2	349,5

Figure 7.8. Residential sector energy demand by fuel type in Base scenario.

Residential sector energy demand rises from 634 PJ to 2165.9 PJ between 2012-2057 corresponding to 129% increase in the same period. The growth in the energy demand is mainly led by natural gas and electricity. Natural gas demand exceeds 1000 PJ in 2057 from 287 PJ in 2012, which is the main fuel for space and water heating and cooking in Turkey. The electricity demand shows also a significant increase in the same period reaching to 762.6 PJ in 2057. There is a slight rise in the coal, which is mainly used in space heating, and this result is in accordance with the Turkey's policy to expand the use of natural gas in Turkey as a cleaner fuel than coal.

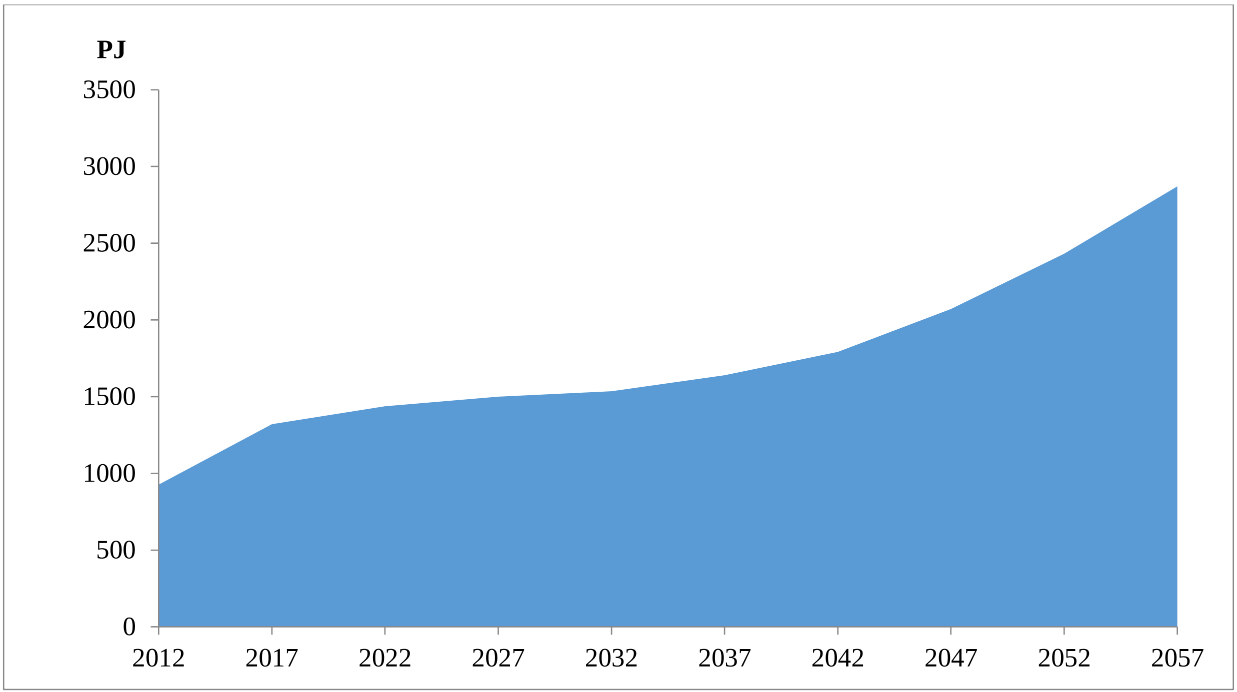
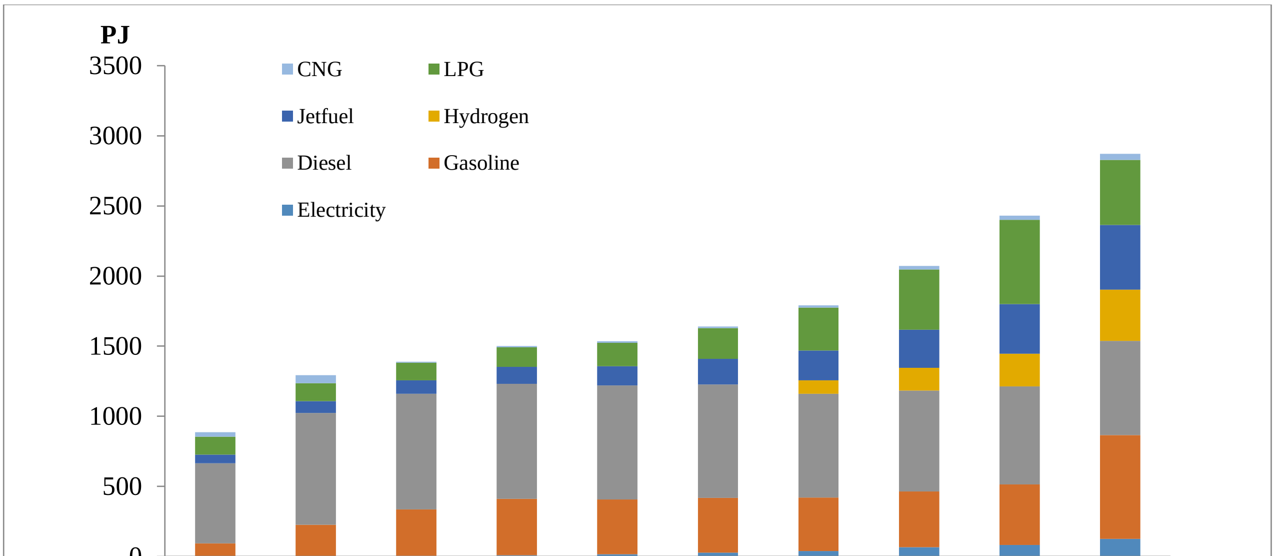


Figure 7.9. Transport sector energy demand in Base scenario.



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
CNG	30,9	56,5	6,6	8,4	9,8	12,2	16,5	24,3	30,5	42,5
LPG	127,5	127,5	127,5	140,2	168,3	218,7	306,3	428,8	600,3	464,1
Jetfuel	63,1	84,2	94,6	120,4	136,5	182,1	210,4	271,5	353	461,6
Hydrogen	0	0	0	0	0	0	98	162	235	364
Diesel	570,9	796,9	825,7	820	813	808,7	740	720	698	673
Gasoline	92,6	224,1	330,8	402,1	389,8	391,6	380,6	398,6	431,3	740,4
Electricity	0,7	2,9	4,5	9,3	17,1	26,9	39,1	66	83	125

Figure 7.10. Transport sector energy demand by fuel type in Base scenario.

The energy demand of the transport sector rises to almost 3000 PJ in 2057 which is 926 PJ in 2012 corresponding to an increase of 223% although there are some fluctuations in the demand in 2027 and 2032. The increase is driven by gasoline and diesel between 2012 and 2037. However, after the year 2037 model tends to invest in hydrogen as a novel technology and demand is dominated by hydrogen between 2042-2057. Hydrogen demand reaches to almost 364 PJ in 2057. On the other hand, for hydrogen supply the model uses coal and natural gas which contributes to formation of GHG gases after 2042 and it is added to industrial sector emissions.

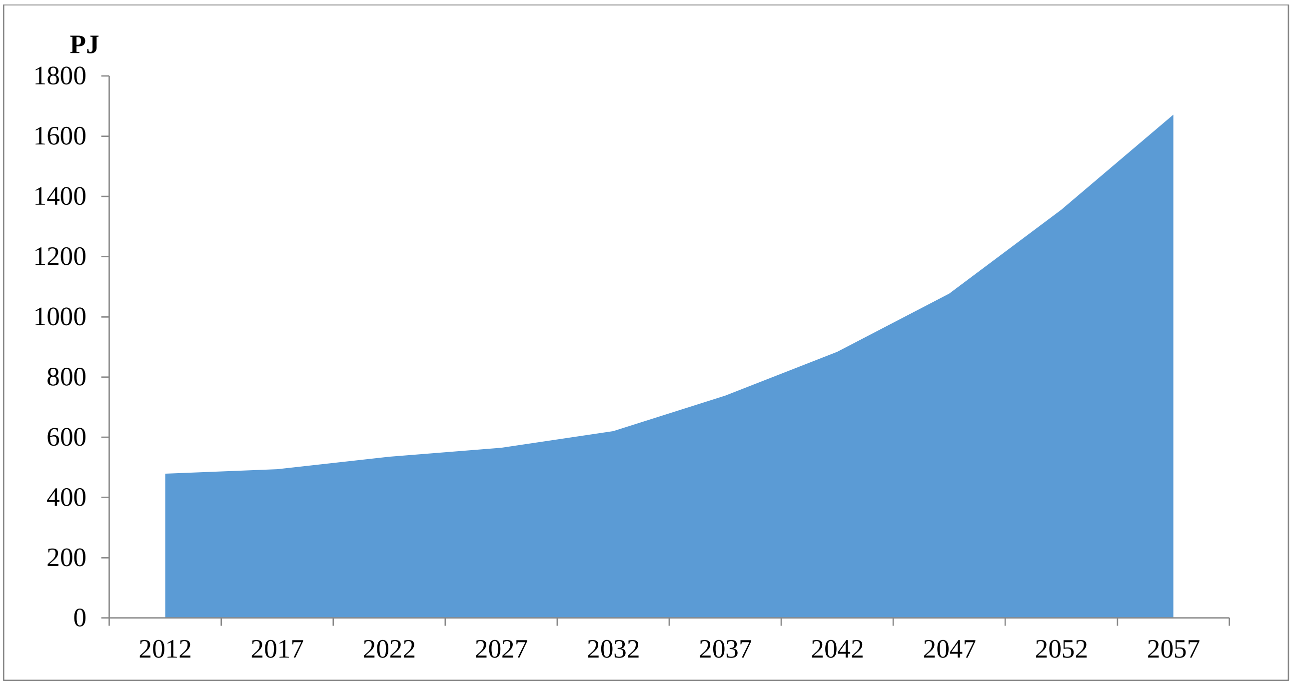
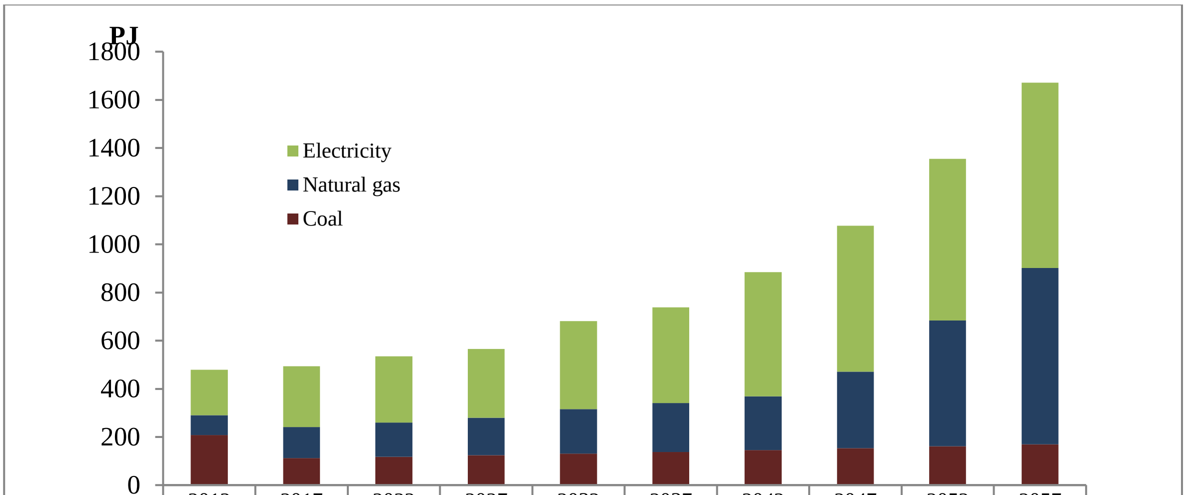


Figure 7.11. Service sector energy demand in Base scenario.



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Electricity	189	252,7	275,4	285,3	365	396,5	515	606,1	671,9	770
Natural gas	82	128,7	141,5	155,7	185	203,5	223,8	317,8	522,8	731,8
Coal	208	112,1	118	124,2	130,8	137,8	145,1	152,8	160,9	169,4

Figure 7.12. Service sector energy demand by fuel type in Base scenario.

Finally, from demand side, the energy demand of service sector rises 479 PJ in 2012 to 1671.4 PJ in 2057. From fuel type, the increase is driven by electricity and natural gas, as expected, since these fuels are mostly used in heating, cooking and lightening activities. The increase in natural gas and electricity demand are almost proportional and reaches to 731.8 PJ and 770 PJ in the year 2057 respectively by gradual increase. On the other hand, the coal consumption decreases from 208 PJ in 2012 to 169.4 PJ in 2057. In 2022 the coal consumption reaches its lowest level, being 118 PJ, and then starts slowly increasing till 2057.

7.1.2. Supply Technologies

From supply point of view total electricity generation, electricity installed capacity and electricity generation results will be given.

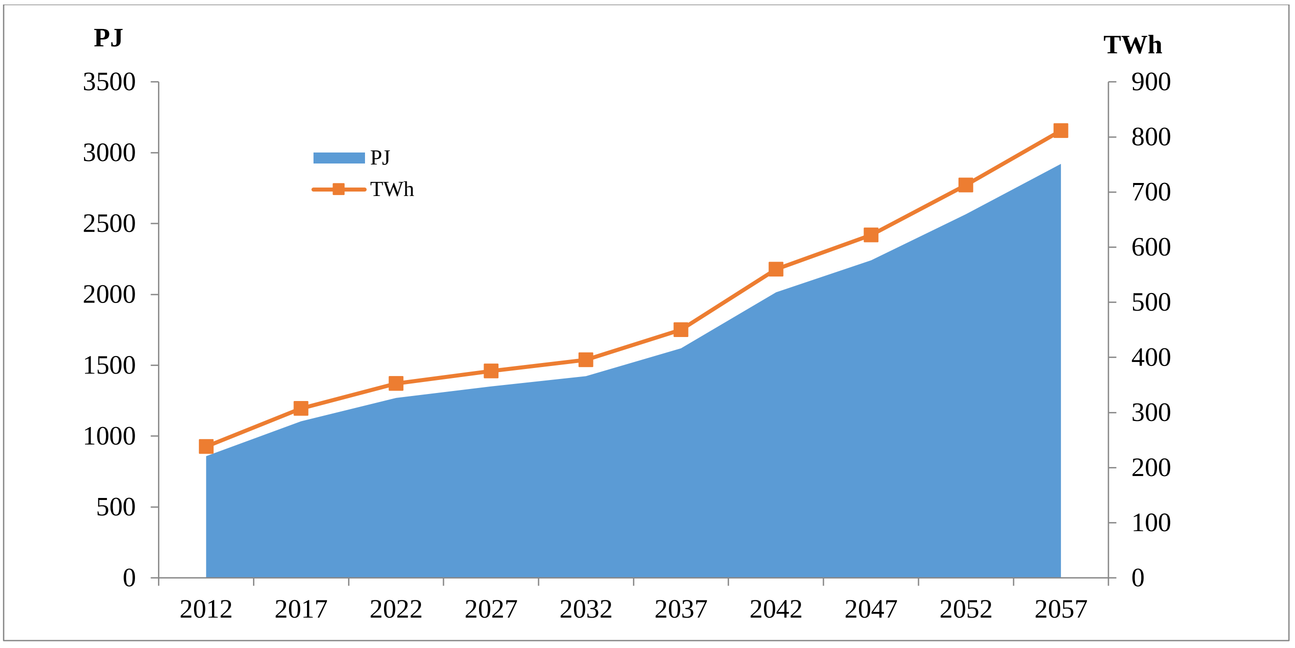


Figure 7.13. Total electricity generation in Base scenario.

According to supply module of the model the electricity generation rises to 811 TWh at the end of 2057, which was 238 TWh in 2012 corresponding to an increase of 240% to meet the growing demand. This result showed similarity with the study carried out by Işık, (2016) who found that Turkish electricity demand rose to 824 TWh by the end of 2052. Moreover, in order to make a comparison, the official results of the electricity demand published by MENR is given below

Table 7.2. MENR long-term electricity demand projections (MENR, 2018).

Year	MENR (Low)	MENR (Reference)	MENR (High)	**BUEMS (Base)**
2022	353.2	359.6	366.4	352
2027	416.6	436.6	458.9	375
2032	476.3	511.6	552.9	454
2037	534.0	585.3	644.9	523

The long-term electricity demand projection is carried out by General Directorate of Energy Affairs as an obligatory duty coming from Electricity Market Law (Law No: 6446). It is carried out covering next 20 years and updated every 2 years. The latest available data belongs to the year 2018. From the table above, it can be seen that the results of the BUEMS base scenario in terms of electricity generation is mostly consistent with the values of MENR Low scenario.

In order to meet this electricity demand, the modelled installed capacity evaluation is given below;

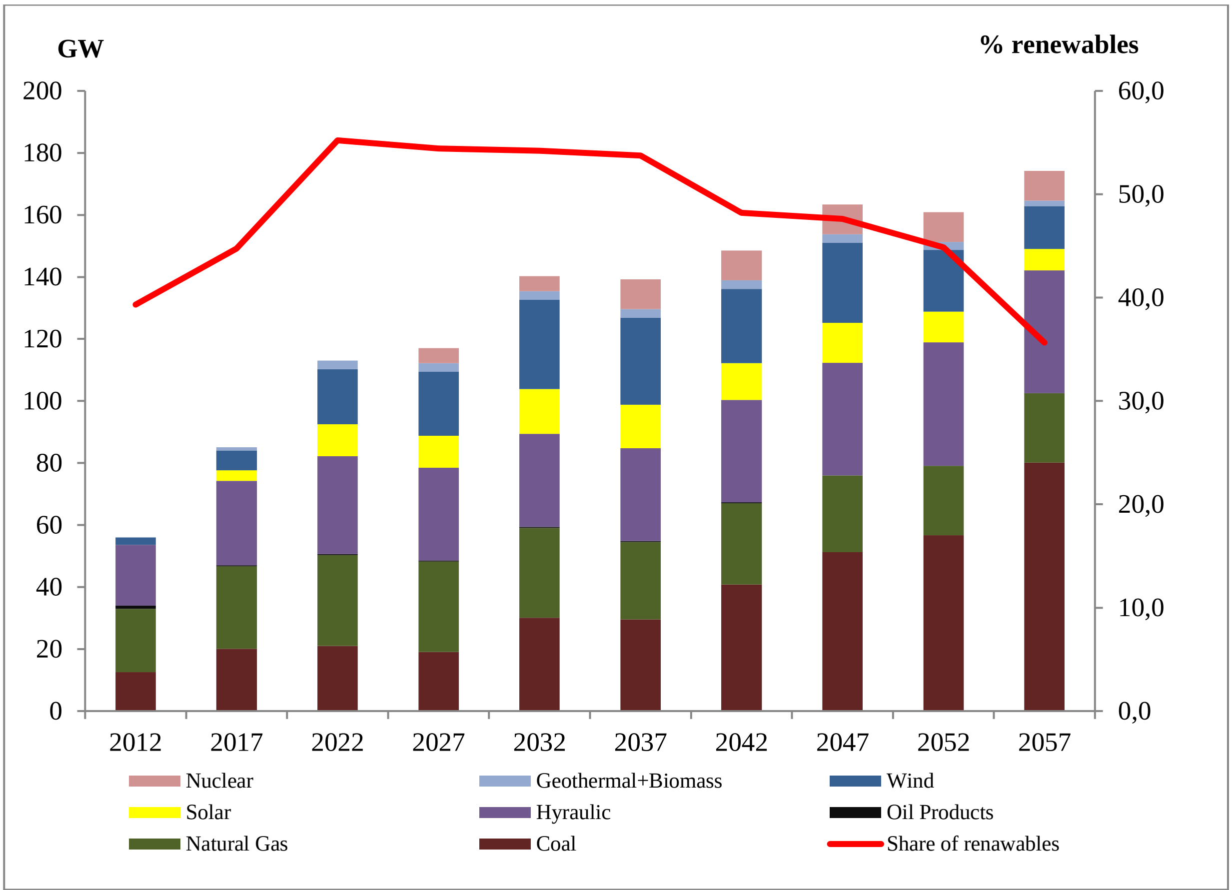


Figure 7.14. Installed capacity evaluation in Base scenario.

As can be seen from the figure above the installed capacity of Turkey exceeds 170 GW (174.2 GW) at the end of 2057 from 56.1 GW in 2012. The highest increase is observed in total coal capacity, rising from 12.6 GW to 80.1 GW in 2057. The capacity of natural gas increases slightly till 2032 and then starts slowly decreasing and reaches to 22.4 GW. This is consistent with Turkey's policy of reducing the share of natural electricity portfolio to decrease gas imports. Between 2022-2037, the total share of renewables and rest of the fuels are equal to each other but then share of renewables starts dropping to 35.6% in total capacity. The total share of renewables was 39.3% in 2012 and this share drops to 35.6% in 2057. From renewables perspective the highest value of installed capacity belongs to hydraulic capacity 39.6 GW, followed by wind and solar being 13.9 and 6.9 GW. It should be noted that hydraulic capacity reaches its maximum in 2057 whereas onshore wind capacity is far from reaching its technical maximum capacity for the same year. Geothermal and biomass have the lowest capacities among renewables. With the addition of two nuclear power plants the share of nuclear in total installed capacity rises to 5.5%. According to 11th Development Plan of Turkey, the total electricity installed capacity of Turkey reaches to 109 GW by the end of 2023. To make a comparison with official data, by the year 2022 Turkey's installed capacity exceeds 113 GW in Base Scenario. On the other hand, Günel, (2017) concluded that the total installed capacity reached to almost 110 GW by the end of 2052 according to BUEMS Base scenario 68 GW of which consist of coal-based power plants.

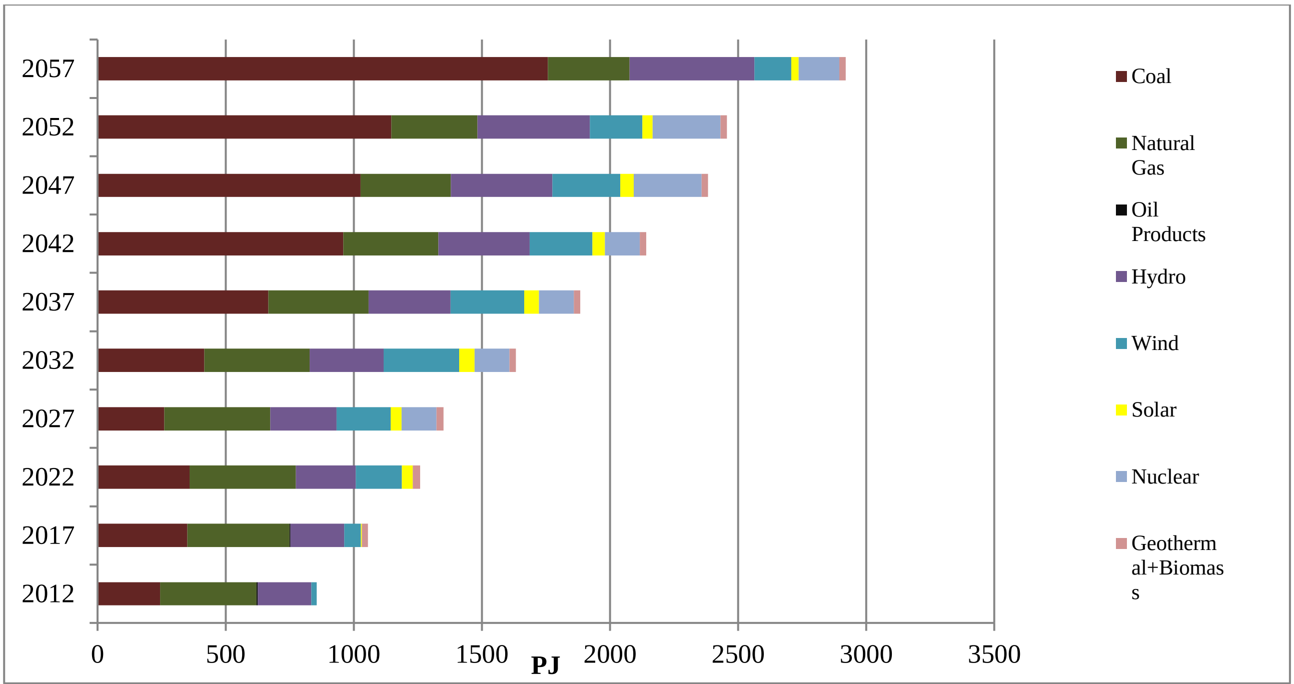


Figure 7.15. Electricity generation by fuel type in Base scenario.

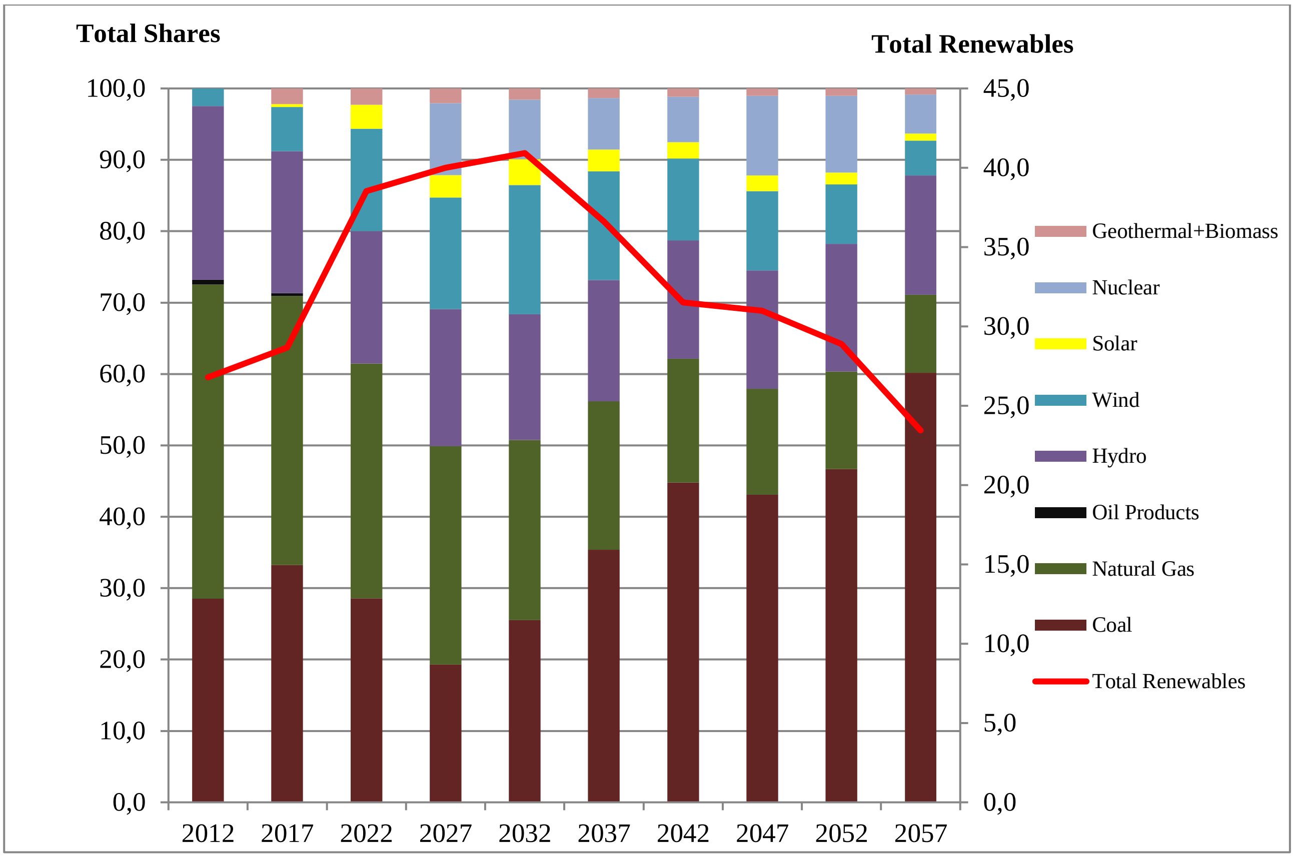


Figure 7.16. Share of fuels in electricity generation in Base scenario.

As can be seen from the figures above, from electricity generation perspective, coal becomes dominant source till 2057. Its share rises from 28.5% in 2012 to 60.2% in 2057. On the other hand, we see a dramatic decrease in the share of natural gas, the share of which drops from 44% in 2012 to almost 10% in 2057. As discussed above the share of natural gas in electricity generation is targeted to decrease. According to 11th Development Plan of Turkey, the share of natural gas in total electricity generation would reduce to 20.7% by 2023. According to base scenario of the model this target has been achieved by 2032.

On the other hand, total share of renewables in electricity generation was 26.8% in 2012 and it increases up to 40% in 2032, however after this year it starts dropping dramatically to 23.4% in 2057, even lower than the share of 2012. Hydraulic has always the highest share among renewables resources followed by wind and solar. The share of hydraulic is 24.3% in 2012 and drops to 16.7% in 2057. Contrary to hydraulic, the share of wind and solar increases from 2.5% to 18.1% and from 0 to 3.6% respectively in 2032. However, after 2032 their share also starts decreasing till 2057 being 4.9% for wind and 1.0% for solar.

In 2027 penetration of nuclear is observed by having 10% share in total electricity generation. At the end of 2057, share of nuclear drops to 5.5%. From the base scenario, it can be concluded that the share of fossil fuels will be higher than renewables in electricity generation and coal would be the dominant fuel among fossil fuels. These results will affect the total emission values which will be investigated below. Işık, (2016) found that by the 2052, the share of coal, natural gas and total renewables in total electricity generation would be 69% 21% and 10% respectively. The results of this study for the coal-based generation are coherent with Işık, (2017). On the other hand, we concluded that by the year 2057 there would be more place for renewables in electricity generation.

7.1.3. Total Emissions

As a result of demand and supply data, the result of the total CO_2 emission values is given below.

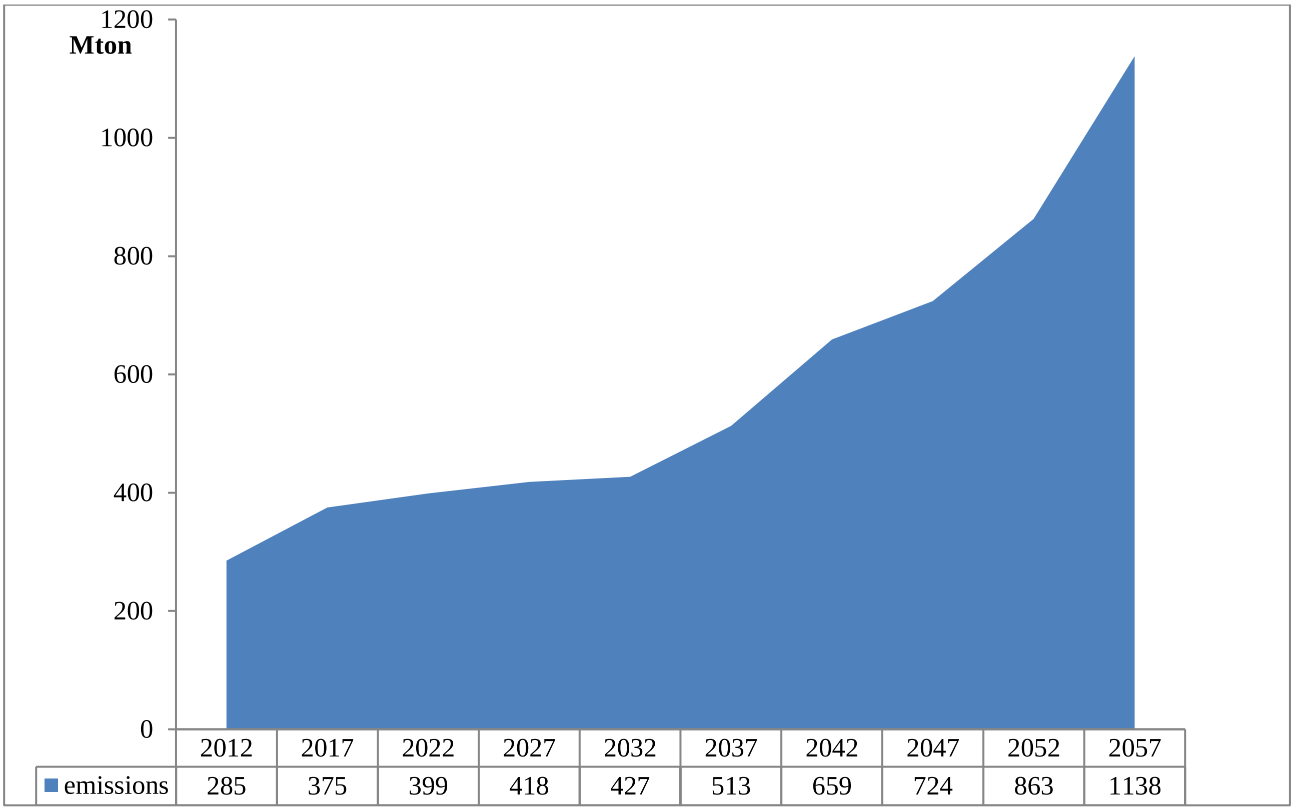


Figure 7.17. Total CO_2 emissions in Base scenario.

As a result of the supply data of the Base Scenario, the total emissions in Turkey exceed 1000 Mton (Million Tons) in 2057 and reaches to 1138 Mton from 285 Mton in 2012. The "% change" in the figure shows the change compared to previous period. The total emissions increase by 300% between 2012-2057. Moreover, during this period emission does not reach a peak value, although there is decrease between 2022-2032, and tends to increase post 2057 period. Işık, (2017) found that total emissions increased to 1600 Mton due to fact that the author obtained higher primary energy supply than this study. On the other hand, Günel, (2017) concluded that total system emissions rose to over 800 Mton. These difference in values stem basically from model structure and available data used in the model.

The figure below shows the sectoral distribution of total emissions.

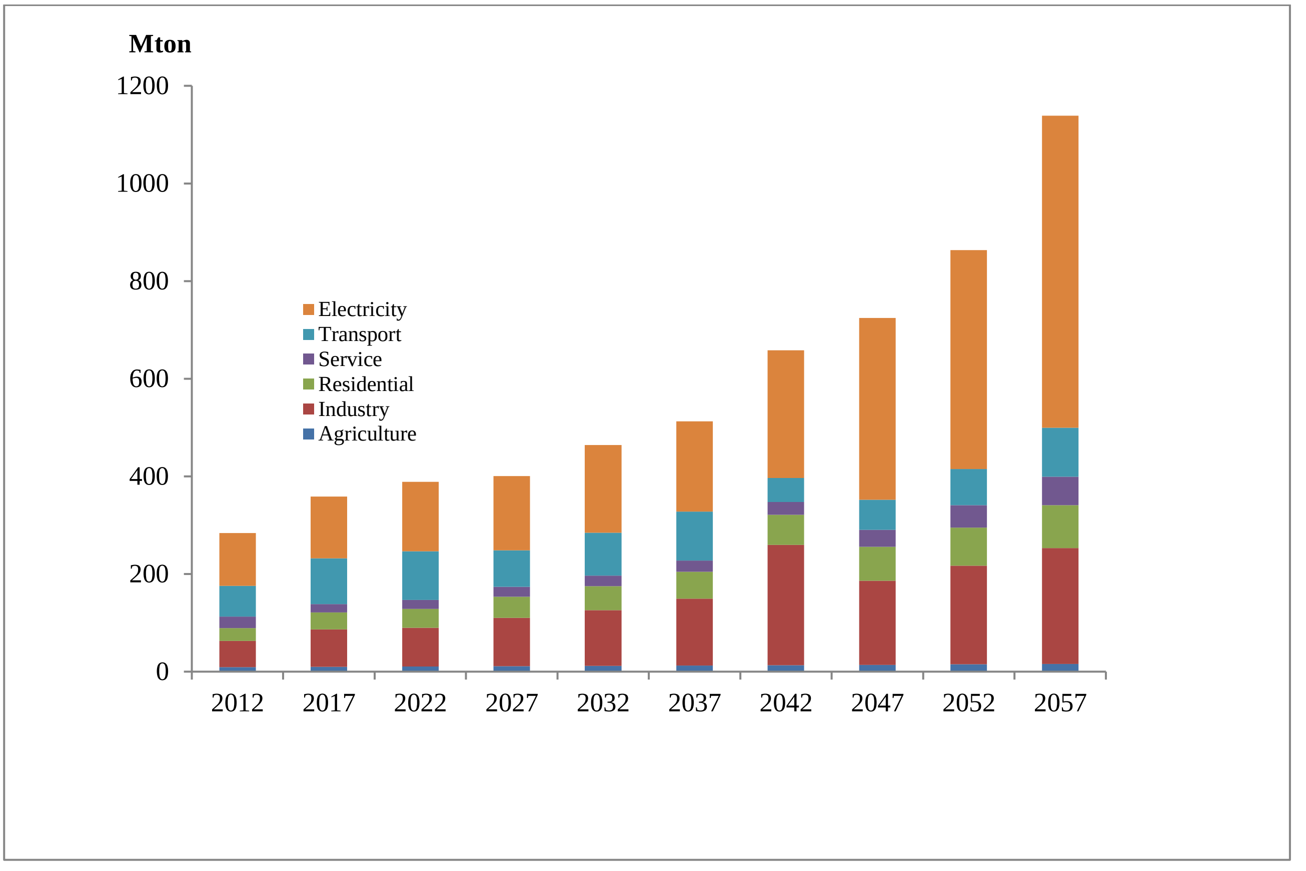


Figure 7.18. Sectoral CO_2 emissions in Base scenario.

As can be seen from the Figure 7.18, the highest emission value after among all sectors belongs to electricity generation.

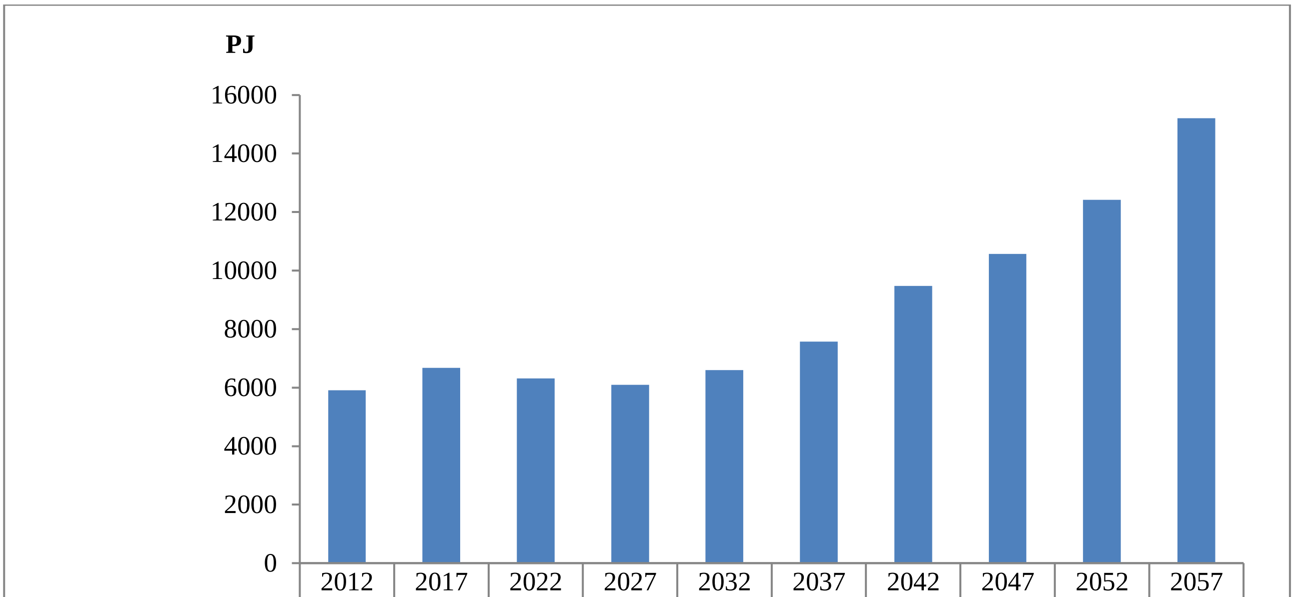
According to Base Scenario, emissions stemming from electricity generation has the highest share in total emission in 2057 by 56 %. On the other hand, throughout the modelling period its share is greater than any other sector. From the figure above, it can be seen that emissions from electricity generation was 152.2 Mton in 2022 and decreases to 126.8 Mton in 2027, where nuclear generation starts. As mentioned above in 2027 the share of electricity generation from nuclear reaches to 10% in total electricity generation. This result shows the importance of nuclear based electricity generation to prevent GHG emissions as indicated by various reports published by International Energy Agency (IEA, 2019) and Intergovernmental Panel on Climate Change (IPCC, 2018).

7.2. Emission Tax Scenarios

Under these scenarios all of the assumptions of Strategic Plan (Base) scenario are kept as they are. Additionally, 10$, 20$ and 30$/t$CO_2$ emission tax are applied to all sectors of the economy and to all emitted CO_2 without any free allowance. In the European Union the carbon price varied roughly between 20-30 $/t$CO_{2\text{-eq}}$ (DG Energy, 2020) in the last quarter of 2019 and the first quarter of 2020, so that a carbon price ranging between 10-30$ was chosen to see the effect of lower and greater carbon price. The results of these scenarios are mostly analyzed from power sector perspective such as installed capacity, electricity generation and related CO_2 emissions.

7.2.1. 10$ Tax Scenario

Under these scenario 10$ of environmental tax is applied to all sectors based on the assumptions of Base scenario. The results are as follows;



	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Total Energy Supply	5913	6680	6319	6093	6596	7577	9476	10565	12420	15203

Figure 7.19. Primary energy supply in 10$ tax scenario.

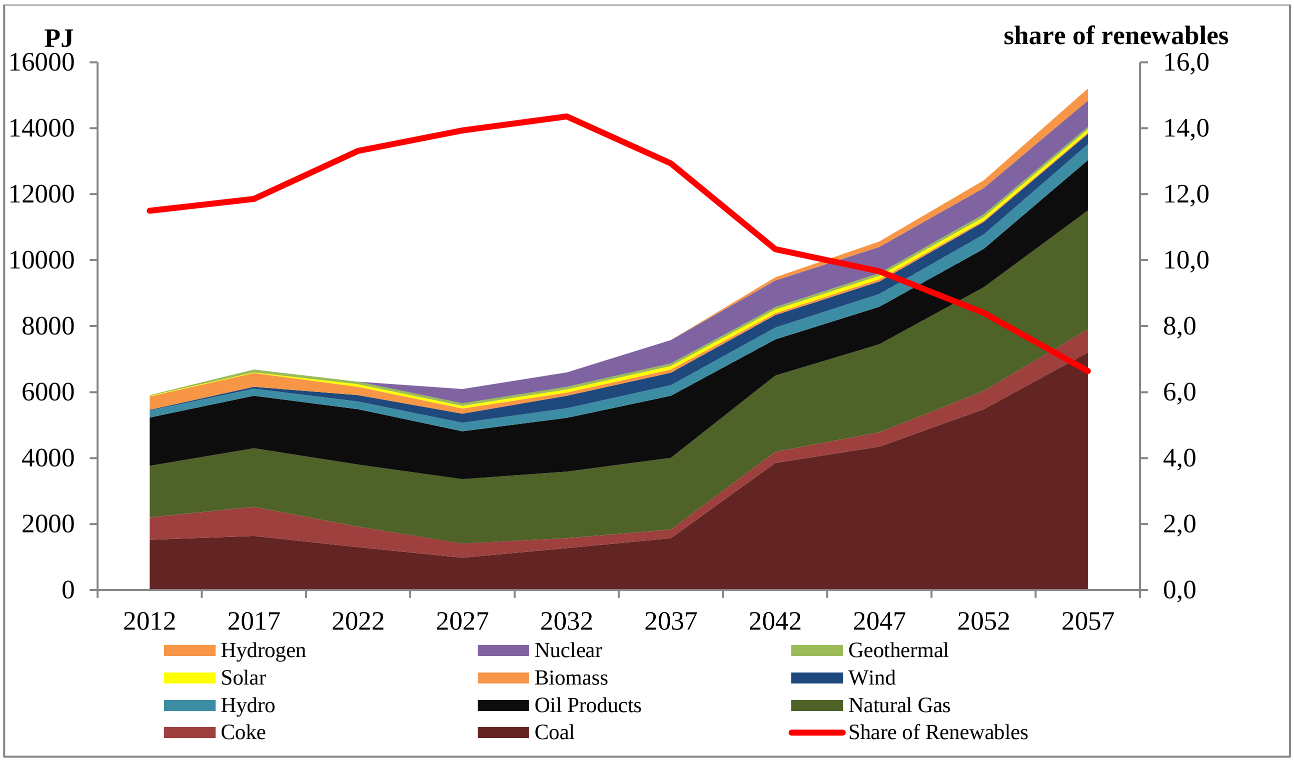


Figure 7.20. Primary energy supply by fuel in 10$ tax scenario.

From Figure 19 and 20, it can be seen that the total primary energy supply is 5913 PJ in 2012 and reaches to 15203 PJ in 2057 corresponding to an increase of 179%. Coal is the main resource in primary energy and it rises to 7201 PJ in 2057 followed by natural gas being 3599 PJ for the same year. The share of renewables is 11.5% in 2012 and it increases up to 14.4% in 2032, then starts decreasing and drops to 6.1% in 2057. From primary energy supply perspective, fossil fuels are dominant throughout the projection years. Comparing to Base scenario, the total primary energy supply drops from 15203 PJ in 10$ tax scenario. Due to the fact that there is CO_2 tax the amount of fossil fuels in total primary energy supply also decreases. For instance, in the Base scenario the amount of coal in total primary energy supply is 9852 PJ in 2057 whereas this value is 7201 PJ in 10$ tax scenario for the same year. On the other hand, value of natural gas shows a slight increase and reaches to 3599 PJ in 2057 in 10$ tax scenario, which is 3152 PJ in Base Scenario for the same year. From renewables perspective, the share of total renewables in primary energy supply was 5.9% in 2057 for the Base scenario and it increases to 6.1% in 10$ tax scenario for the same year.

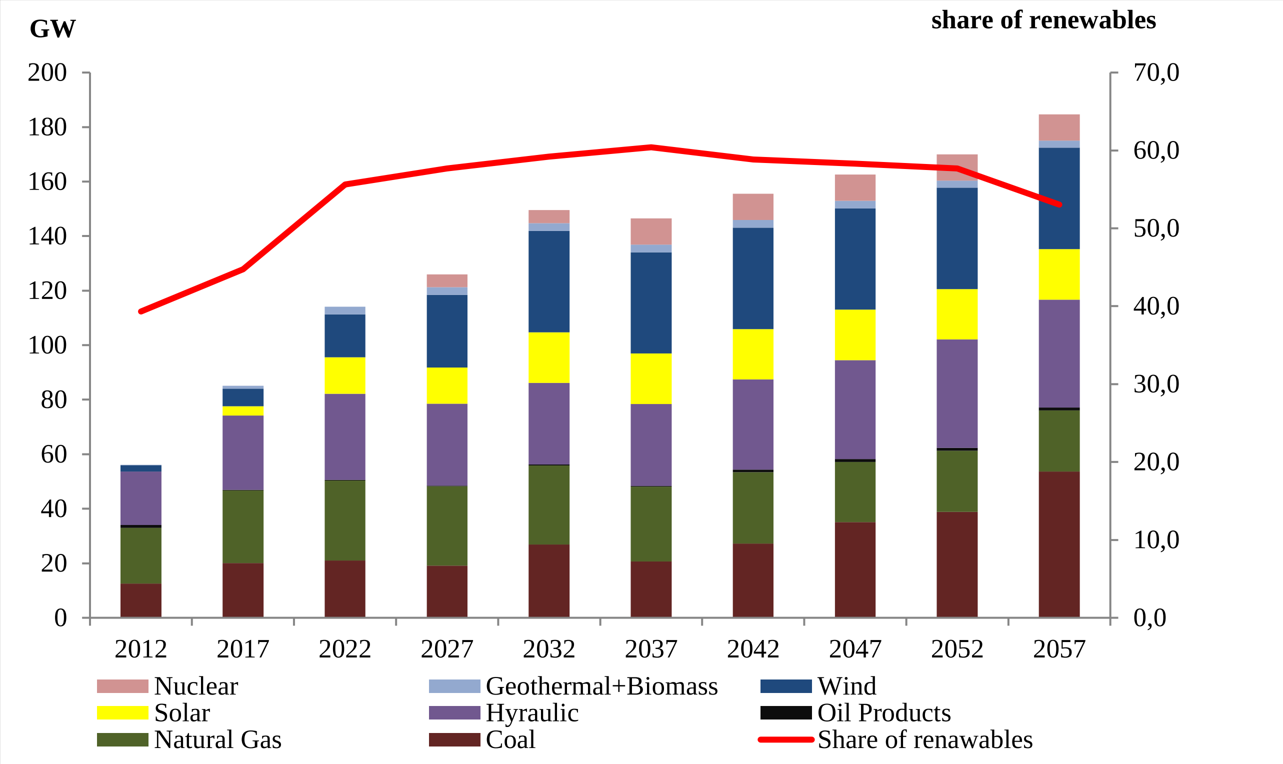


Figure 7.21. Installed capacity evaluation under 10$ tax scenario.

The total installed capacity exceeds 180 GW in 2057 in 10$ tax scenario, which is 174 GW in Base Scenario for the same year. The total coal capacity is 53.7 GW in 2057 and it is 80 GW in Base scenario therefore it shows a dramatic decrease due to environmental tax application. Natural gas capacity remains steady for the both scenarios. It is worth to mention that the model invests to wind capacity and total technical on shore capacity of wind in Turkey is utilized under this scenario and reaches to 37 GW in 2032 and remains unchanged till the end of 2057. The total share of renewables was 35.6% in Base scenario in it increases to 53% in 10$ tax scenario. Similar to wind, total hydro capacity is also used and reaches almost to 40 GW. Wind capacity also reaches its maximum in 2032 as 28.5 GW and remains unchanged till 2057. From these results it is possible to say that under environmental tax the model invests more on renewables as expected.

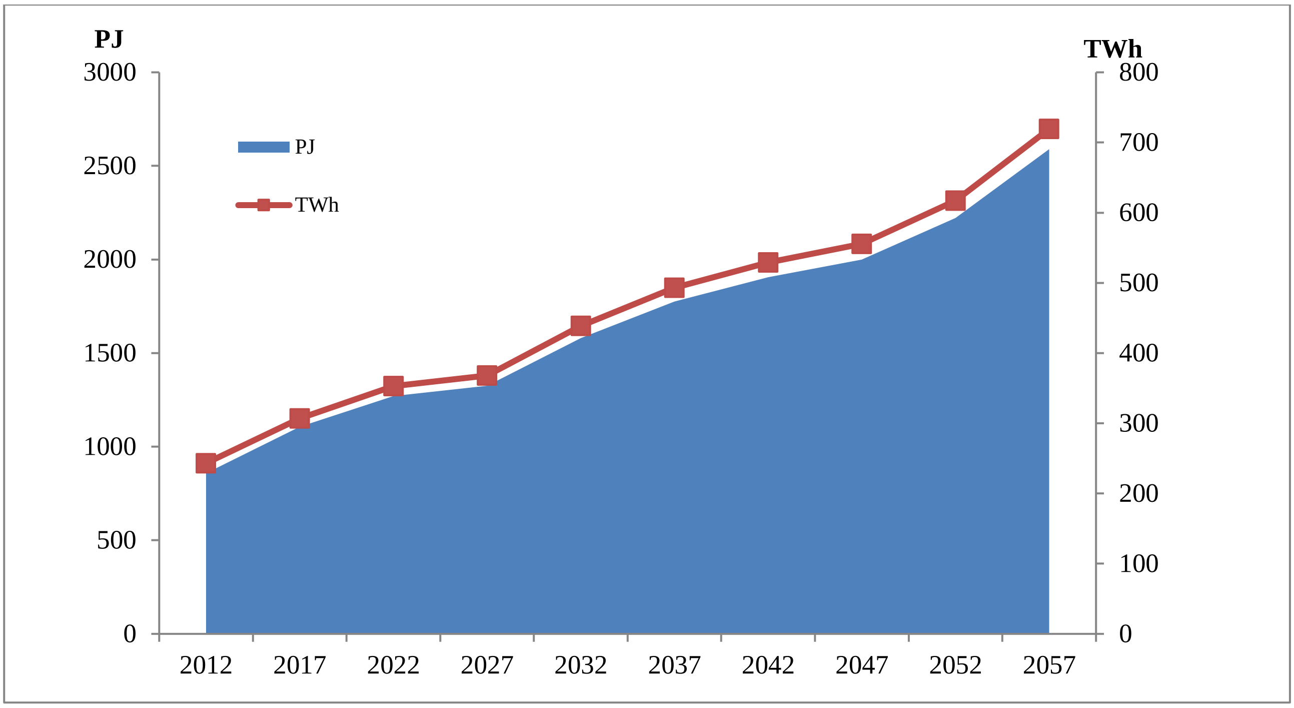


Figure 7. 22. Total electricity generation in 10$ tax scenario.

Total electricity generation reaches to 719 TWh in 2057, which is 243 TWh in 2012, corresponding to an increase of almost 200%. The value of 2057 is almost 90 TWh lower than that of 2057 in Base scenario.

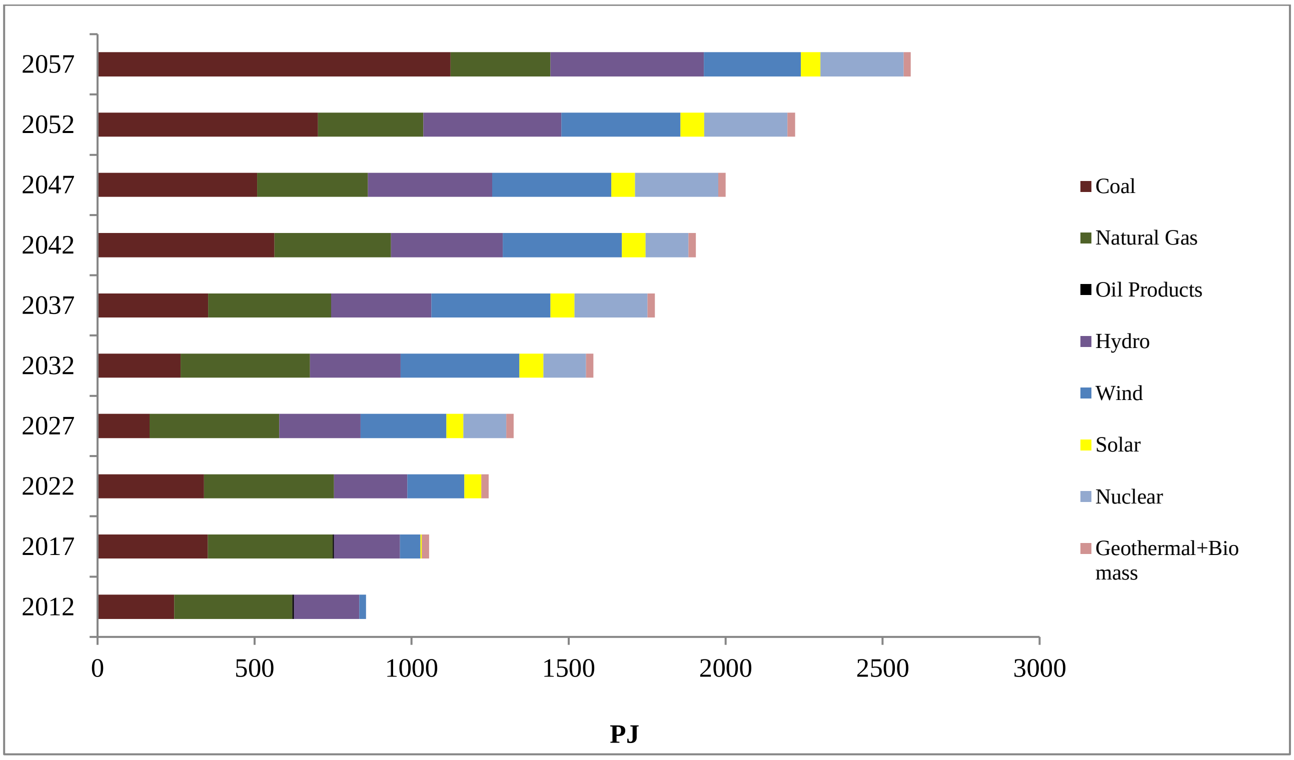


Figure 7.23. Electricity generation by fuel type in 10$ tax scenario.

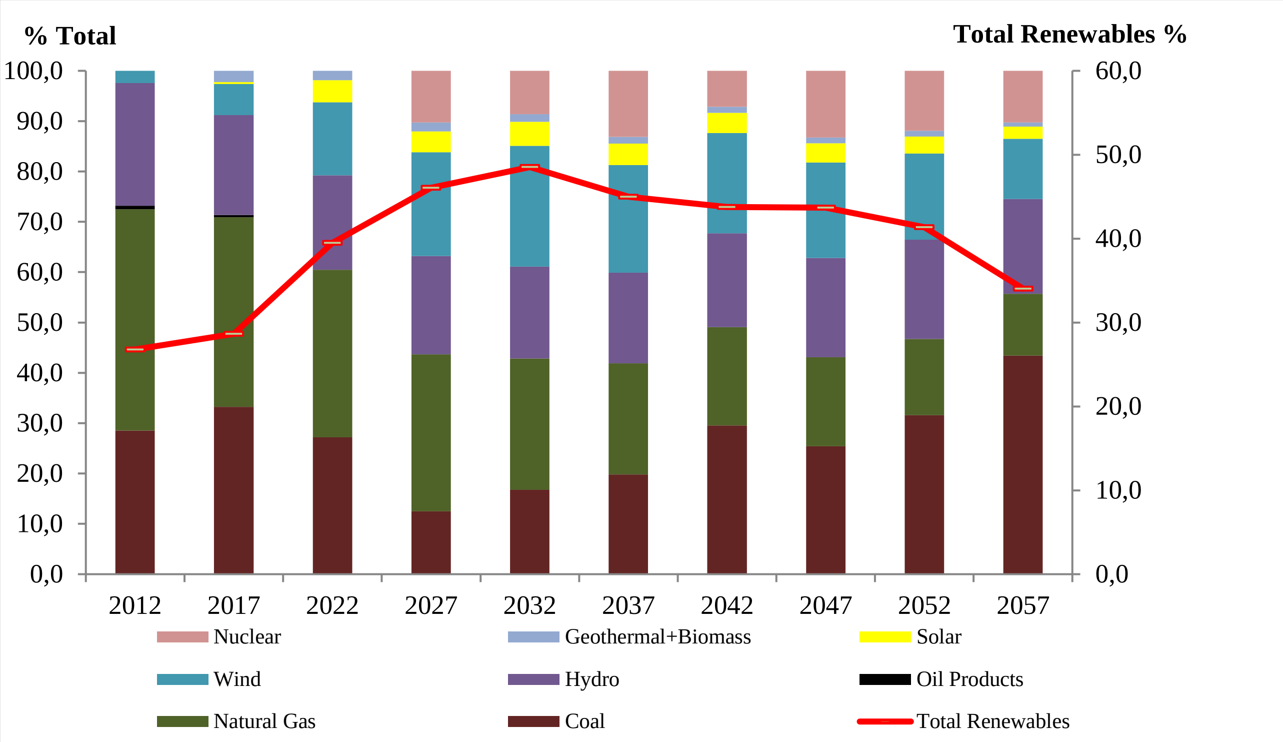


Figure 7. 24. Fuel shares in electricity generation in 10$ tax scenario.

The figures above show the distribution of resource-based electricity generation. The share of coal rises to 43.4% in 2057 from 28.5% in 2012. However, it should be noted that compared to Base Scenario its share decreases from 60% to 43.4% in 2057. Similar to Base scenario, dramatic decrease in generation from natural gas also observed and the share of natural gas drops from 44% to 12.3% in 2057. However, compared to Base scenario there is a slight increase in its share for the year 2057 (from 10.9% to 12.3% for the year 2057). The share of nuclear remains almost unchanged for the both scenarios.

On the other hand, significant increase in the share of total renewables is observed when two scenarios are compared. For the Base, the share of total renewables was 23.4% in 2057 and it reaches to 34% in 10$ tax scenario. Moreover, in the 10$ tax scenario the share of renewables is 26.8% in 2012 and this share increases by 7.2% in 2057. The highest contribution comes from hydraulic resources followed by wind and solar.

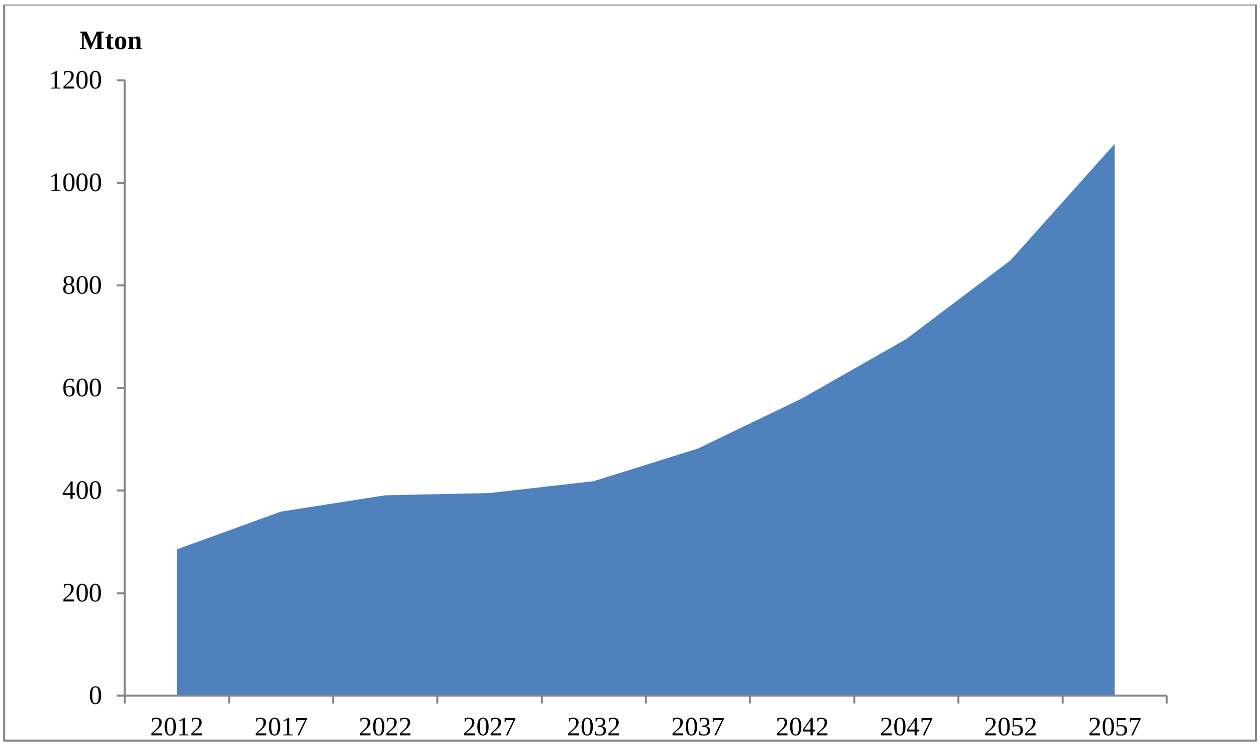


Figure 7.25. Total CO_2 emissions in 10$ tax scenario.

Total emissions exceed also 1000 Mton in this scenario and does not reach a peak value same as Base scenario. However total emissions are lower than Base scenario. For instance, in the Base scenario total emissions was 1138 Mton and it drops to 1076 Mton for the same year due to the effect of tax application.

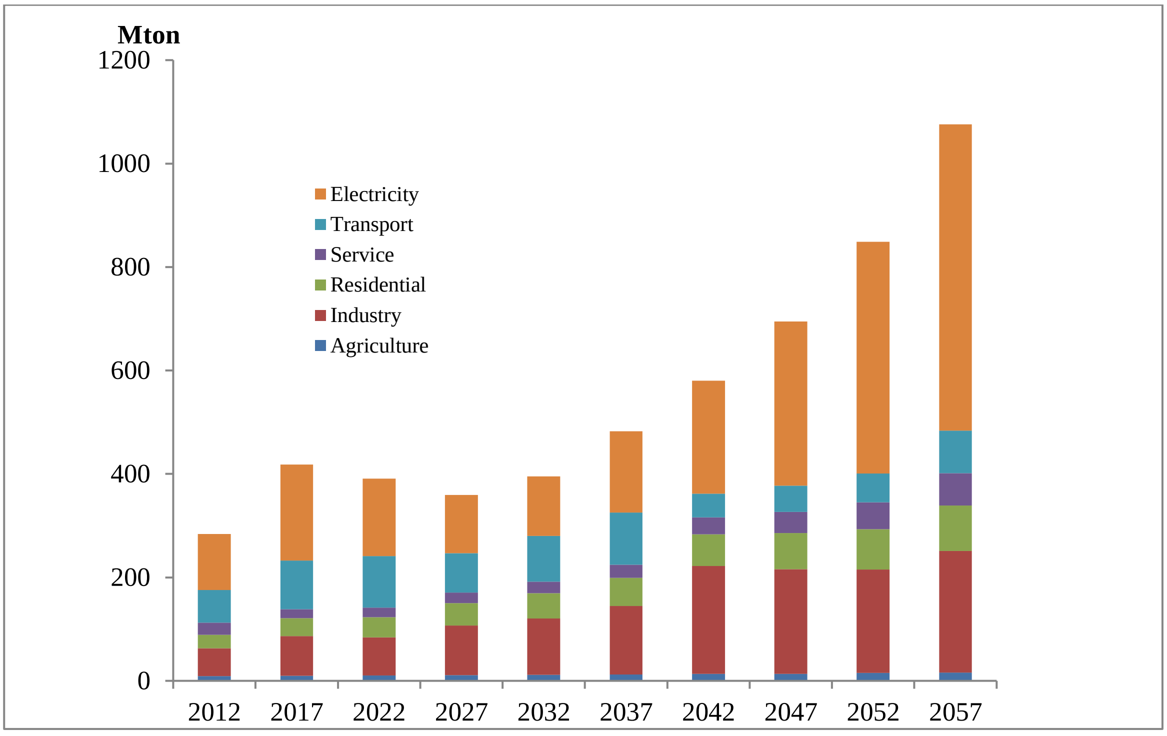


Figure 7.26. Sectoral CO_2 emissions in 10$ tax scenario.

From sectoral distribution of emissions, it can be observed that electricity sector has the highest share among all sectors. From electricity generation perspective, it is observed a considerable decrease in the emissions compared to Base scenario. In Base scenario emissions resulting from electricity generation was 638.9 Mton for 2057 and this value is 592.3 for 10$ tax scenario corresponding to an increase of more than 100 Mton. The main reason is the decrease of the share of coal in electricity generation and increase of renewables. However, under this scenario electricity generation emission does not reach a peak value as in the case of Base Scenario.

7.2.2. 20$ Tax Scenario

Under this scenario same assumptions are kept as the Base scenario and 20$ of tax is applied to all sectors.

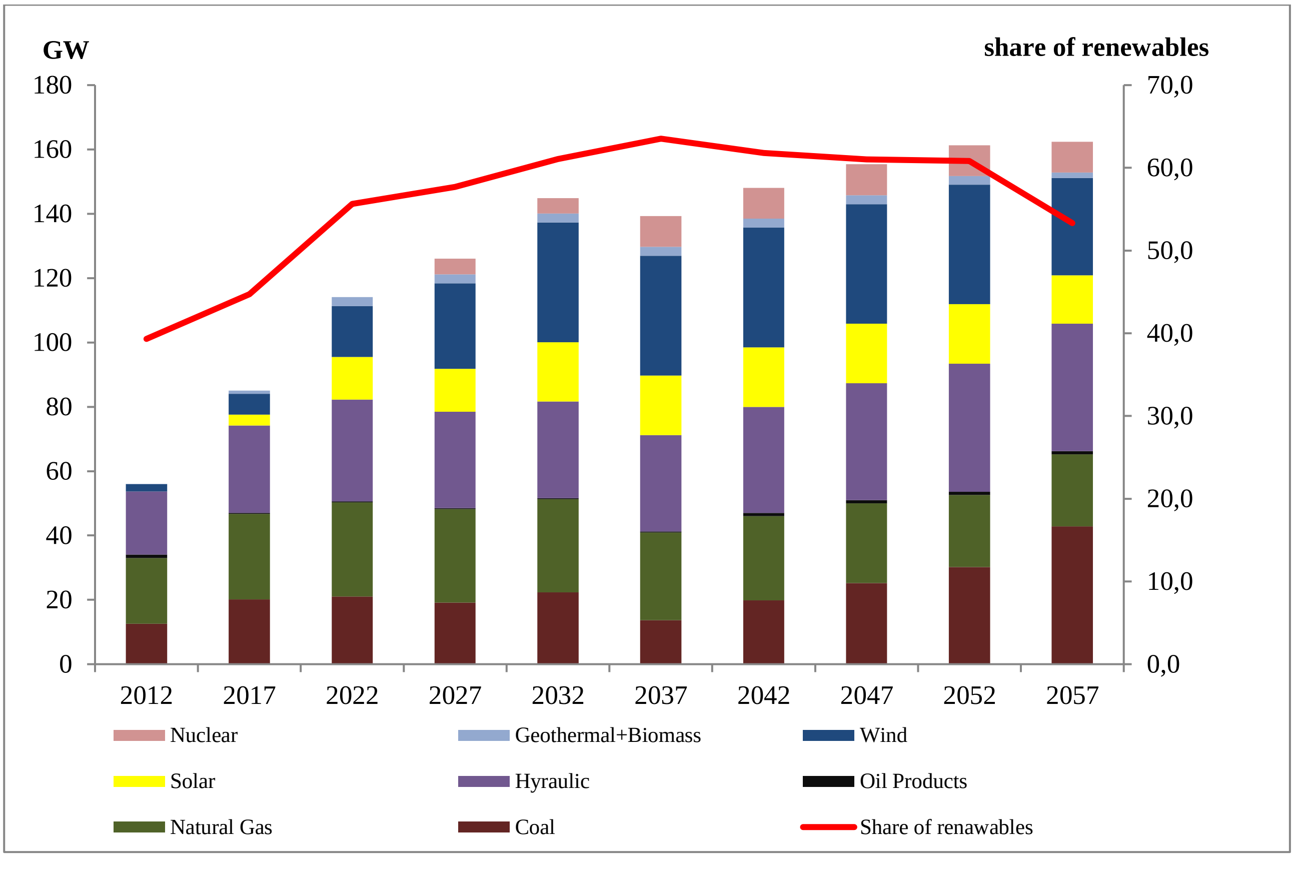


Figure 7.27. Installed capacities in 20$ tax scenario.

In this scenario total installed capacities exceeds 160 GW which is lower than Base and 10$ tax scenario. Similar to 10$ tax, coal capacity shows a remarkable decrease and drops to 42.8 GW in 2057 which is 80.1 GW and 53.7 GW for the Base and 10$ tax scenarios respectively for the year 2057. The capacity of natural remains almost same for all of the scenarios.

From total renewables perspective, the share of total renewables reaches to 53.3% in 2057 and renewables become the leading sources in total installed capacities. It reaches its highest share in the year 2037 with over 63%.

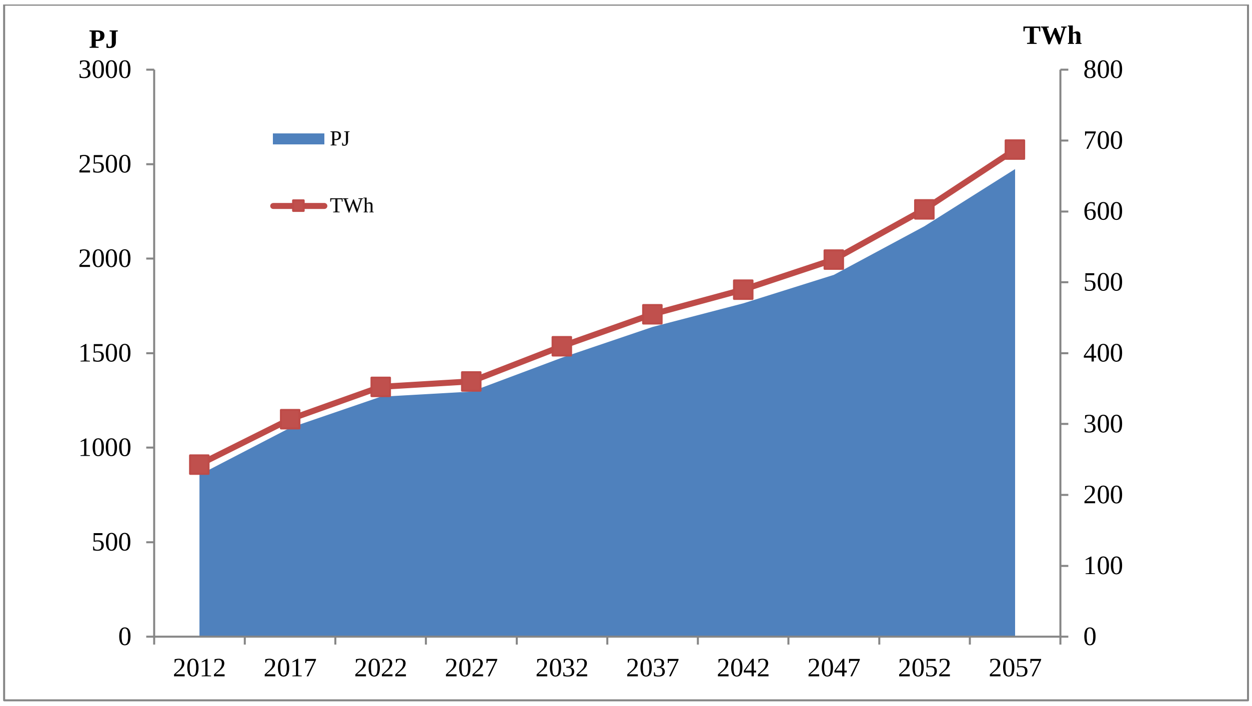


Figure 7.28. Total electricity generation in 20$ tax scenario.

In 20$ tax scenario electricity generation reaches to 687 TWh in 2057 from 243 TWh in 2012, which is lower than base and 10$ tax scenario.

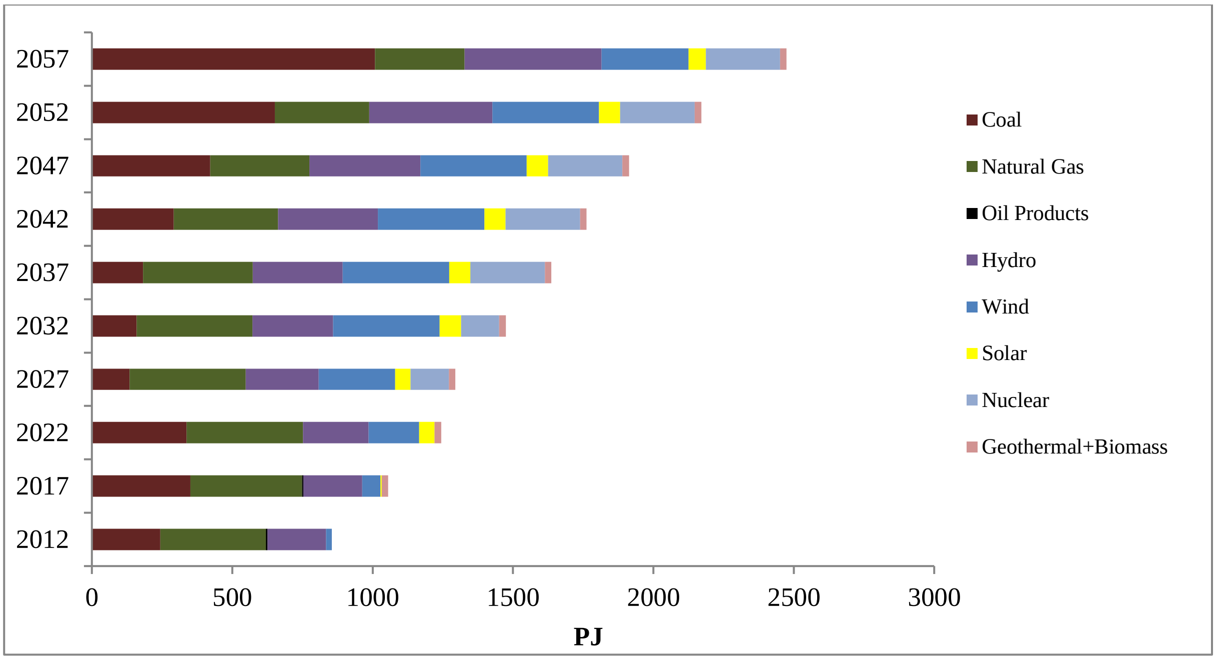


Figure 7.29. Electricity generation by fuel type in 20$ tax scenario.

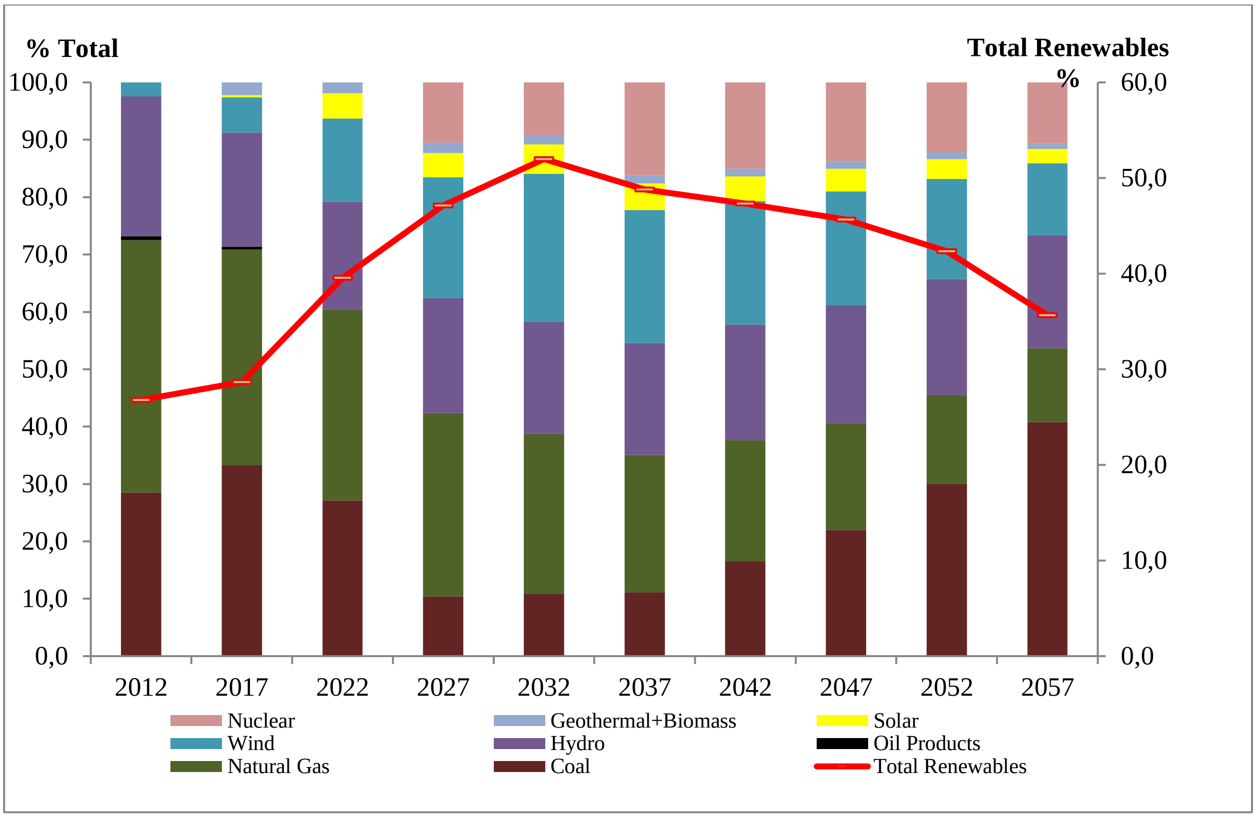


Figure 7.30. Fuel shares in electricity generation in 20$ tax scenario.

From electricity generation perspective although the share of coal increases in 2057 compared to 2012, its share decreases to 40.8% compared to Base and 10$ tax scenarios being 60% and 43.4% respectively for the year 2057. While in 2012 the share of fossil fuels in electricity generation was over 70%, this share decreases to almost 50% in 2057. In this scenario, contrary to others, the share of nuclear in total generation rises to over 10% in total generation, which was 5.5% in other scenarios. The share of total renewables is 35% which is higher than both Base and 10$ tax scenarios. The share of hydro is 19.7%, wind is 12.5 and solar is 2.5% in 2057. In tax scenarios the share of renewables in total electricity generation increases rapidly and reaches their maximum between 2032-2037 and then starts decreasing. The main reason is that the model invests more on renewables and their technically maximum available capacities are reached during this period.

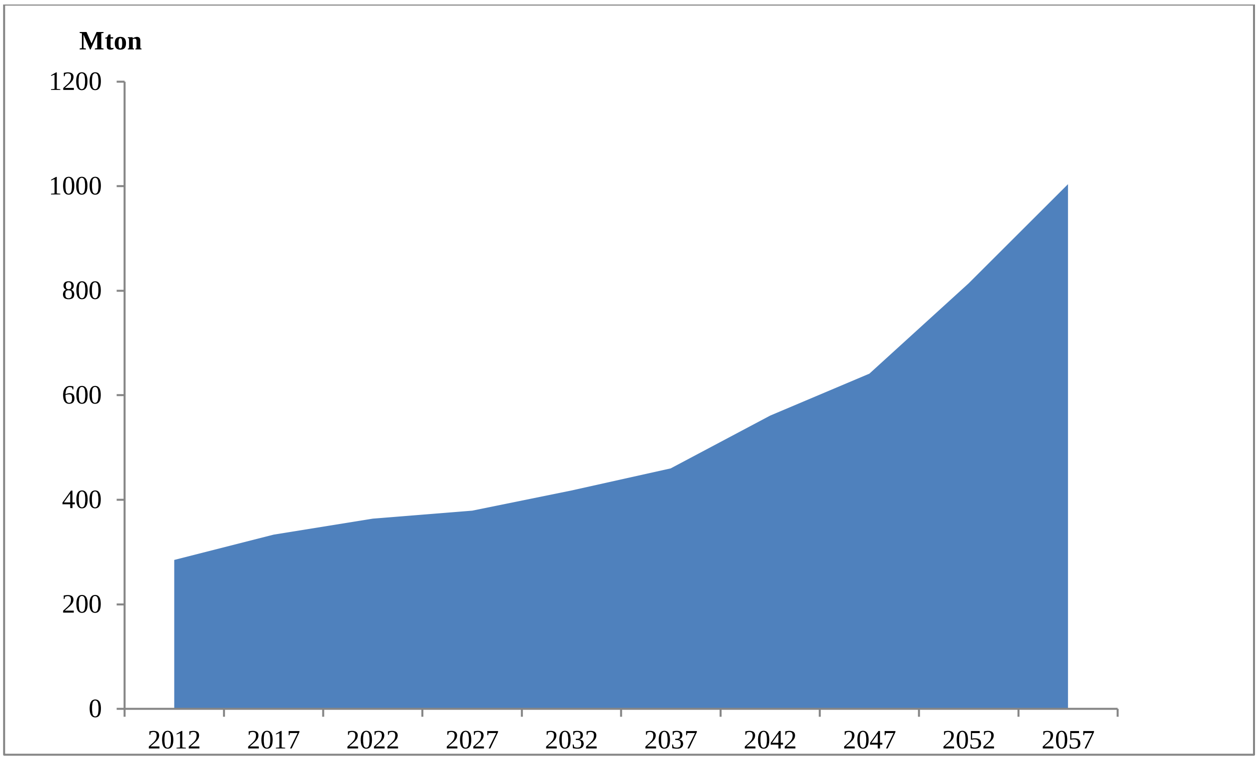


Figure 7.31. Total emissions in 20$ tax scenario.

In this scenario total emissions reaches to 1000 Mton at the end of 2057 from 285 Mton in 2012. This value is lower than both Base and 10$ tax scenario where total emissions were 1138 and 1076 Mton respectively.

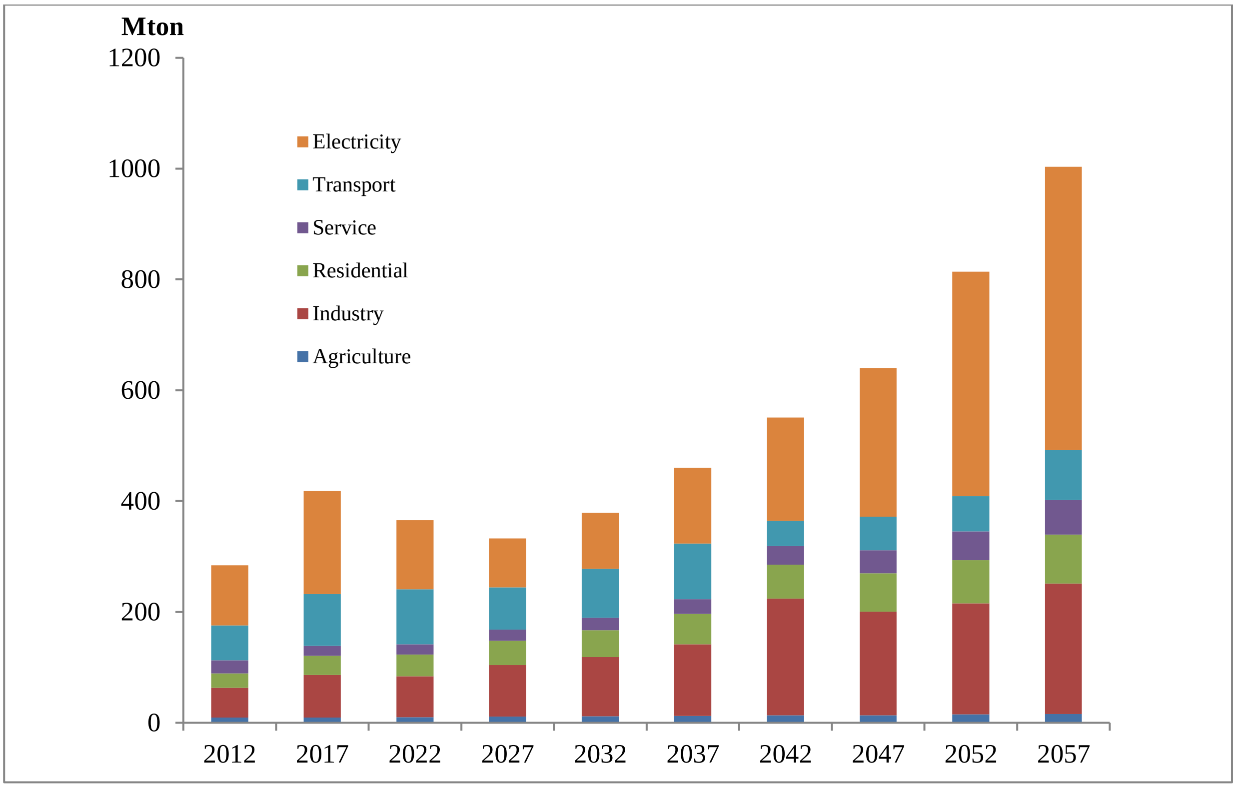


Figure 7.32. Sectoral distribution in 20$ tax scenario.

As can be seen from the figure above the emissions coming from the electricity generation reaches to 511.3 Mton in 2057 and this value is lower than other two scenarios due to the fact that share of fossil fuels decreases whereas renewables shows an increase. However, no peak value was observed as in the case of previous scenarios and electricity sector is still the largest contributor to total system emissions.

7.2.3. 30$ Tax Scenario

In this scenario 30$ tax is applied under the same conditions as Base scenario. The results are as follows;

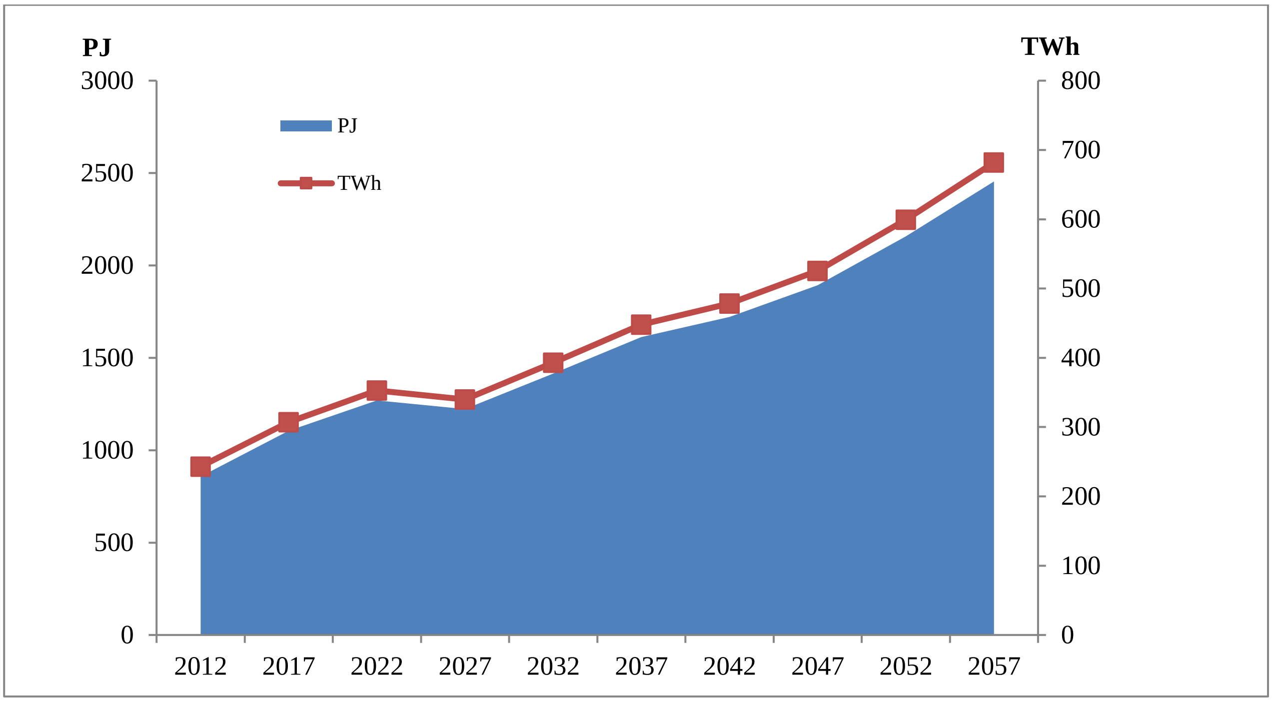


Figure 7.33. Electricity generation in 30$ tax scenario.

The total electricity generation reaches to 682 TWh in 2057 from 243 TWh in 2012. This value is almost similar to 20$ tax scenario but lower than Base and 10$ scenarios.

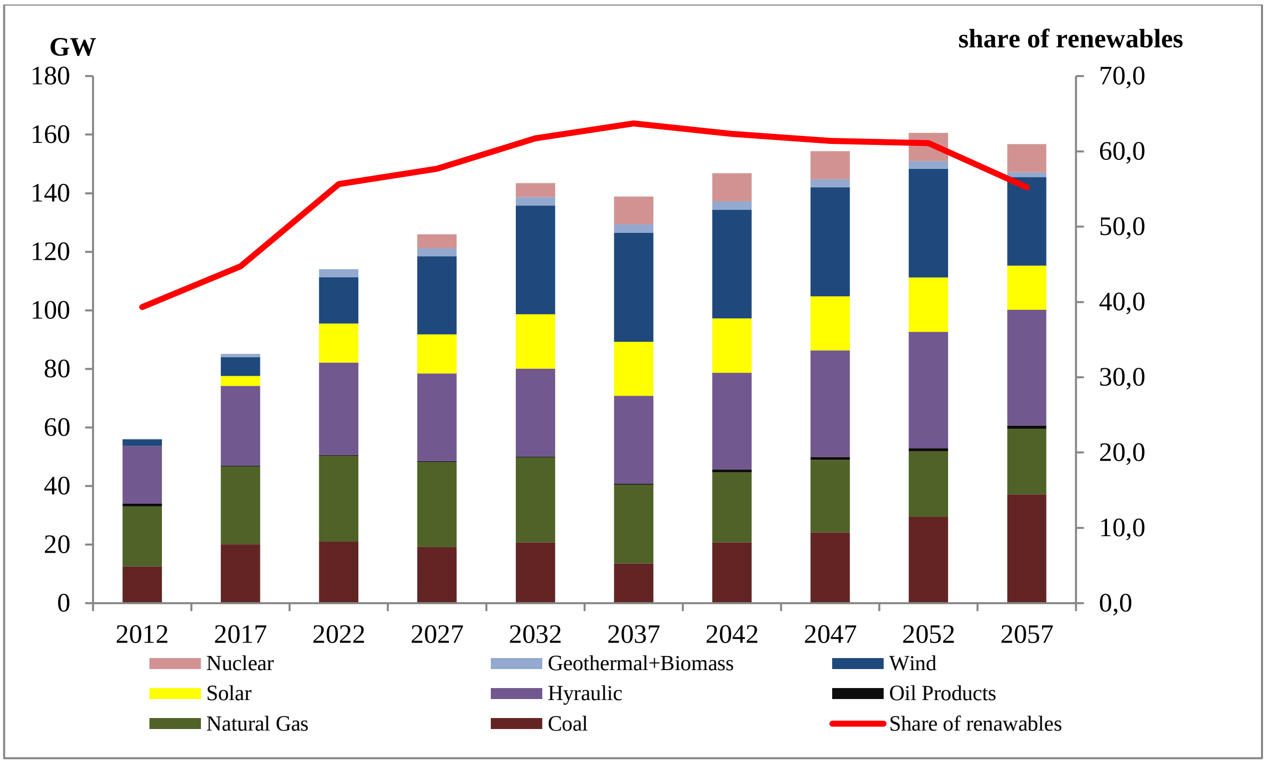


Figure 7.34. Installed capacities in 30$ tax scenario.

The total installed capacity increases to almost 160 GW (156.8 GW exactly) in 2057 from 56.1 GW in 2012. The value of the year 2057 is slightly lower than all scenarios. From fossil fuel perspectives the share of coal in total electricity generation reaches its lowest value of 37.2 GW for the year 2057 among all scenarios. The share of natural gas is almost same in all scenarios although some fluctuations are observed in interval years. As mentioned in the above sections this is consistent with Turkey's policy to decrease share of natural gas.

Total share of renewables reaches its maximum level of 2057 year in 30$ tax scenario being 55.2%. As explained above the model tends invest on renewables in tax scenarios and share of renewables reaches their maximum available level in 2032 or 2037 for both installed capacity and electricity generation. Therefore, their share in total capacity and electricity generation starts dropping till 2057.

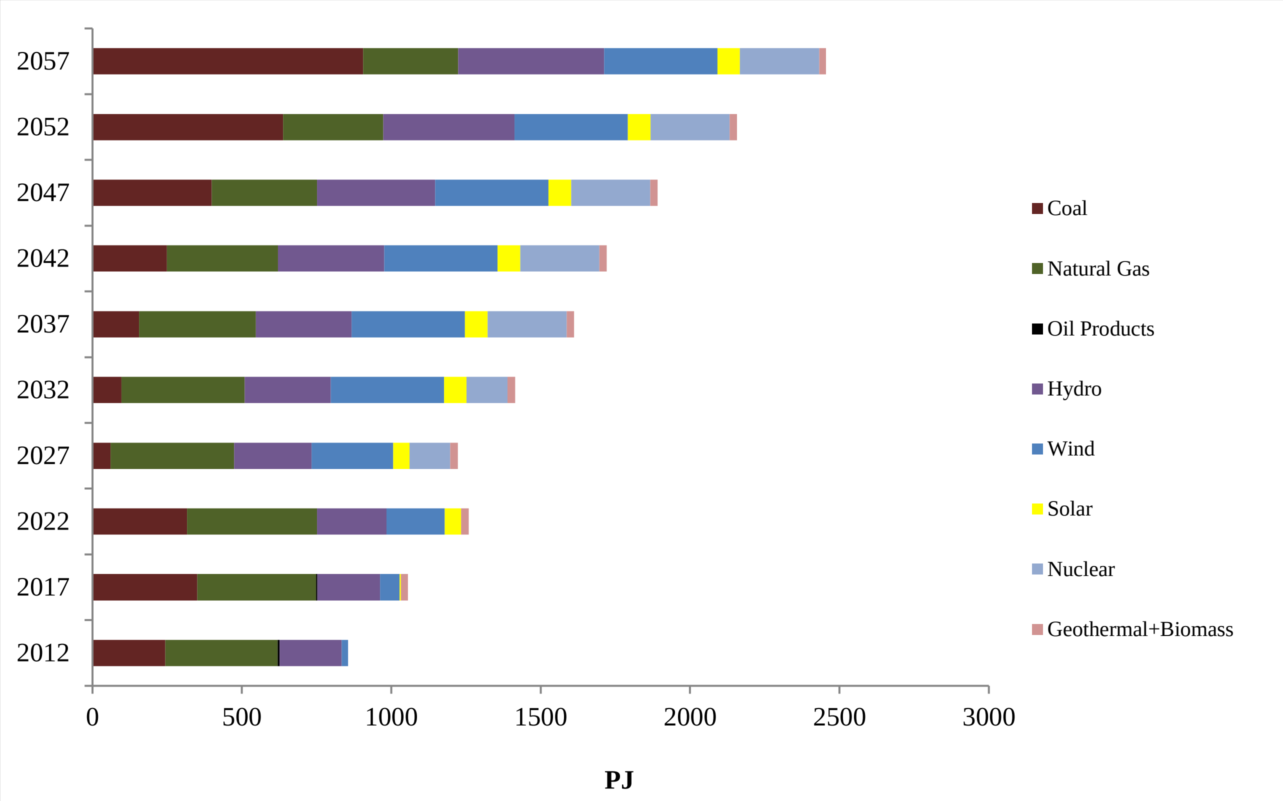


Figure 7.35. Electricity generation by fuel type in 30$ tax scenario.

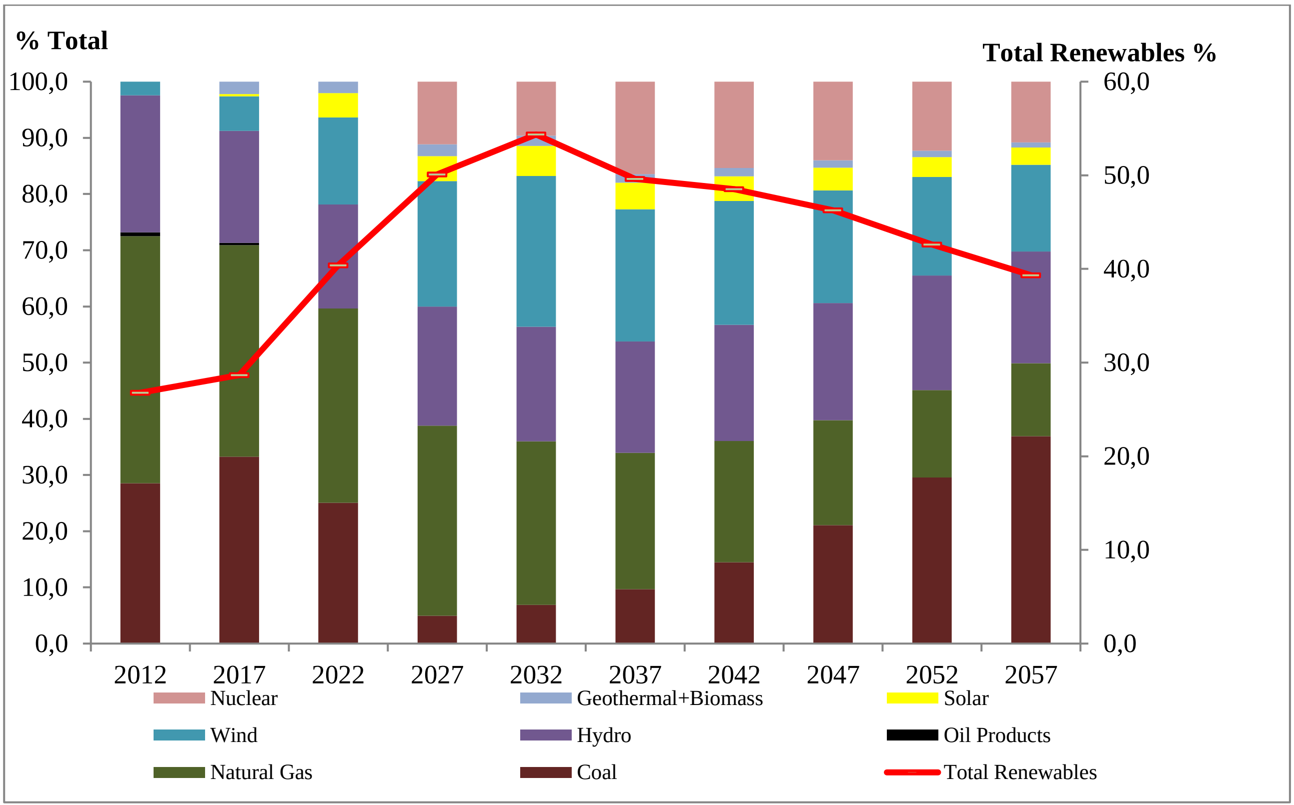


Figure 7.36 Share of fuels in electricity generation in 30$ tax scenario.

According to Figures 7.35 and 7.36 the share of coal in electricity generation reaches to 36.9% in 2057 from 28.5% in 2012. The value of 2057 is the lowest value among all scenarios. Similar to 20$ tax scenario the share of nuclear exceeds 10% in total generation. Similar to coal, the lowest share of natural gas in total generation was observed in 30$ tax scenario being 13% for the year 2057. This value is 44% for the year 2012 and shows a dramatic decrease till 2057. For other scenarios the share of natural gas was approximately 22% for the year 2057.

On the other hand, total renewables show the highest share by reaching almost 40% in 2057 in total generation, led by hydro, wind and solar respectively. All of these resources reaches their highest share for the year 2057 in 30$ tax scenario compared to other scenarios.

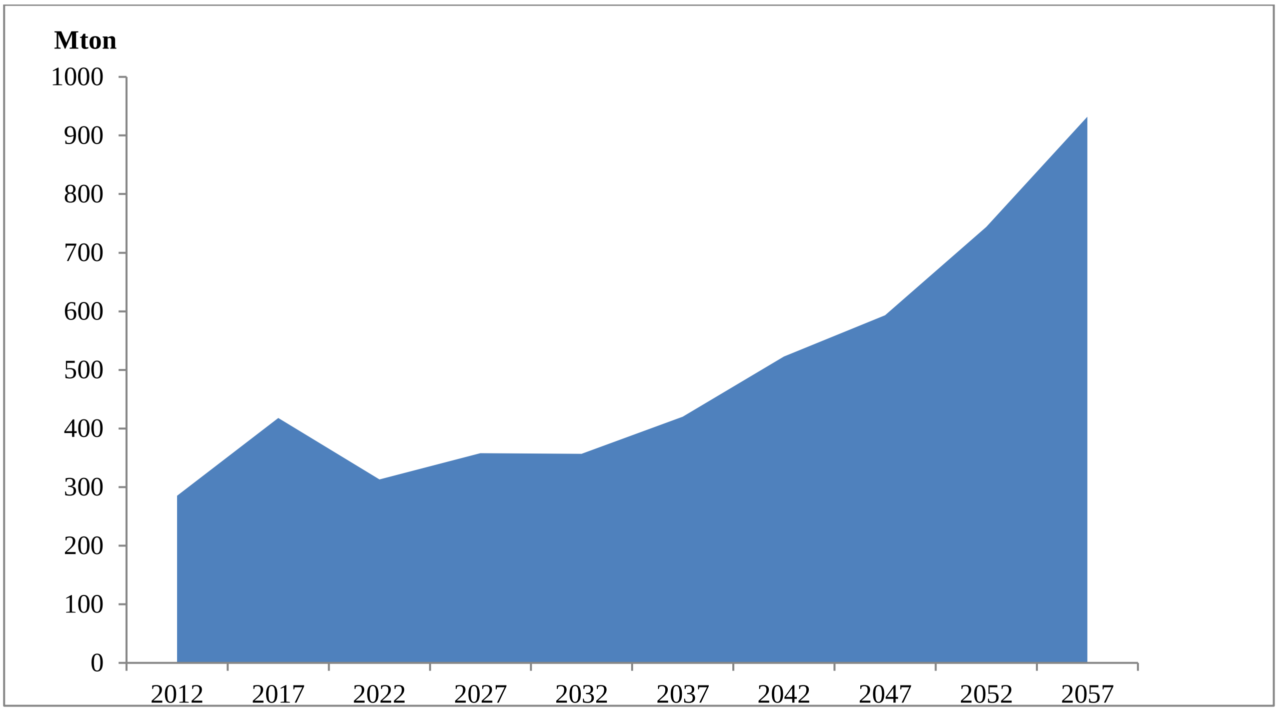


Figure 7.37. Total emissions in 30$ tax scenario.

According to Figure 35, total emissions drops under 1000 Mton for the first time under 30$ tax scenario. The emissions rise from 285 Mton in 2012 to 932 Mton for the year 2057.

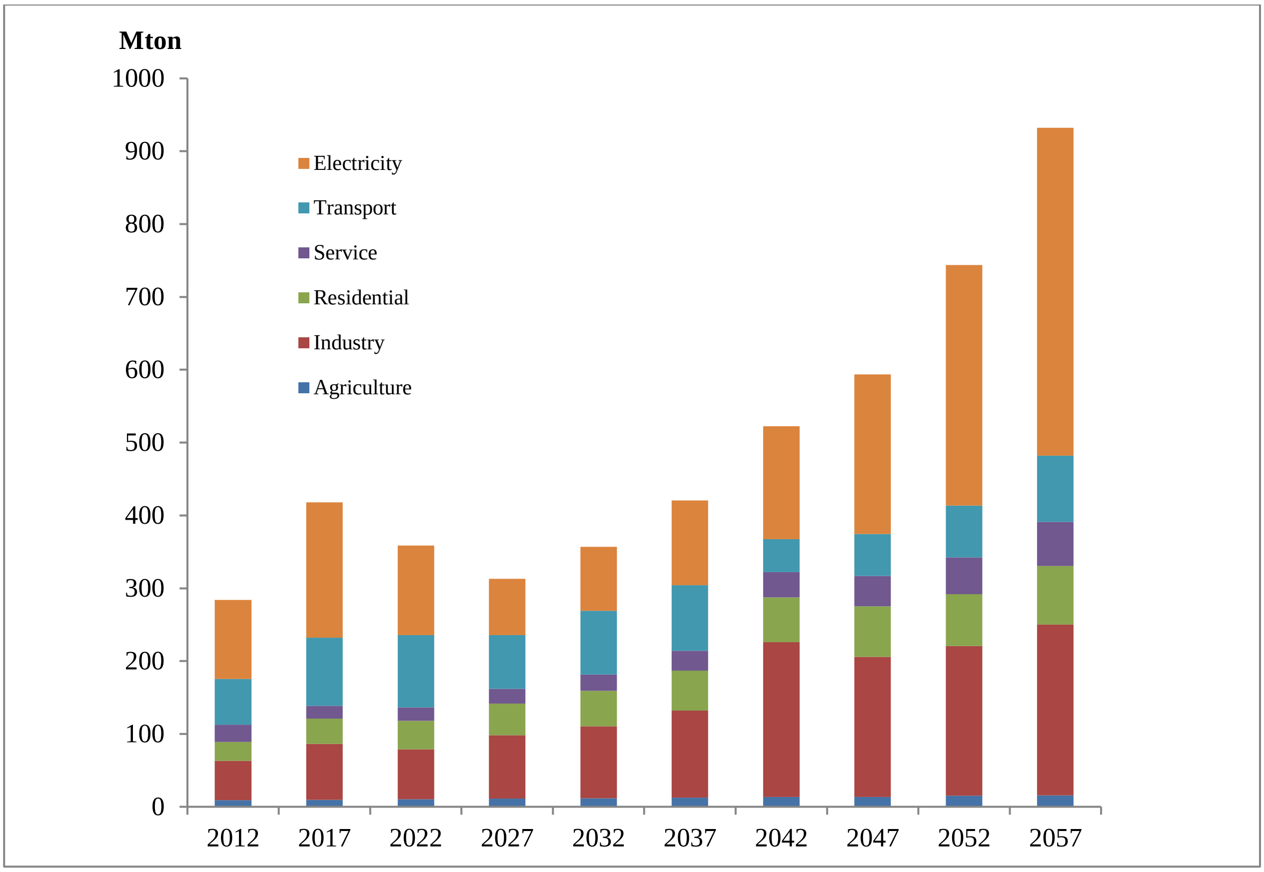


Figure 7.38. Sectoral distribution in 30$ tax scenario.

Emissions from electricity generation reaches to 450.2 Mton in 2057. This value is the lowest among all tax scenarios for the year 2057 and for the first time emission drops below 500 Mton. Besides, after 2017 the emissions start dropping significantly, up to 77.2 Mton in 2027 and then starts increasing due to the fact that share of coal in electricity generation starts increasing simultaneously after that year. On the other hand, it should be noted that lowest emission values are obtained as the tax value increases. Another important point is that generally, the respond of the emissions from electricity sector is high to tax application meaning that tax application is a favorable way to reduce emissions in this sector.

7.2.4. Scenario Comparison

Figure 7.39. Electricity generation by scenarios.

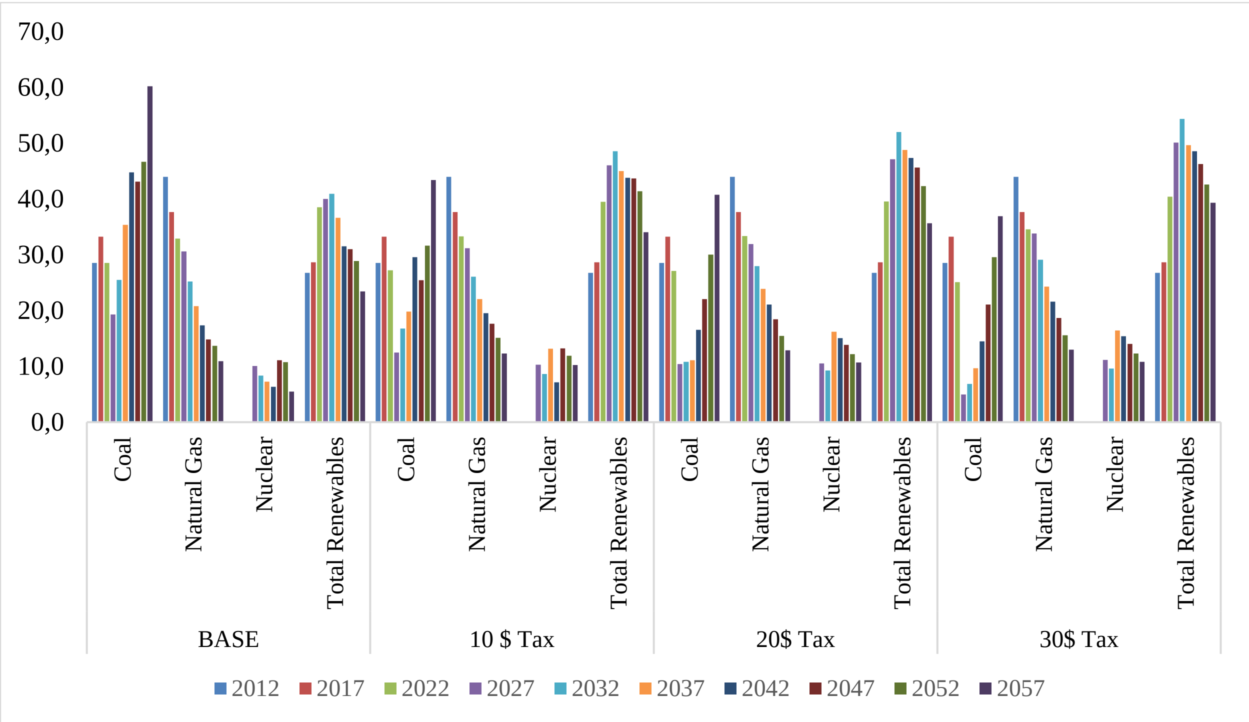


Figure 7.40. Share of fuels in electricity generation by scenarios.

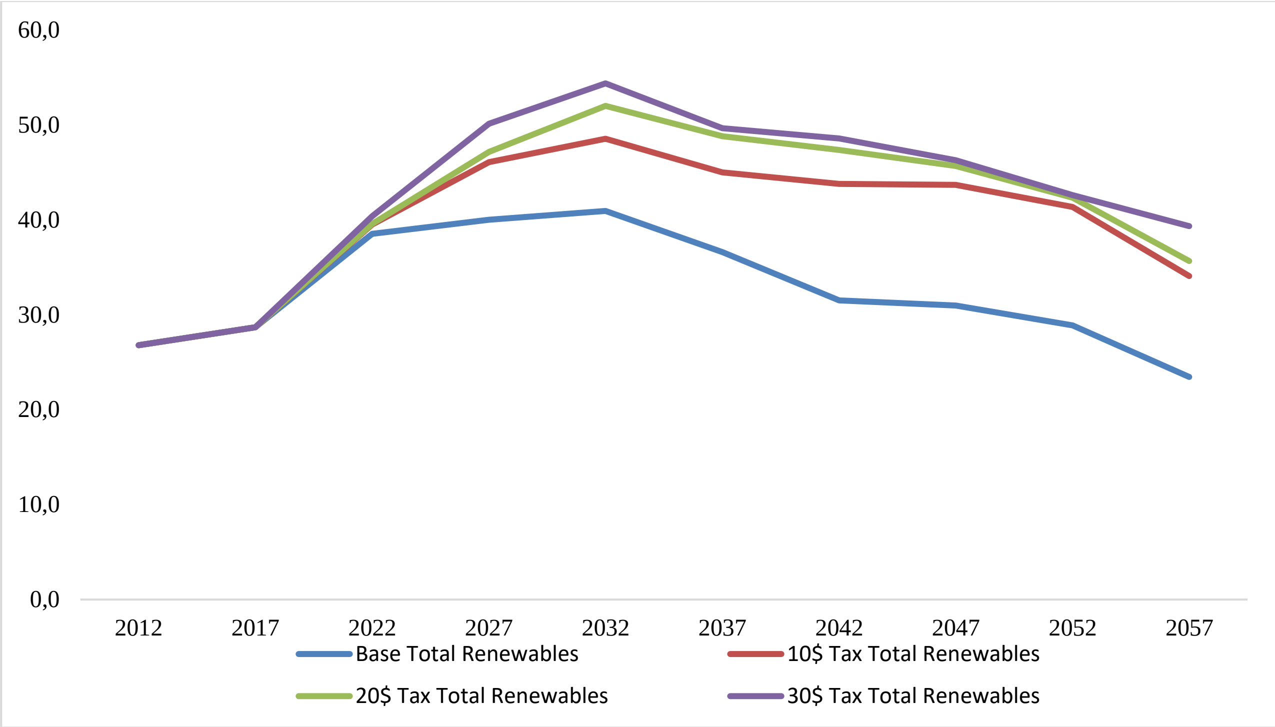


Figure 7.41. Share of total renewables in electricity generation by scenarios.

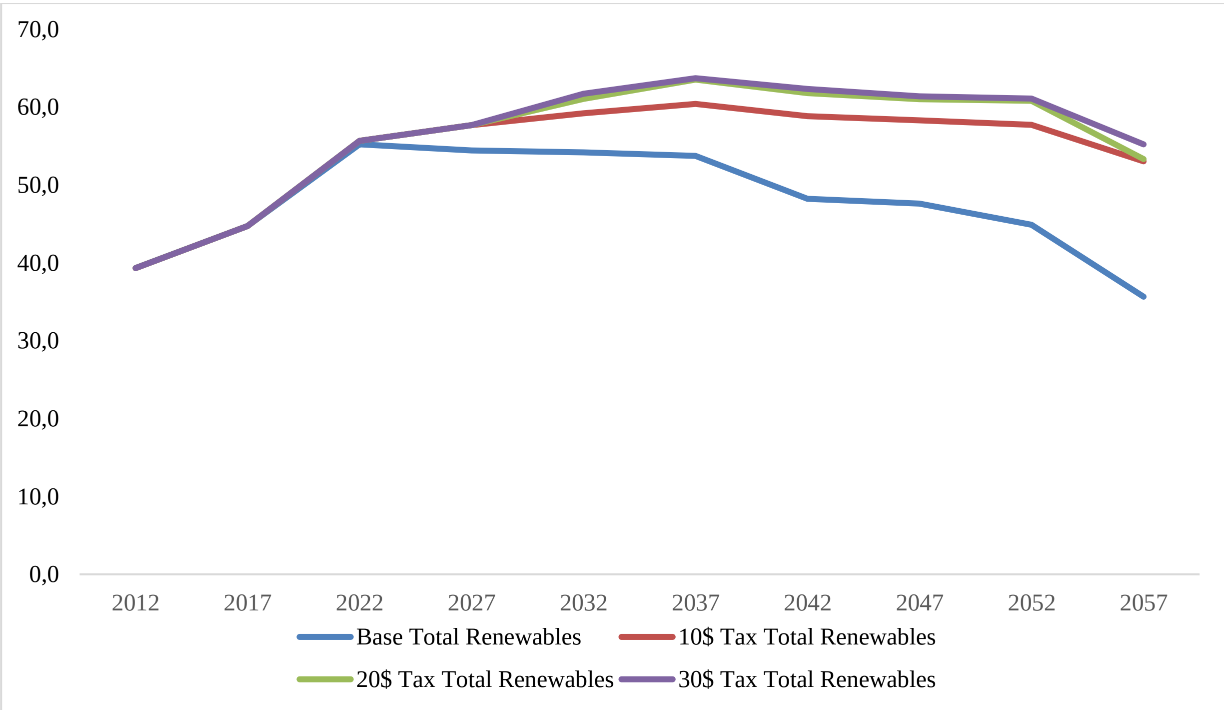


Figure 7.42. Share of total renewables in installed capacity by scenarios.

Figure 7.43. CO_2 emissions resulting from electricity generation.

As can be seen from the figures above, with rising tax application on emissions, lower emission values are obtained. Moreover, the share of renewables both in installed capacity and electricity generation rise in higher tax scenarios. Similarly, the share of nuclear also increases as carbon-free generation source. This situation highlights the necessity of nuclear as base-load capacity in power system.

Table below compares the total cost of the Tax Scenarios

Table 7.3. Total system cost in tax scenarios (2012 million US $).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**	**2057**
Base (SP)	47292	76627	88575	97303	115000	131790	137920	164700	196590	235550
10$ Tax Scenario	47354	76639	92003	100780	119300	137080	145550	169390	203470	245120
20$ Tax Scenario	47387	76645	95781	104170	123190	141520	151550	176000	210130	254210
30$ Tax Scenario	47526	76686	99283	107310	126410	145080	157470	182940	217200	263550

The total cost of the system rises when tax is applied on total emissions. In case of 30$ tax application, 850 Mtons of total CO_2 emission mitigation was realized between 2012-2057 in electricity sector.

7.3. Emission Restriction Scenarios

Under these scenarios Base Scenario (Strategic Plan) was used as indicative for emissions. Based on the emission values of the Base Scenario, 10, 20 and 30 % total emission reduction targets were applied respectively for each 5 year of projection period starting from year 2032. Differently from Base and Tax Scenarios, technical offshore wind potential was also taken into consideration, which is 11 GW, and the maximum available wind capacity was fixed to 48 GW, so that the model cannot exceed maximum installed wind capacity. No tax was applied on emissions.

7.3.1. 10% Emission Reduction Scenario

Under this scenario it has been assumed that the total emissions would be as follows according to 10% decrease in total emissions:

Table 7.4. Emission values under 10% scenario

Year	Emissions (Mton)
2012	285
2017	418
2022	399
2027	352
2032	371
2037	449
2042	605
2047	684
2052	798
2057	1014

In the model the emission values were fixed to the values above and the model was run.

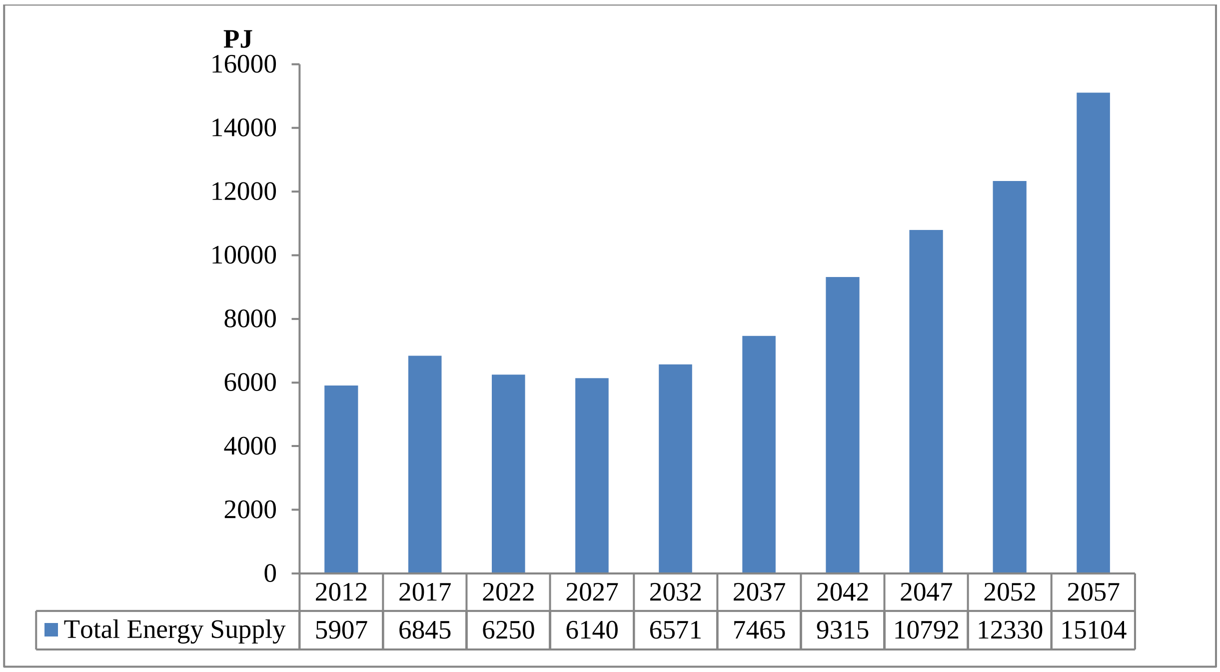


Figure 7.44. Primary energy supply of 10% emission reduction scenario.

According to this scenario the total primary energy supply reaches to 15104 PJ in 2052, which was 5907 in 2012. Although there has been observed a decrease in 2022 and 2027 compared to previous 5 year of period, starting from 2032 primary energy supply starts recovering. Compared to Base Scenario, in 2057 it is observed that total primary energy decreases from 16067 PJ to 15104 PJ due to the decrease in the coal supply. In the Base scenario coal supply is 8435 PJ whereas in 10% reduction scenario it becomes 7044 PJ. Compared to Base scenario natural gas supply and renewables increase because of emission restriction, hence natural gas was used as a clean transition fuel and it was observed from coal to gas switch.

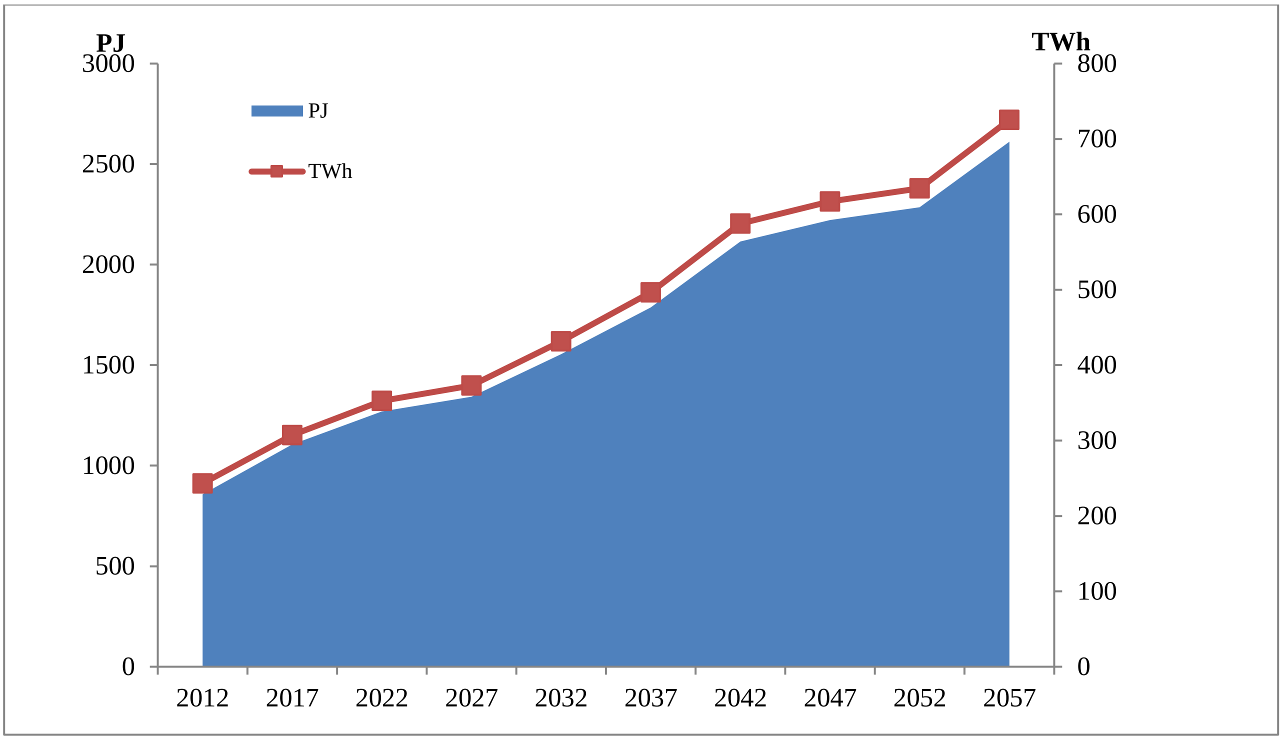


Figure 7.45. Total electricity generation in 10% emission reduction scenario.

From electricity perspective, according to 10% reduction scenario, total electricity generation reaches to 725 TWh in 2052 from 243 TWh in 2012. Compared to Base scenario in 2052 electricity generation reduced to 725 TWh in 2052 from 811 TWh due to the decrease in electricity generation form coal. Coal based generation reduced to 1042 PJ from 1757 PJ in 2052 compared to Base Scenario. This decrease was offset by the increase in wind, solar and nuclear based generation.

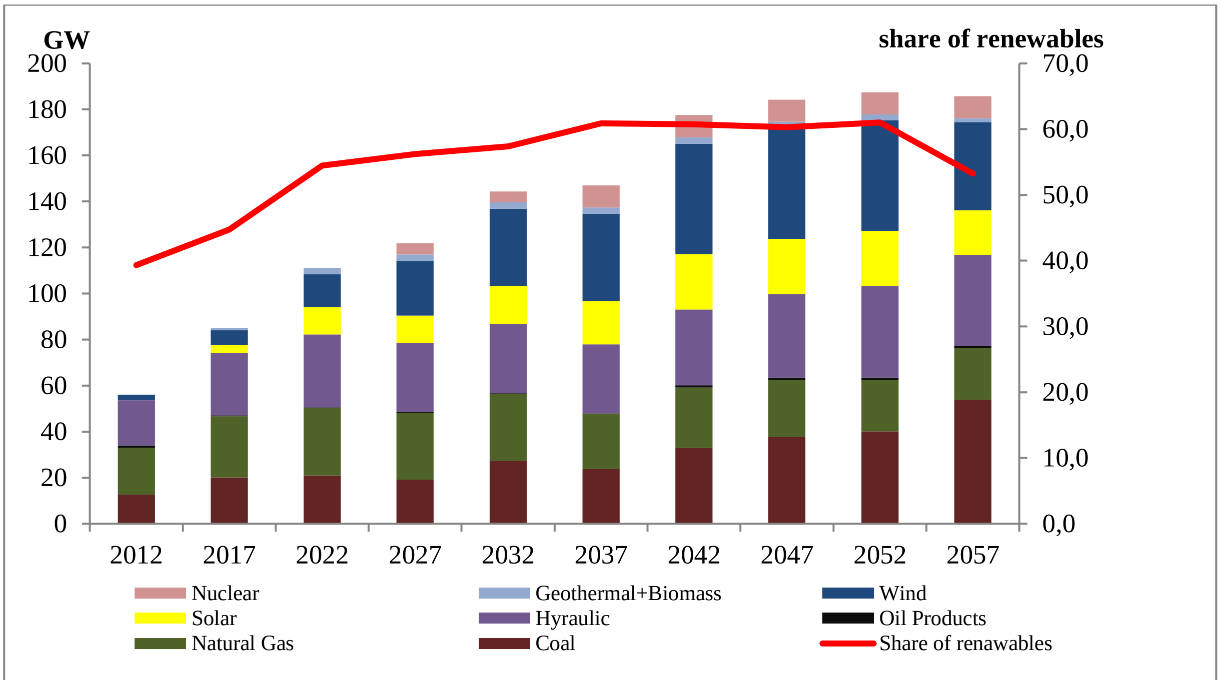


Figure 7.46. Total installed capacity in 10% emission reduction scenario.

According to 10% emission reduction scenario, total installed capacity exceeds 180 GW as of 2052. Starting from 2027 first and in 2037 second nuclear plant becomes operational. Technical wind capacity reaches its maximum in 2042 as 48 GW. In the Base scenario, total coal capacity was 80.1 GW in 2052 and it decreases to 53.2 GW in the same year according to 10% increase scenario. Total installed capacity of natural gas remains constant for the both scenario in 2052. It should be noted that the share of the total renewable capacity exceeds 50% in 2052, which was 35.6% in Base scenario. The main reason behind this increase is the addition of wind and solar capacity and decrease in coal-based capacity.

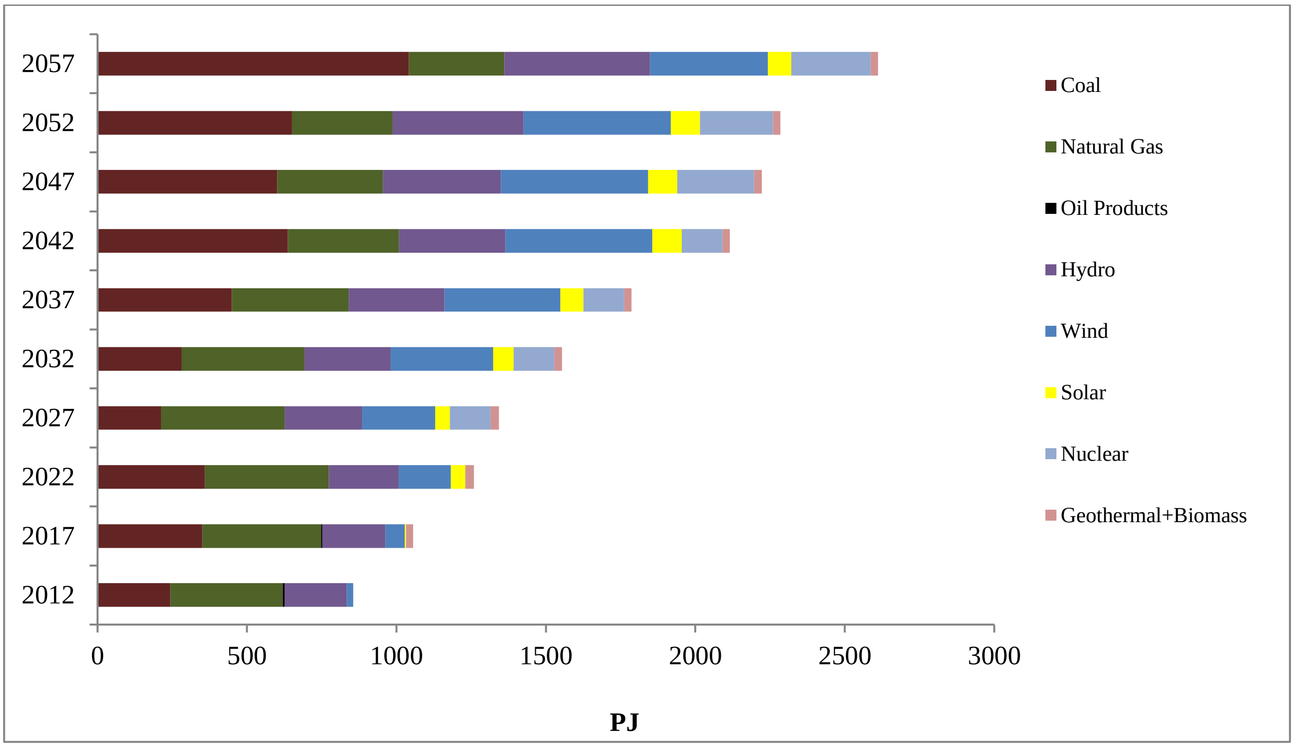


Figure 7.47. Electricity generation by fuel in 10% emission reduction scenario.

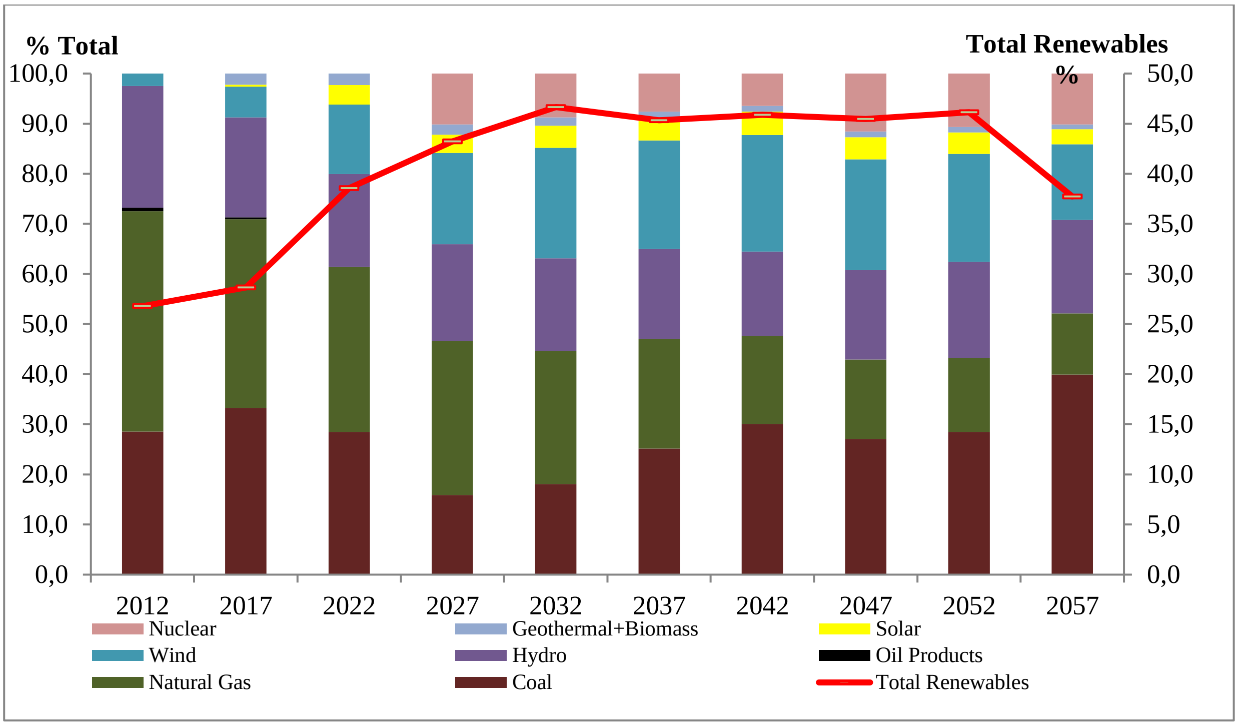


Figure 7.48. Fuel shares in electricity generation 10% emission reduction scenario.

The Share of total renewables in electricity generation rose from 26.8% in 2012 to 37.7% in 2052 due to emission reduction. It was observed a remarkable decrease in natural gas based generation between 2012-2052, in accordance with the target to reduce imported resources in electricity generation. Coal-based generation remain an important part of in the generation portfolio. However, its share remarkably decreases compared to the Base Scenario, from 60.2% to 39.9% in 2052. In the renewable resources, it is possible to observe that hydro based generation is almost same for the Base and 10% emission reduction scenario. On the other hand, wind and solar based generation increase compared to Base Scenario.

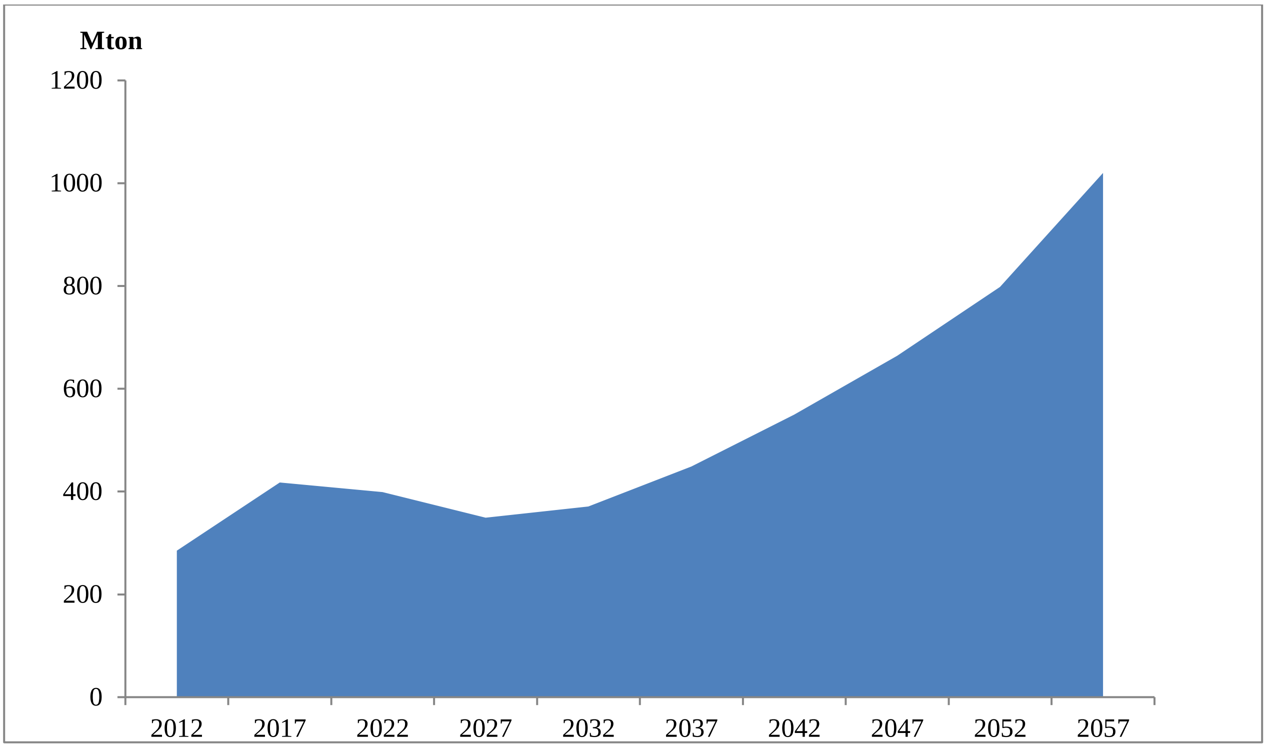


Figure 7.49. Total emissions in 10% emission reduction scenario.

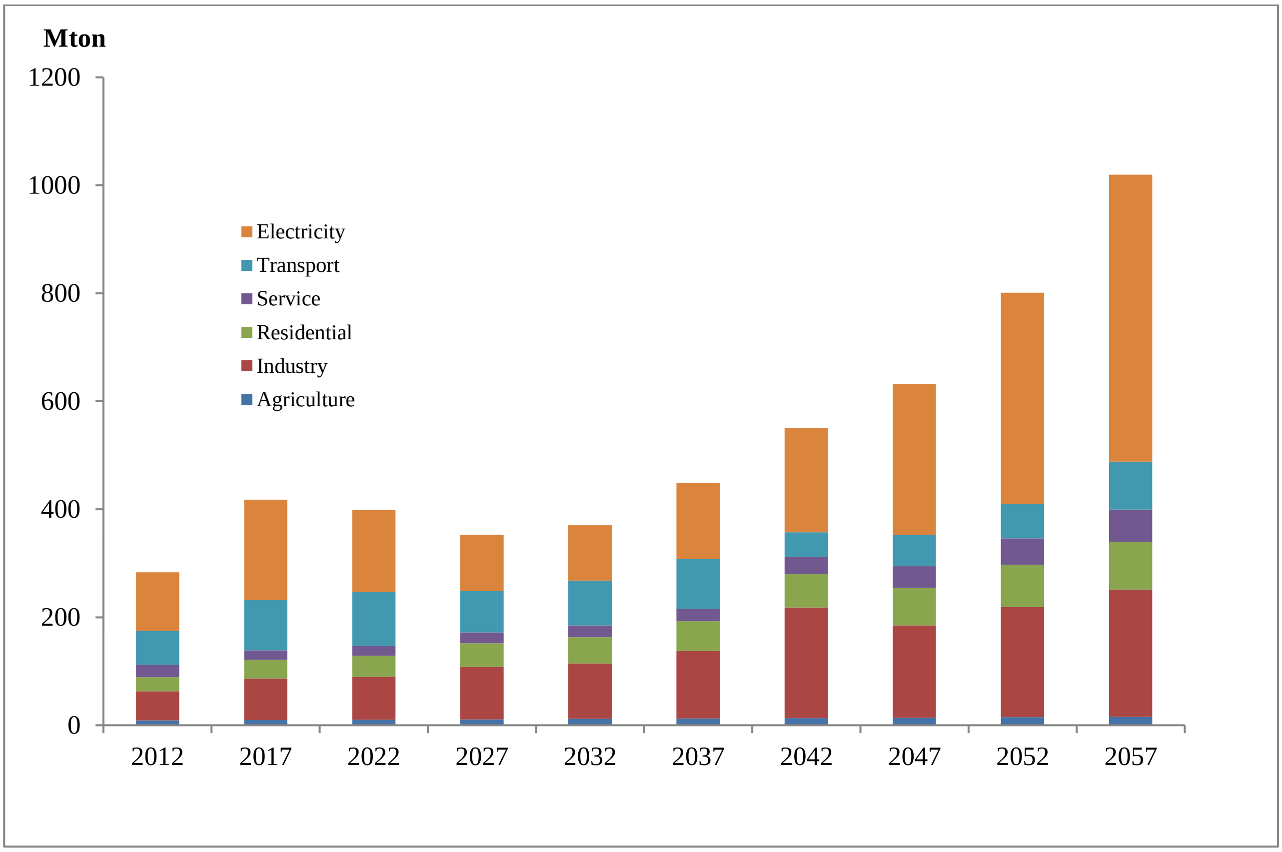


Figure 7.50. Total sectoral emissions in 10% emission reduction scenario.

As indicated above, 10% emission reduction target in total emissions was set starting from 2032 compared to Base Scenario. As a result of that assumption, total emissions reduced to 1020 Mtons in 2052. Electricity generation is the largest contributor to total emissions.

From electricity generation perspective, total emissions rose to 531,1 Mtons in 2057 from 108,6 Mtons in 2012. In the Base Scenario, emissions from electricity generation was 638,9 Mtons in 2057 and in 10% emission reduction scenario it reduced to 531,1 Mtons. The main reason as explained in the above is the decrease in coal-based generation and increase in the share of renewables in total electricity generation due to imposed emission restriction.

7.3.2. %20 Emission Reduction Scenario

Under this scenario it has been assumed that the total emissions would be as follows according to 10% decrease in total emissions:

Table 7.5. Emission values under 20% scenario

Year	Emissions (Mtons)
2012	285
2017	418
2022	394
2027	338
2032	334
2037	399
2042	538
2047	608
2052	709
2057	912

In the model the emission values were fixed to the values above and the model was run.

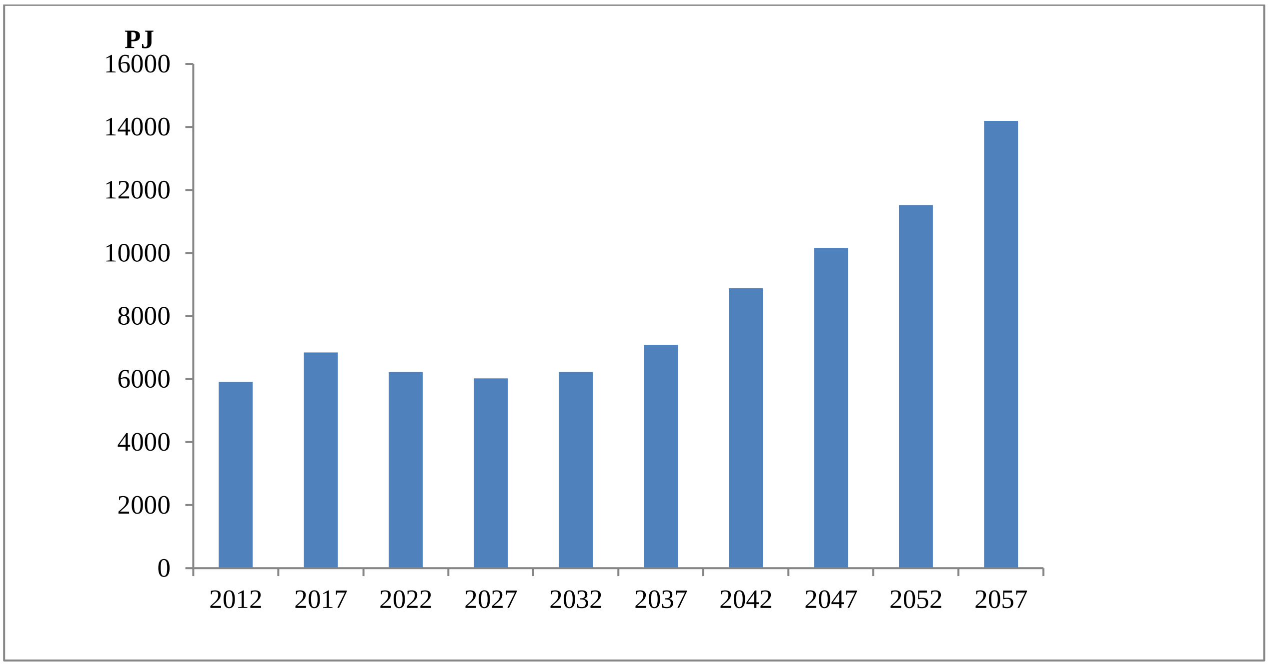


Figure 7.51. Primary energy supply of 20% emission reduction scenario.

According to this scenario, the total primary energy supply reaches to 15346 PJ in 2052, which was 5907 in 2012. Compared to Base and 10% Emission Reduction Scenarios, in 2052 it is observed that total primary energy decreases from due to the decrease in the coal supply. In the Base scenario coal supply is 9852 PJ; in 10% reduction scenario it becomes 7044 PJ and it decreases to 6013 PJ in 2052. Compared to Base and 10% scenarios the decrease in the coal supply was offset by the increase in natural gas supply and renewables due to the stricter emission restriction.

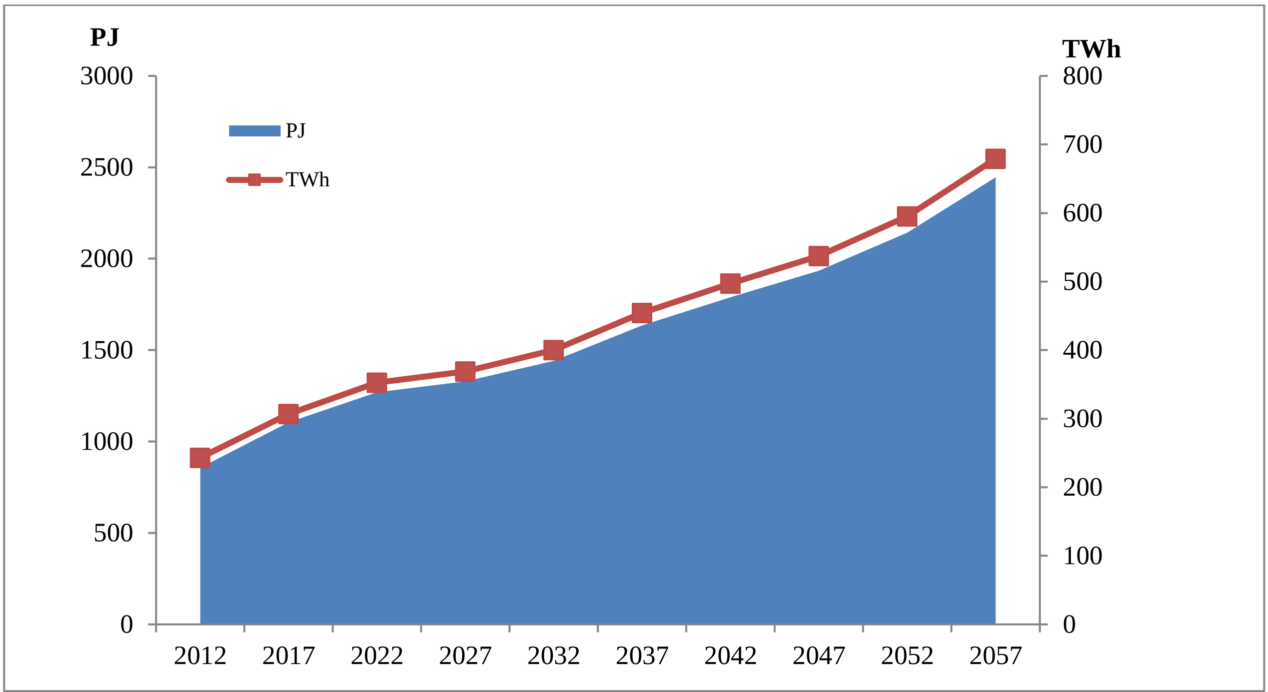


Figure 7.52. Total electricity generation in 20% emission reduction scenario.

From electricity perspective, according to 20% reduction scenario, total electricity generation reaches to 679 TWh in 2052 from 243 TWh in 2012. Compared to Base and 10% scenarios in 2052 electricity generation reduced to 679 TWh from 725 TWh in 2052 from 811 TWh respectively due to the reduction of coal-based generation that will be analyzed below.

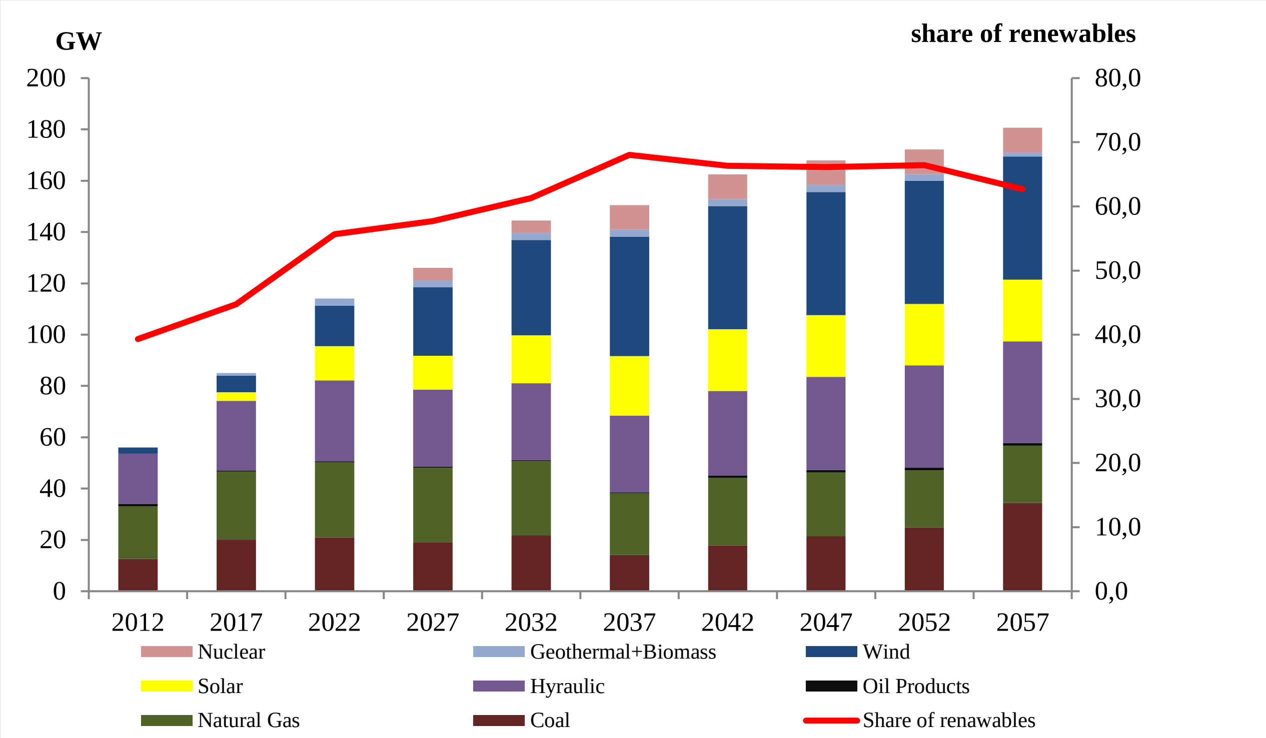


Figure 7.53. Total installed capacity in 20% emission reduction scenario.

Similar to the 10% reduction scenario total installed capacity exceeds 180 GW in 2052. Moreover, the share of renewable based capacity reaches almost 60% mostly due to wind followed by hydro and solar capacity. The coal-based capacity was 80.1 GW and 53.2 GW for the Base and 10% Reduction Scenarios respectively in 2052 and it decreases to 34.4 GW for the 20% Reduction Scenario. Starting from 2042 all technically available wind capacity was commissioned.

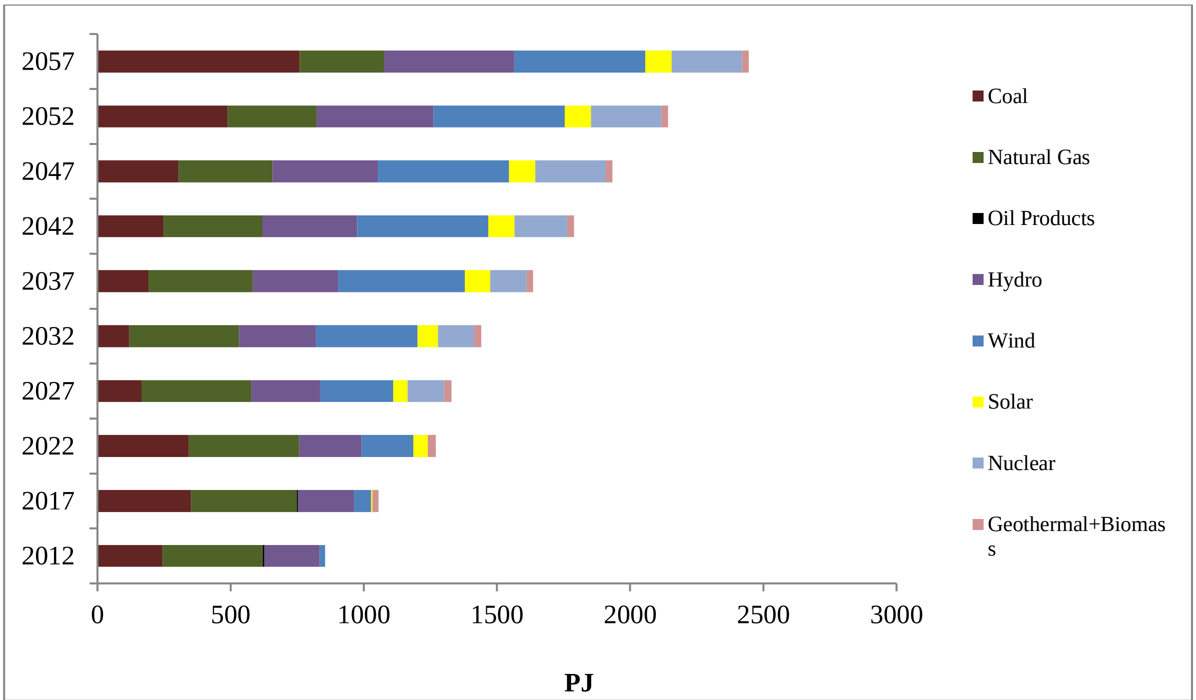


Figure 7.54. Electricity generation by fuel in 20% emission reduction scenario.

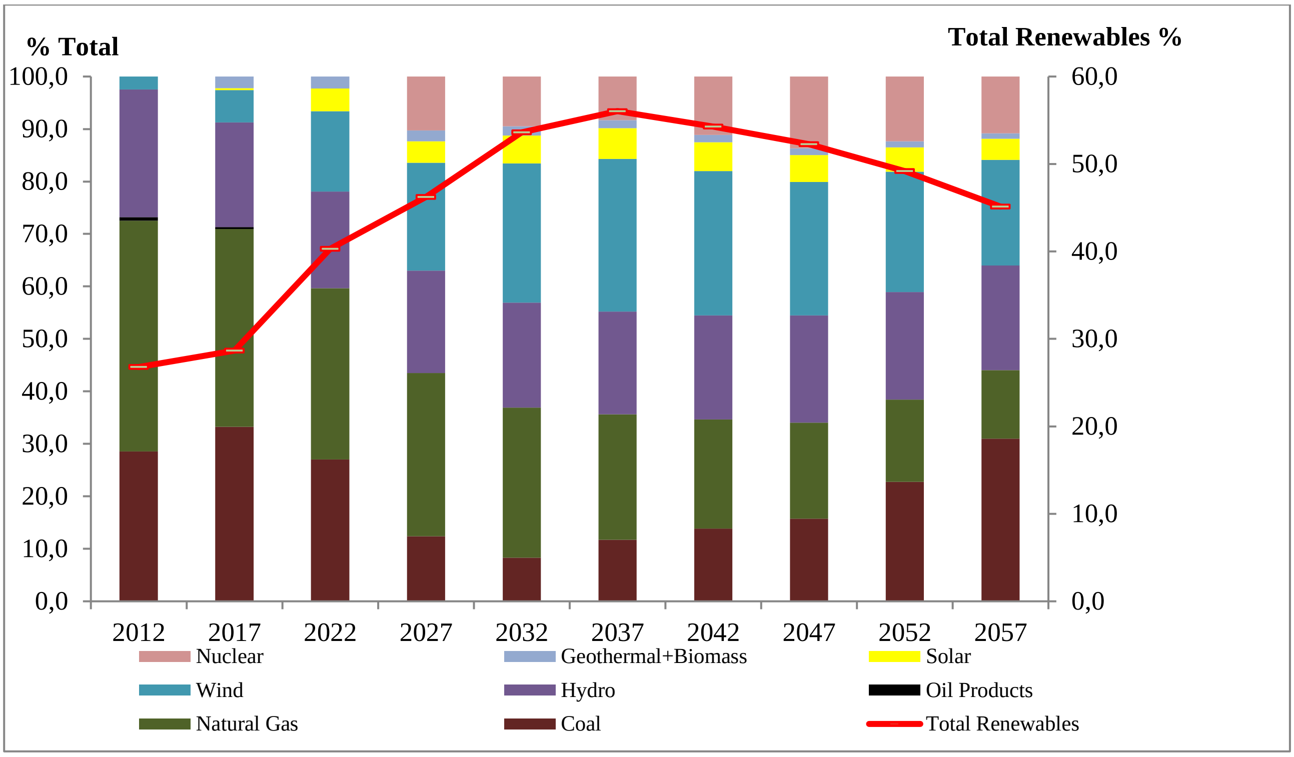


Figure 7.55. Fuel shares in electricity generation 20% emission reduction scenario.

According to Figures 50 and 51 the share of total renewables in electricity generation rose from 26.8% in 2012 to 45.1% in 2057 due to stricter emission reduction. This share is larger compared to Base and 10% Reduction Scenarios as expected. Similar reduction was also observed in natural gas-based generation between 2012-2057, in accordance with the target to reduce imported resources in electricity generation. Coal-based generation remain the largest part in the generation portfolio nevertheless its share continues to decrease with stricter emission controls and reduces to 31% in 2057. However, its share remarkably decreases compared to the Base Scenario, from 60.2% to 39.9% in 2052. In the renewable resources, wind-based generation surpasses hydro based generation starting from 2042 and remain constant till 2057.

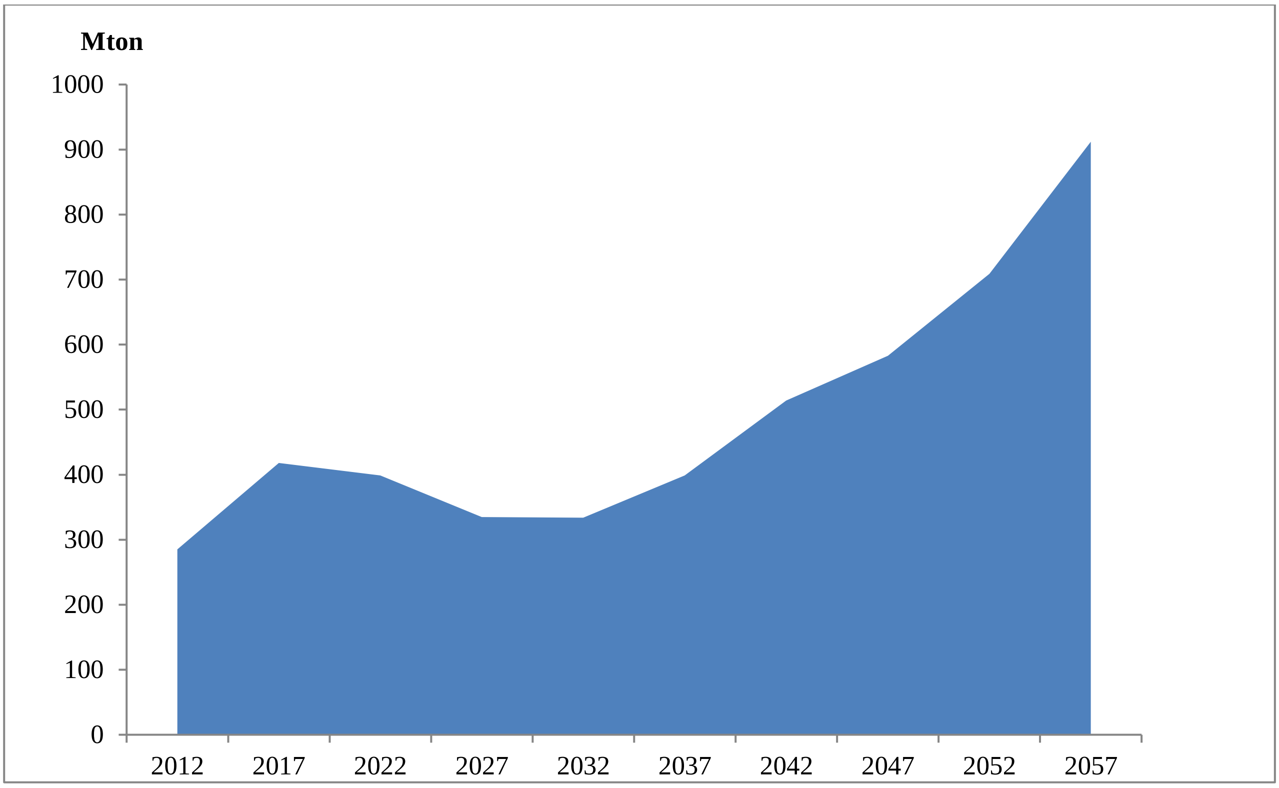


Figure 7.56. Total emissions in 20% emission reduction scenario.

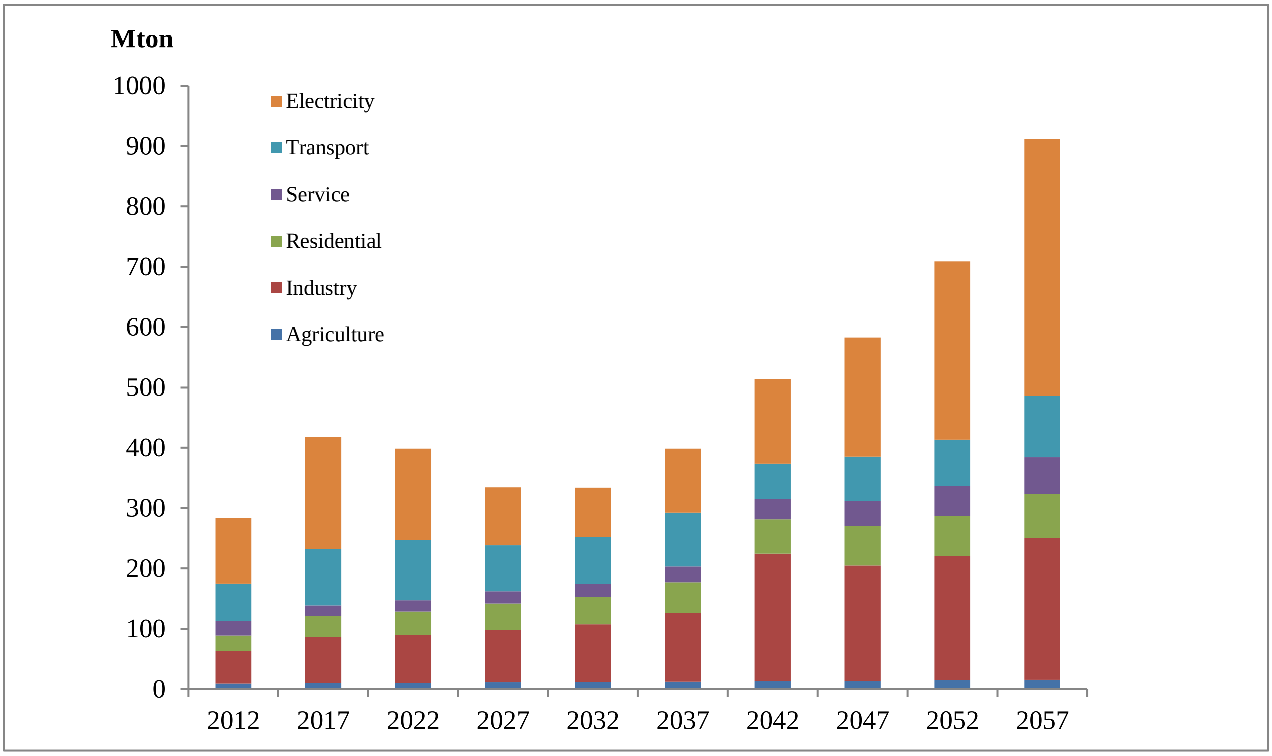


Figure 7.57. Total sectoral emissions in 20% emission reduction scenario.

After the application 20% emission reduction target in total emissions compared to Base Scenario. total emissions reduced to 912 Mtons in 2057. Electricity generation is the largest contributor to total emissions similar to the 10% Reduction Scenario. Emissions from electricity generation reaches to 425,7 Mtons in 2057 which is lower than Base and 10% Reduction Scenario which are 638,9 Mtons and 531,1 Mtons respectively.

7.3.3. %30 Emission Reduction Scenario

Under this scenario it has been assumed that the total emissions would be as follows according to 30% decrease in total emissions:

Table 7.6. Emission values under 20% scenario

Year	Emissions (Mtons)
2012	285
2017	418
2022	394
2027	338
2032	289,1
2037	349,3
2042	471,1
2047	532
2052	620,9
2057	798

In the model the emission values were fixed to the values above and the model was run.

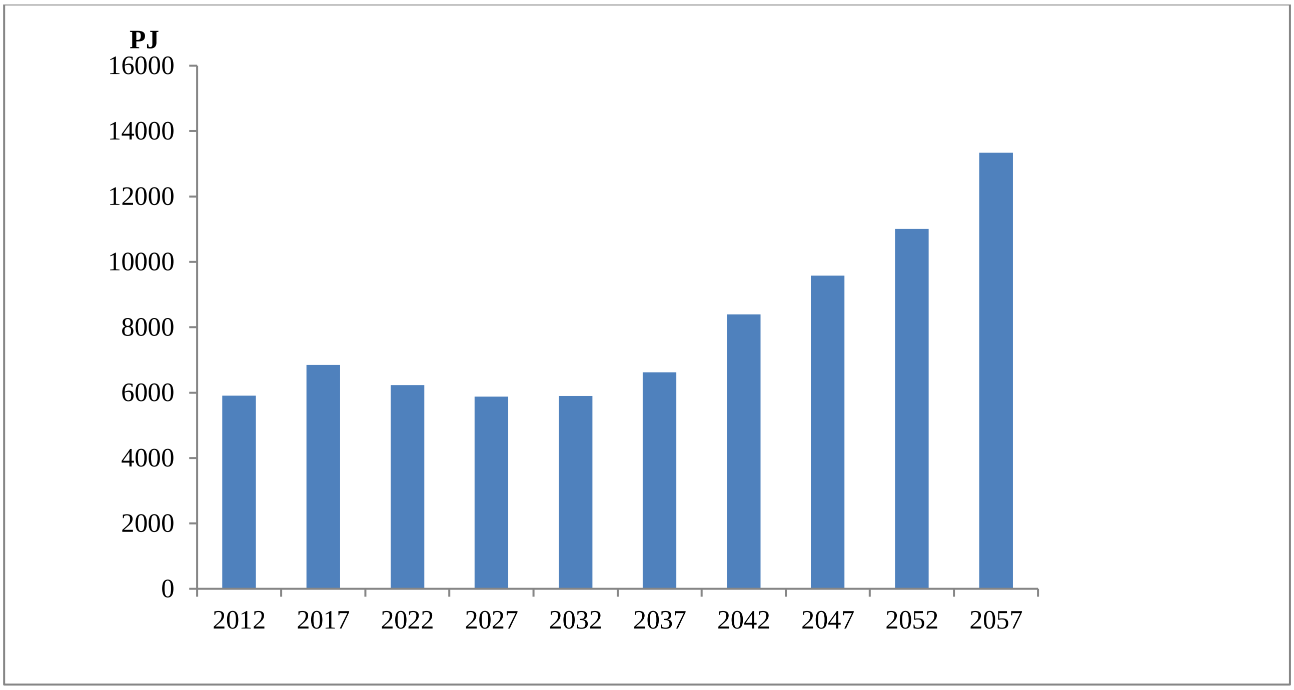


Figure 7.58. Primary energy supply of 30% emission reduction scenario.

In this scenario, the total primary energy supply reaches to 14330 PJ in 2057, which was 5907 in 2012. Similar to other Emission Reduction Scenarios, in 2057 it is observed that total primary energy decreases mainly due to the decrease in the coal supply. Compared to Base scenario, coal supply almost reduces 50% and becomes 4814 PJ in 2057. As another conventional fossil fuel, in all reduction scenarios natural gas supply value increases and mostly used in residential and service sector rather than electricity generation. Differently from other emission reduction scenarios coke supply also shows a significant decrease.

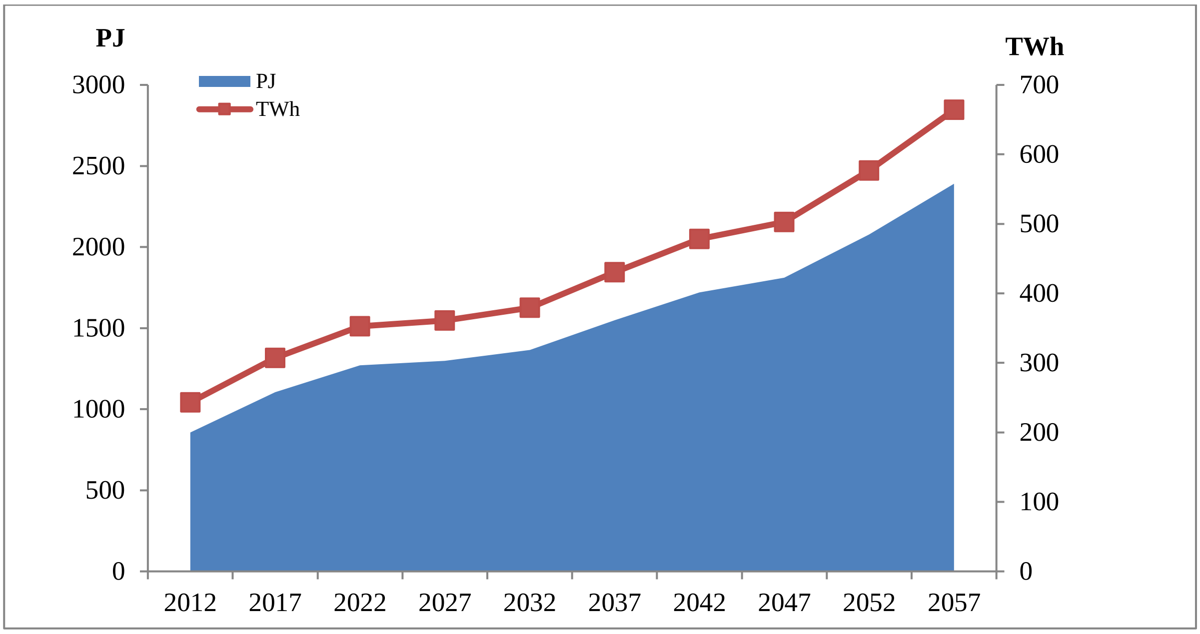


Figure 7.59. Total electricity generation in 30% emission reduction scenario.

Electricity generation under 30% reduction scenario reaches to 664 TWh in 2057 from 243 TWh in 2012. Generation from renewables reaches their highest value compared to Base, 10% and 20% Reduction Scenarios whereas coal-based generation faces dramatic decrease between 2012-2057. In all scenarios generated electricity primarily used in industry sector followed by services and residential sectors, which is in accordance with current consumption trends in Turkey.

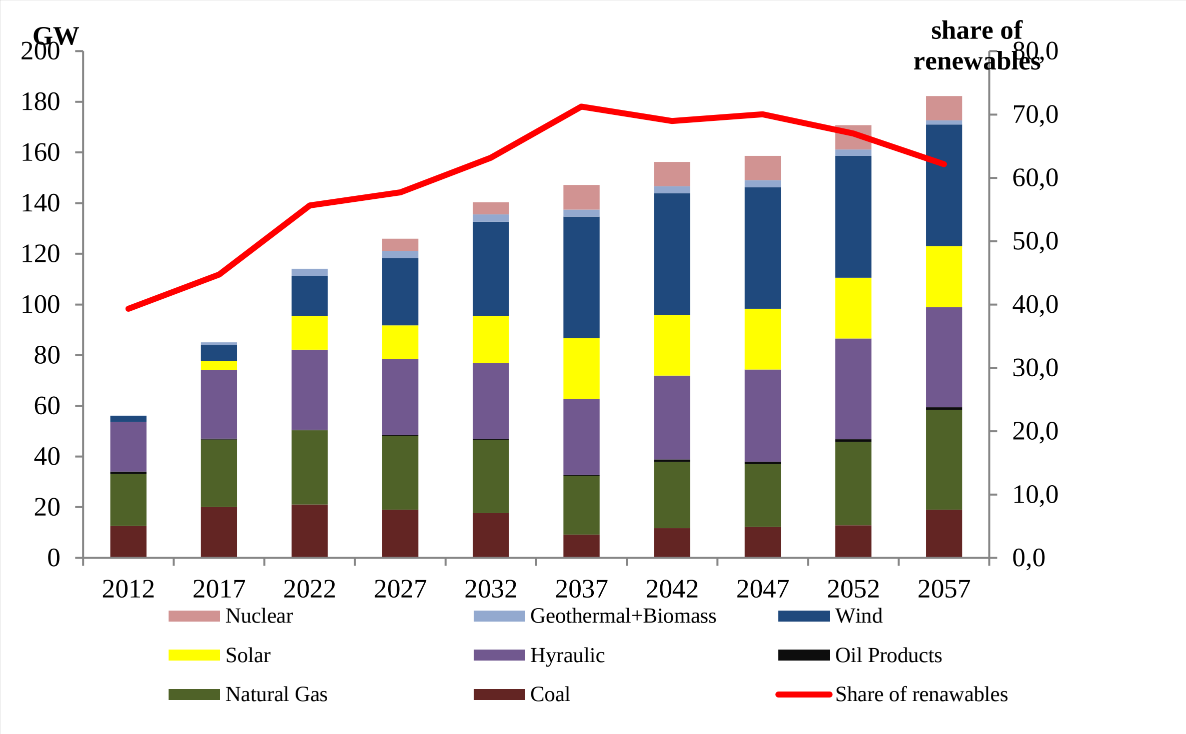


Figure 7.60. Total installed capacity in 30% emission reduction scenario.

Similar to all emission reduction scenarios total installed capacity exceeds 180 GW in 30% emission reduction scenario as well. Share of renewables in total installed capacity rises to 62.2% in 2057 primarily due to utilization of all technical wind capacity followed by hydro and solar capacity additions but this share is slightly lower than 20% Reduction Scenario. Coal capacity reaches its lowest value among reduction scenarios for the year 2057 and becomes 19.1 GW. This means that the model tends to invest more on renewables and tries not to put additional coal capacity to realize emission targets. Another important point is that in the 10% and 20% reduction scenarios while the model does not prefer to invest on natural gas capacity, in 30% reduction scenario, to compensate coal installed capacity loss, model starts commissioning new natural gas fired. For instance, in both 10% and 20% reductions scenarios the natural gas installed capacity is 22.4 GW, however in 30% reduction scenario gas fired capacity reaches to almost 40 GW (39.3). This situation also shows the importance of conventional base-load plants to balance the high penetration of renewables as intermittent resources. In all reduction scenarios share of renewables in total generation reaches their maximum in 2037 and after that period, model increases the share of coal and a slight decrease in the share of renewables is observed till 2057.

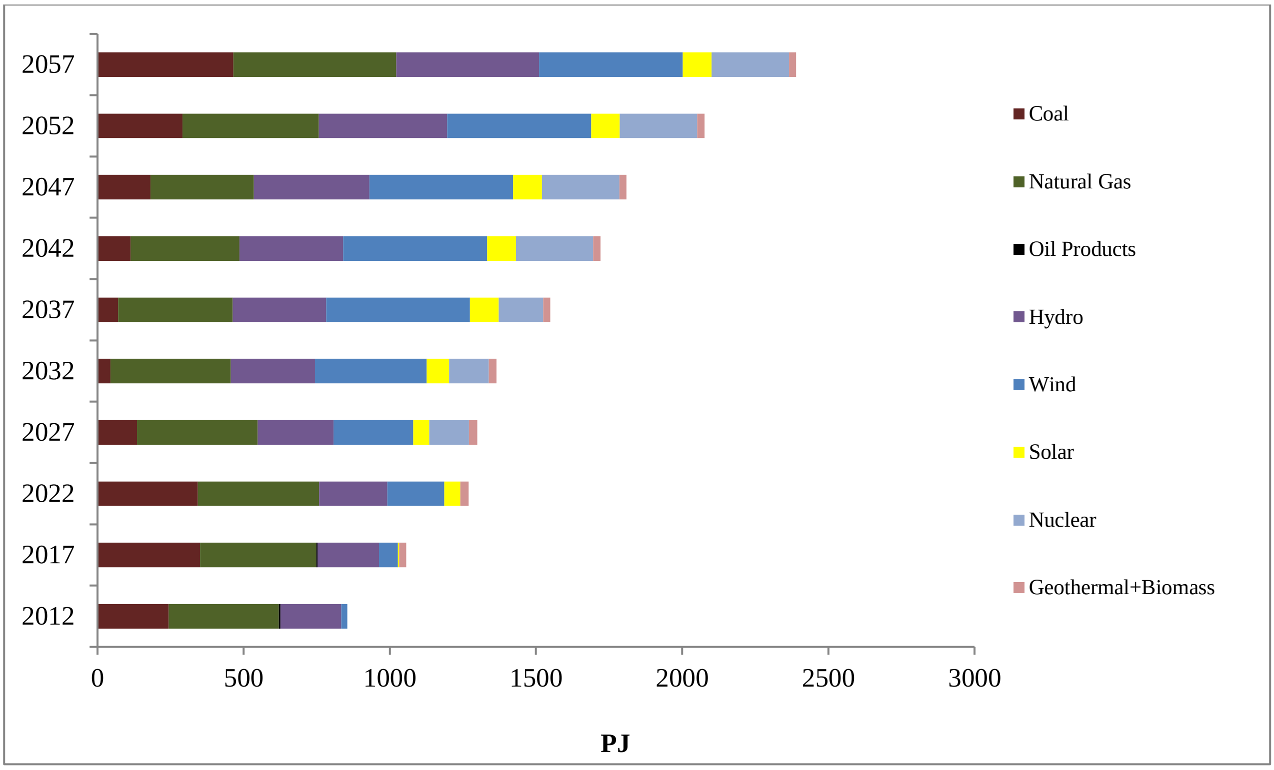


Figure 7.61. Electricity generation by fuel in 30% emission reduction scenario.

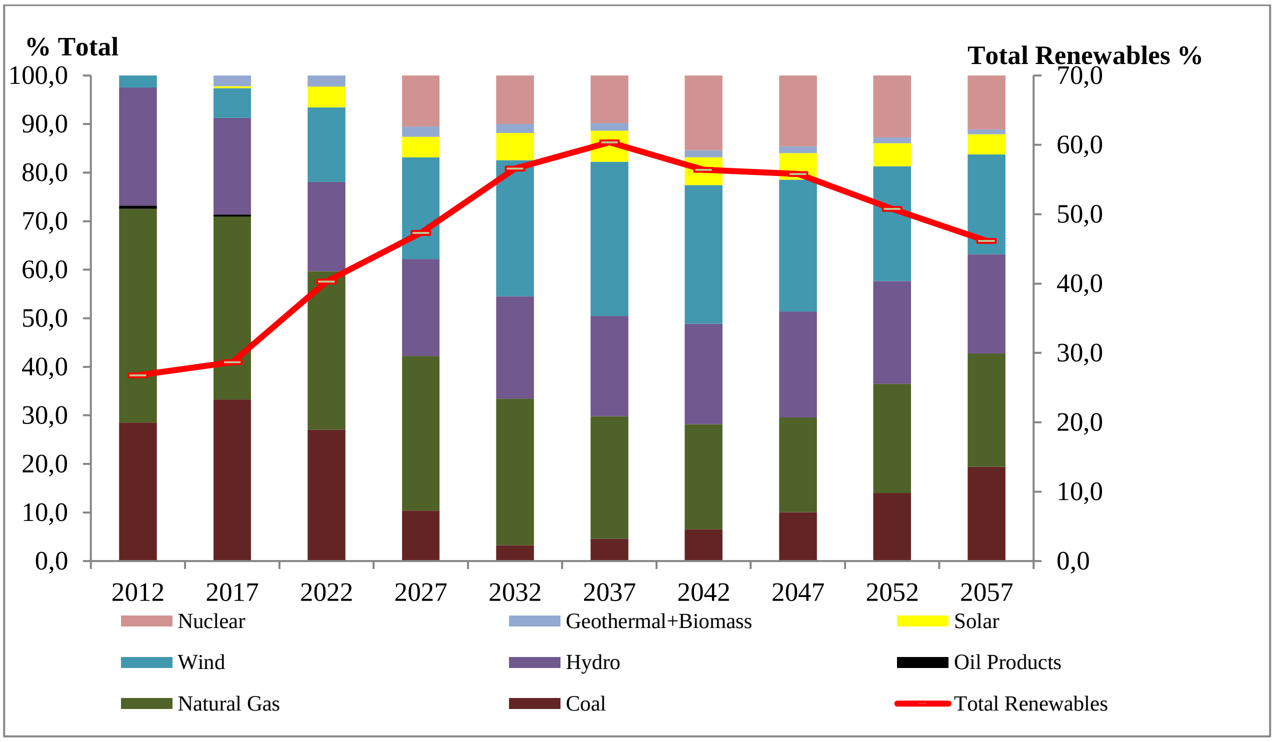


Figure 7.62. Fuel shares in electricity generation 30% emission reduction scenario.

As shown in the Figure, the share of renewables in the total electricity generation reaches their maximum value and it becomes 46.2%. For the first time share of wind surpasses the share of coal in electricity generation in the year 2057. The share of coal-based generation reduces even to 6% in

2042 and then parallel to installed capacity, its share in electricity generation starts increasing and reaches to 19.1% in 2057. As indicated in installed capacity part above, the share of natural gas in electricity generation becomes 23.3% in 2057, which is the highest share among Emission Reduction and Base scenarios for the respective year. For the 10% and 20% reduction scenarios approximately 497 PJ of natural gas was used for electricity generation in 2057 while 860 PJ was used in 30% reduction scenario for the same year. Similar to the installed capacity analysis explained above, in the year 2037 renewables reaches their highest value in electricity generation by 60.4% and then it starts reducing with the penetration of second nuclear plant and new coal capacity additions.

From these figures it is also meaningful to comment that power system is highly decarbonized via the use of renewables and nuclear in 30% Reduction Scenario and the importance of nuclear power generation is once put forward by this scenario.

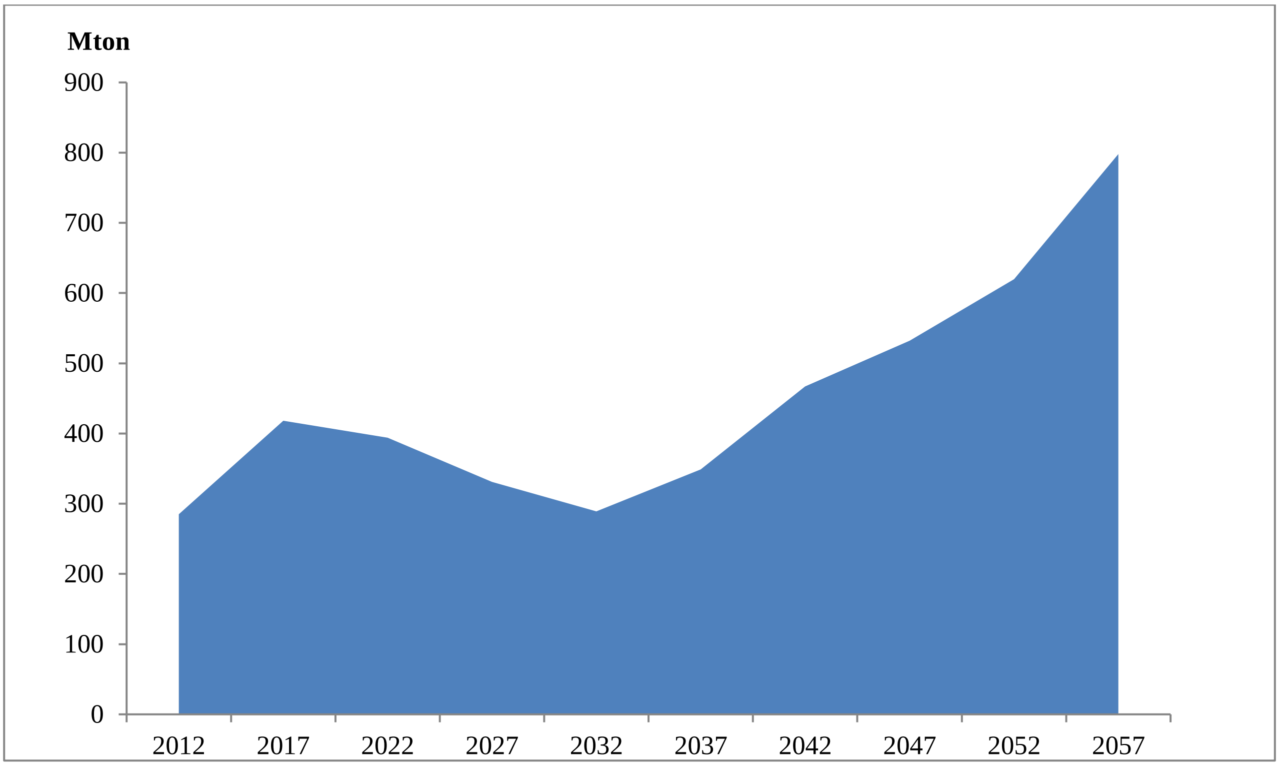


Figure 7.63. Total emissions in 30% emission reduction scenario.

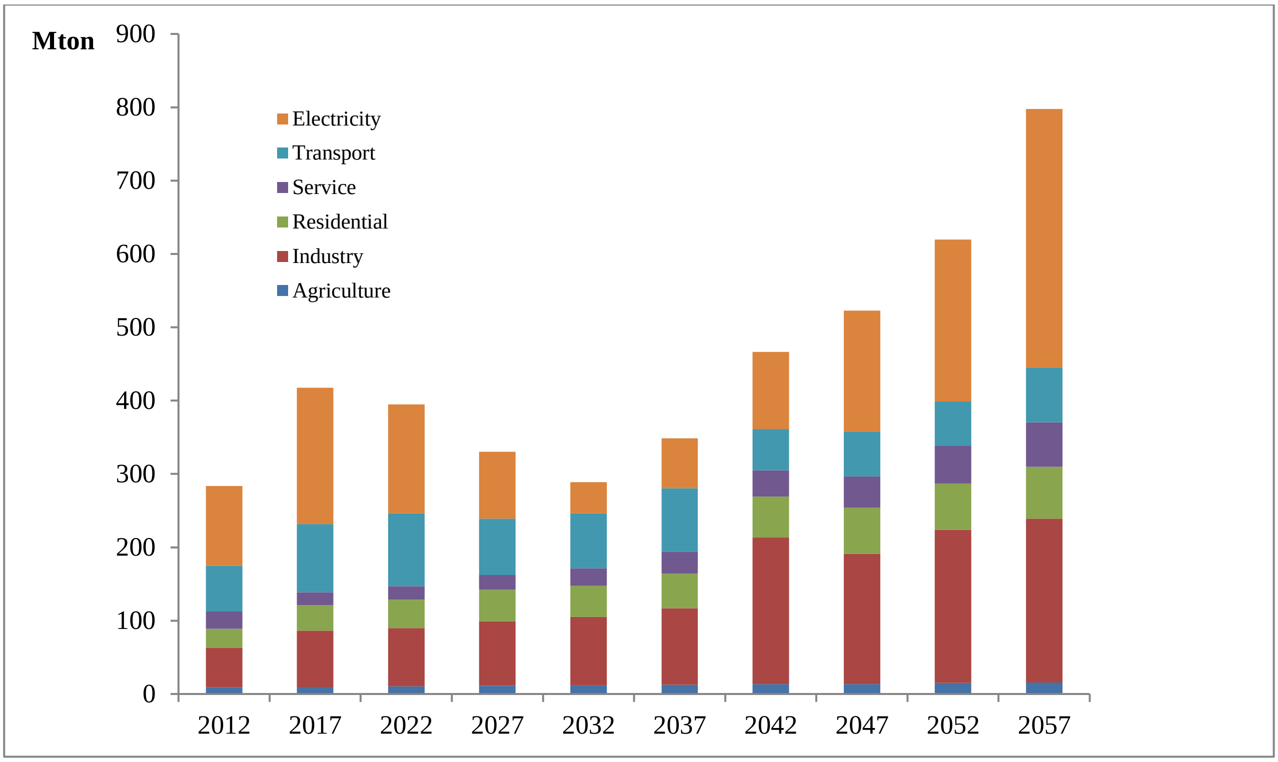


Figure 7.64. Total sectoral emissions in 30% emission reduction scenario.

As a result of 30% emission reduction target in total emissions, compared to Base Scenario, total emissions reduced to 798 Mtons in 2057. Electricity generation is the largest contributor to total emissions similar to the 10% and 20% Reduction Scenario. Emissions from electricity generation reaches to 352,6 Mtons in 2057. As the ratio of emission restriction increases, the model invests more on renewables and use nuclear at its maximum level. Nevertheless, in all scenarios model use conventional fossil fuel capacity as back-up to balance renewable integration. It should be also noted that in all scenarios, whether tax or reduction scenarios, electricity sector responds to emission reduction and as a result it is possible to comment that other sectors are not easy to decarbonize although their emission values are lower than that of electricity sector.

7.3.4. Scenario Comparison for Emission Reduction Scenarios.

Based on the model results scenario comparisons are as follows in terms of share of renewables in installed capacity and electricity generation, total electricity generation and CO2 emission values stemming from electricity generation.

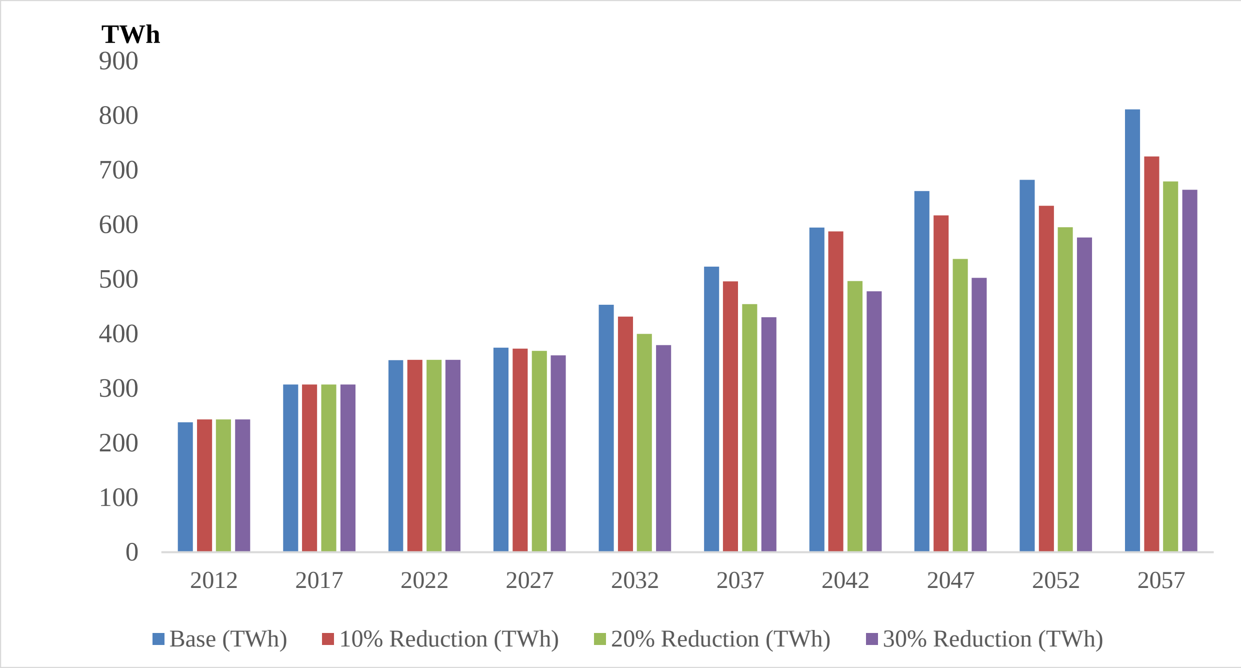


Figure 7.65. Electricity generation comparison of emission reduction scenarios.

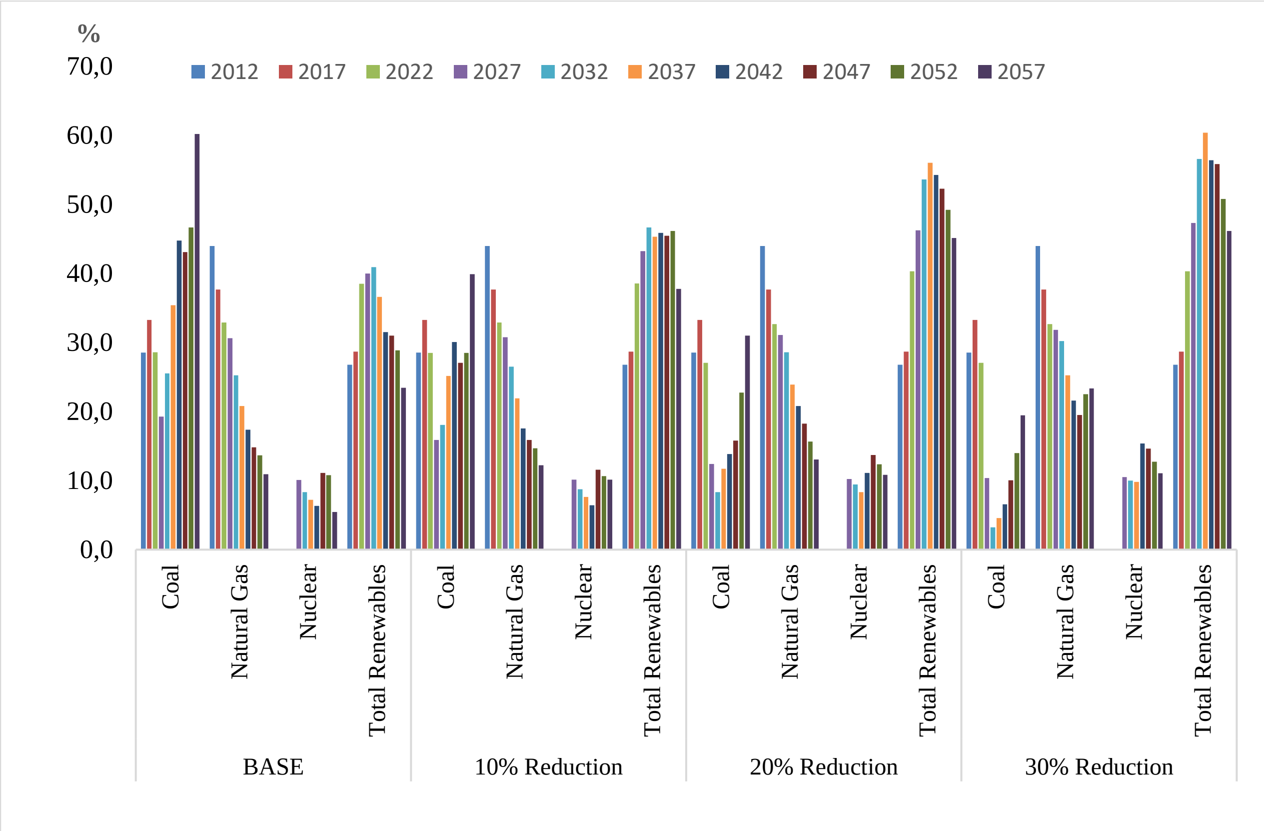


Figure 7.66. Share of fuels in electricity generation comparison of emission reduction scenarios.

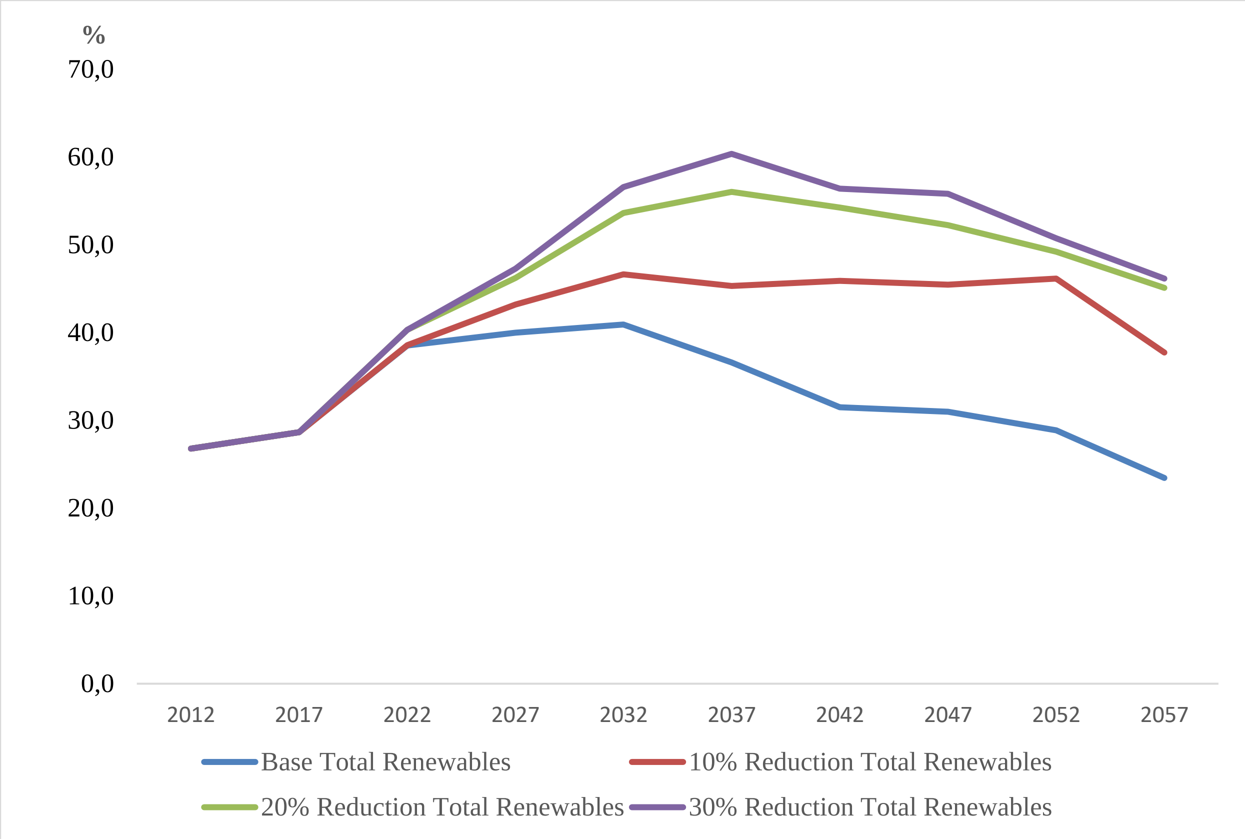


Figure 7.67. Share of renewables in electricity generation comparison of emission reduction scenarios.

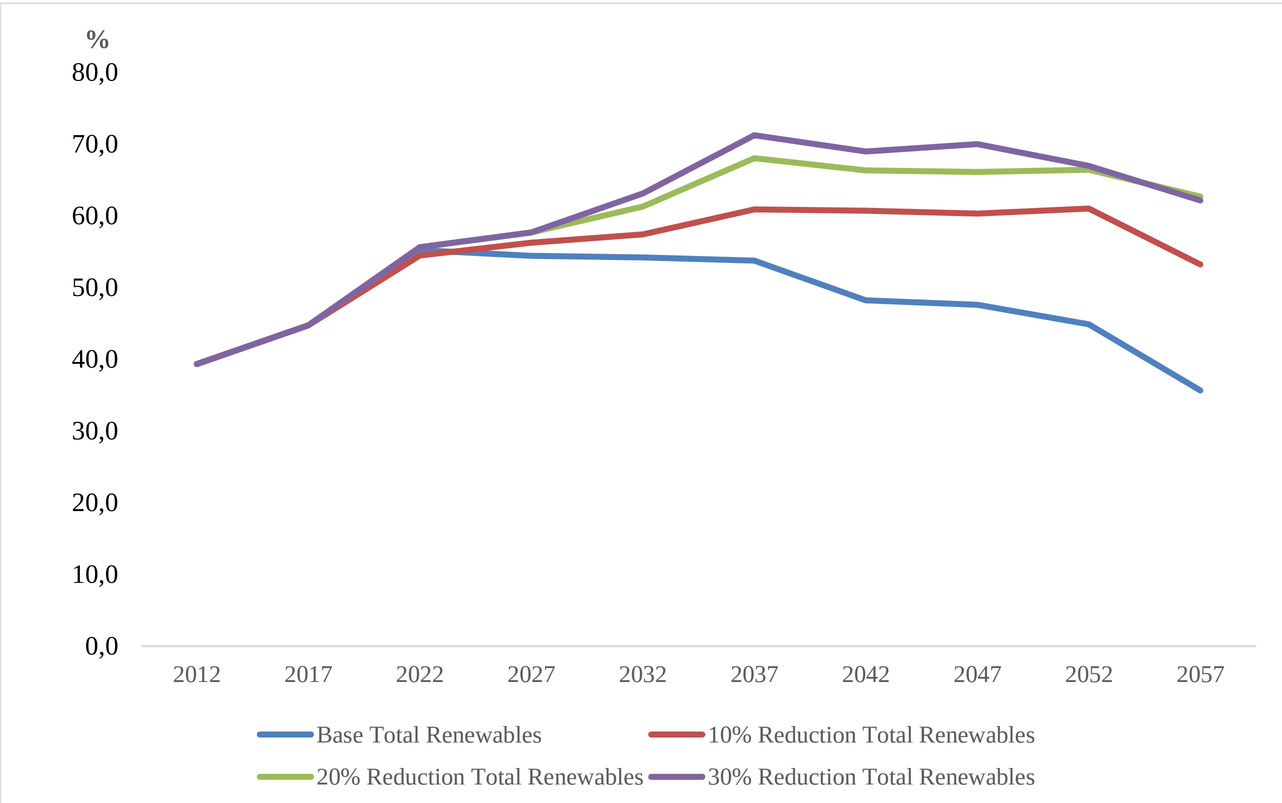


Figure 7.68. Share of renewables in installed capacity comparison of emission reduction scenarios.

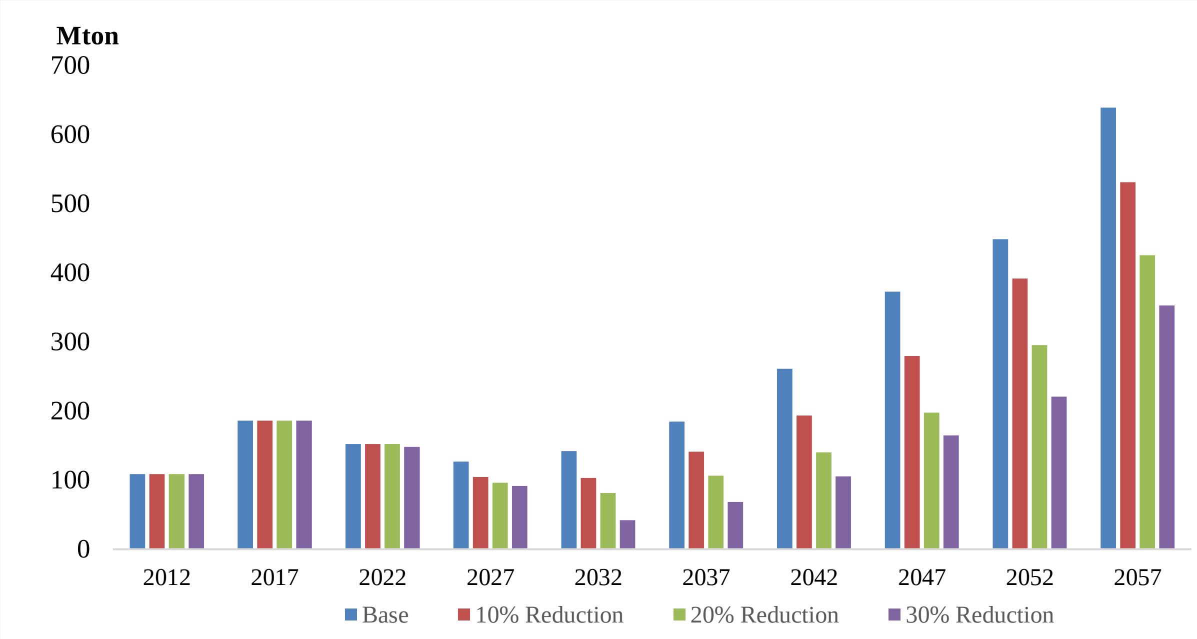


Figure 7.69. Comparison of CO_2 emissions of electricity generation of emission reduction scenarios.

Comparing all three Reduction Scenarios and the Base Scenario, the lowest CO2 emission coming from electricity generation, was obtained in 30% Reduction Scenario between 2012-2057. In all three scenarios after the year 2042 the emissions start increasing as a result of slight increase in coal-based generation. From renewables point of view, the highest share in electricity generation was obtained in 30% Reduction, where as in terms of installed capacity 20% and 30% Reduction Scenarios the share of renewables was almost identical with a slight difference in the favor of 20% Reduction Scenario. To sum up, as the emission reduction target increases, the model invests more on renewables both in total capacity and electricity generation.

On the other hand, when a comparison is made between tax scenarios and emission reduction scenarios, the share of renewables is higher in reduction scenarios. Moreover, in tax scenarios, emission level resulting from electricity generation are higher than reduction scenarios. Therefore, it could be concluded that emission reduction targets are more effective to obtain lower emission values. Total system cost comparison is listed in the table below.

Table 7.7. Total system cost in emission reduction scenario (2012 million US $).

	2012	2017	2022	2027	2032	2037	2042	2047	2052	2057
Base (SP)	47292	76627	88575	97303	115000	131790	137920	164700	196590	235550
10%Reduction Scenario	47368	76657	88580	97669	116070	133260	140380	164300	196980	238850
20%Reduction Scenario	47392	76667	88770	98052	117000	134700	141960	166680	197400	237010
30%Reduction Scenario	47546	76701	88821	98087	119350	136470	146330	173530	206260	242080

As it can be seen from the table above, total system cost increases as the emission target rises. The model invests relatively on renewables sources rather than cheap conventional sources, such as coal, to meet to emission criteria. For instance, in 30% Reduction Scenario 1361 Mtons of total emission reduction was achieved throughout 2012-2057. For that scenario average emission mitigation cost is approximately 32$/ton CO_2.

7.3.5. Peak Emissions Scenario

In this scenario it has been assumed that, similar to 10% Emission Reduction Scenario, emissions were reduced by 10% for every 5 years of intervals compared to Base Scenario; in the year 2052 emissions reaches its peak value and for the year 2057 emissions starts decreasing compared to year 2052. It has been also applied 30$ tax on emissions.

It should be also mentioned that the model was run assuming that in Turkey in the years 2032 and 2052, total emissions would be reduced to 1990 level. However, under this assumptions model gave infeasible solutions indicating that total energy demand could not be satisfied by available energy resources under this restriction. Thus, above-mentioned scenario was used to control peak emission value.

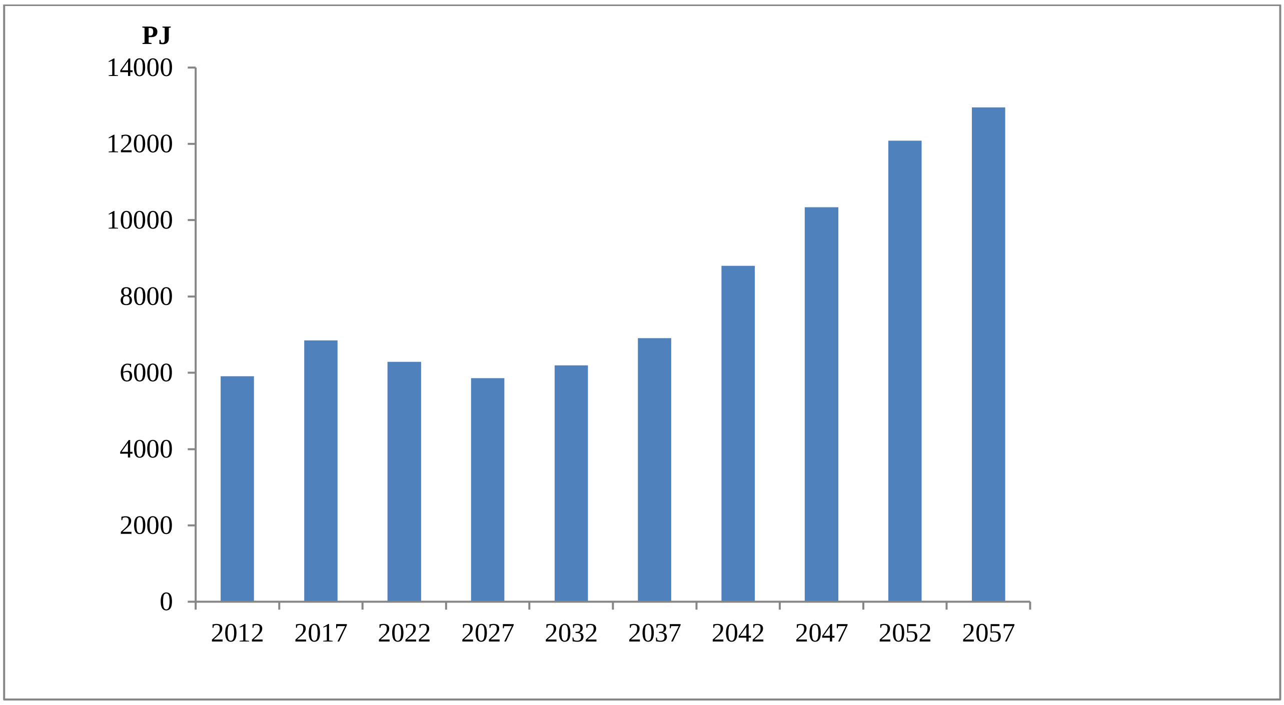


Figure 7.70. Primary energy supply of peak emissions scenario.

In this scenario, the total primary energy supply reaches to 12956 PJ in 2057, which was 5907 in 2012. It is observed that in 2057 total primary energy decreases mainly due to the decrease in the coal and hydrogen supply in transport. Compared to Base, Tax and Emission Reduction Scenarios scenario, coal supply reduces to its lowest level and becomes 3799 PJ in 2057. As another conventional fossil fuel, natural gas supply value increases to 4976 PJ as its highest level among all scenarios. Although, coal supply faces its lowest value, coal-based generation and installed capacity increases compared to 30% and 20% Emission Reduction Scenarios due to the fact that coal is mostly used in electricity sector whereas natural gas supply increases in industry.

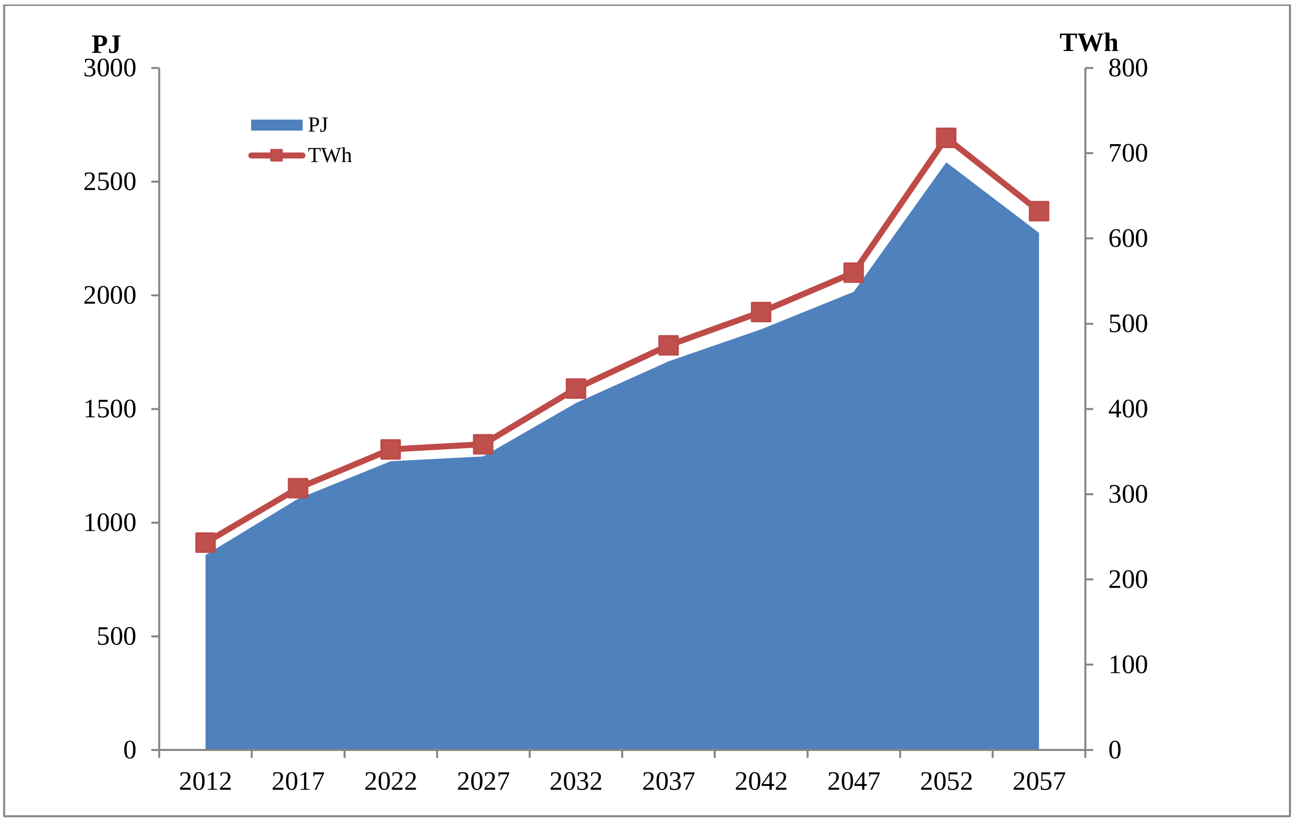


Figure 7.71. Total electricity generation in peak emissions scenario.

Electricity generation under Peak Emissions Scenario reaches to 632 TWh in 2057 from 243 TWh in 2012. Similar to other scenarios generated electricity used mostly in industry followed by services and residential sector. In this scenario it is also observed that electricity generation decreased after year 2052. Due to emission restriction coal-based generation starts decreasing after 2052 and it was slightly offset by the increase in natural gas-based generation.

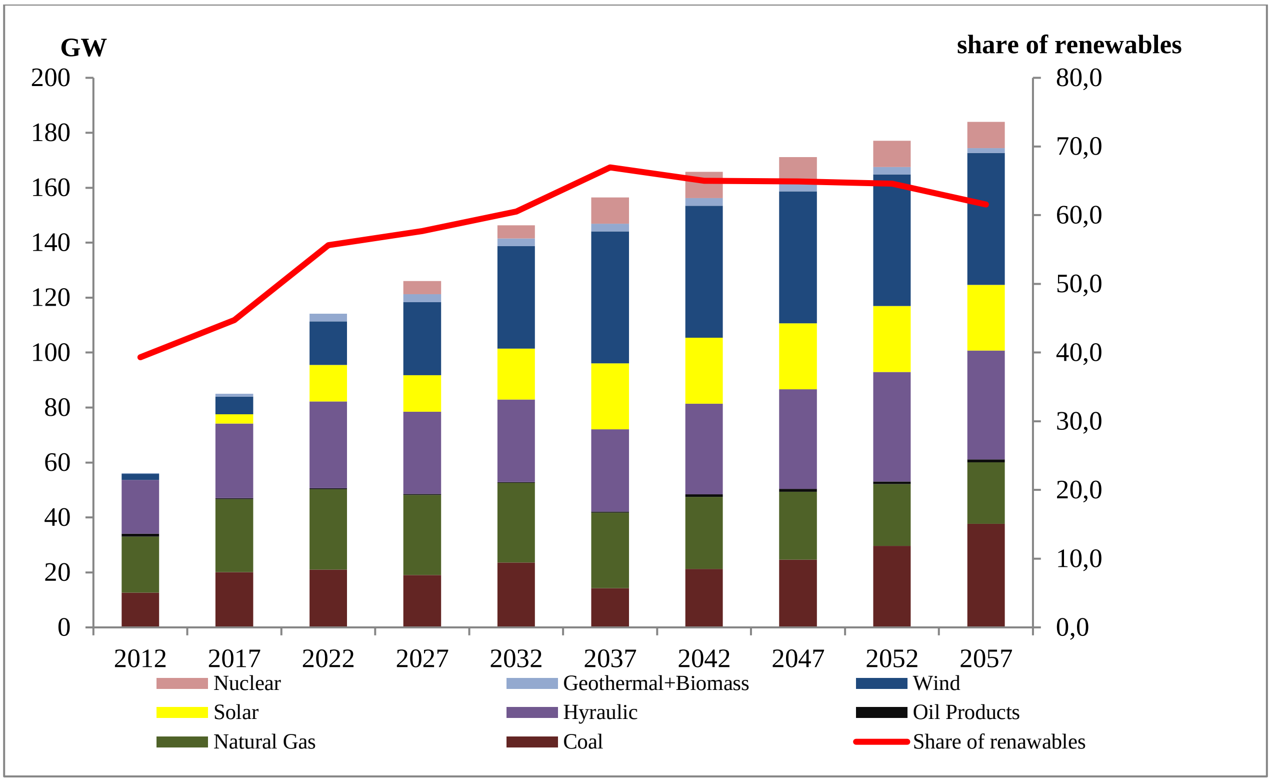


Figure 7.72. Total installed capacity in peak emissions scenario.

Similar to all emission reduction scenarios total installed capacity exceeds 180 GW in Peak Emissions Scenario as well. Share of renewables in total installed capacity rises to 61.6% in 2057 which is approximately the same share as in 20% and 30% Reduction scenarios. As indicated in supply section, although coal supply reduces to its lowest level, is share in coal capacity increases compared to 30% Reduction Scenario due to the fact that it is primarily used in electricity generation. Compared to other conventional resources coal price is lower and model use coal resources to reduce system cost. In terms of natural gas, it is mostly used in industry rather than electricity generation so that its share in installed capacity reduces starting from year 2037. Similar to 30% Reduction scenario renewable capacity reaches their maximum value as of 2037 and remains stable throughout 2057.

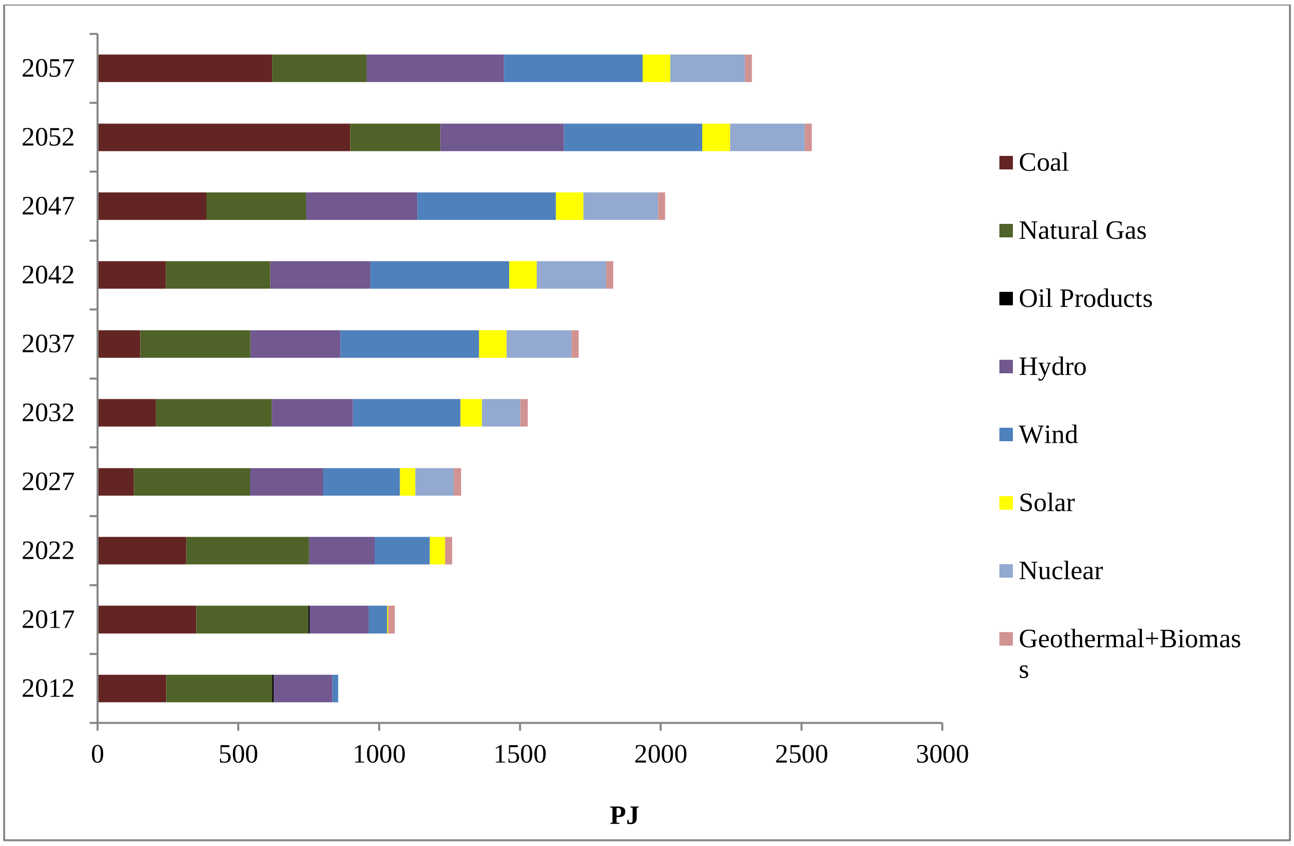


Figure 7.73. Electricity generation by fuel in peak emissions scenario.

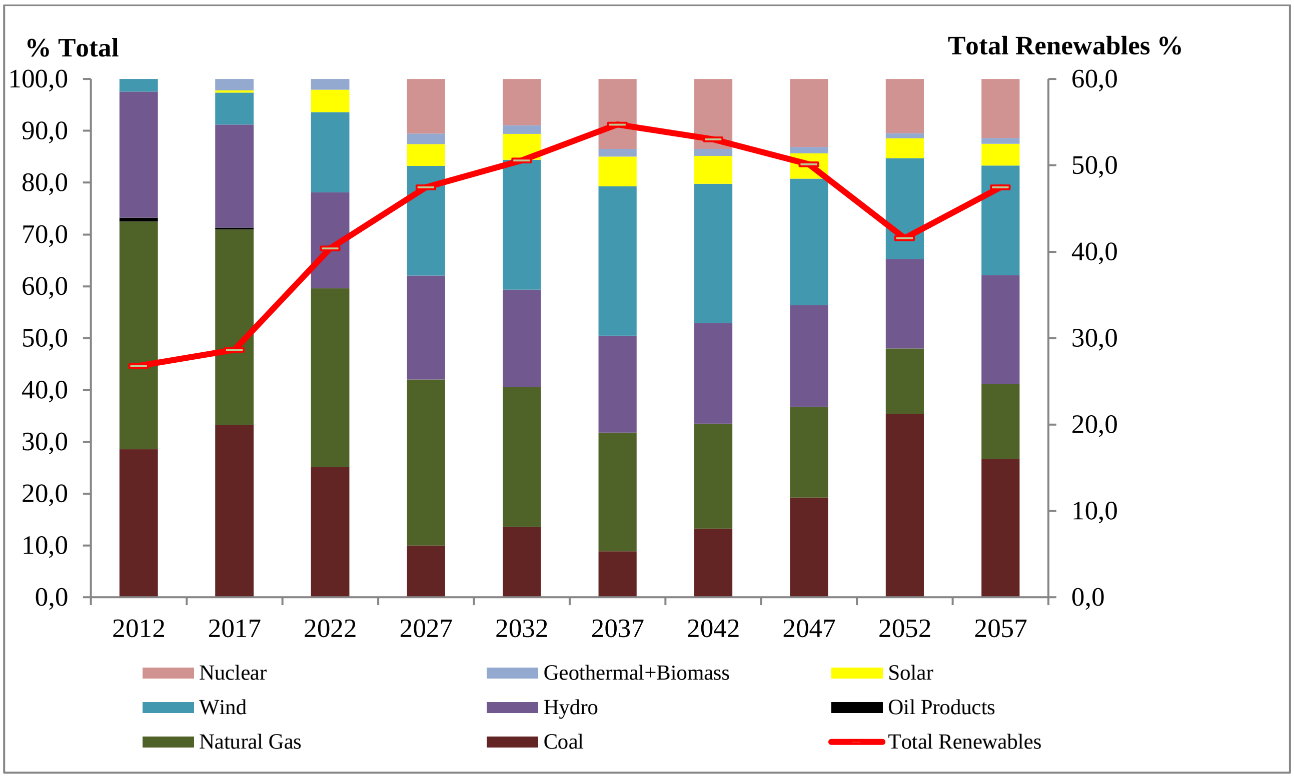


Figure 7.74. Fuel shares in electricity generation in peak emissions scenario.

As indicated above in order to meet the electricity consumption in residential, services and transport sector electricity generation increases compared to 30% Reduction Scenario and hence; coal-based capacity and generation shows an increase as well. As shown in the Figure 7.73 and 74, after 2042 the share of coal in electricity generation starts increasing till 2052 and as a result, the share renewables in the total electricity generation starts reducing however it rises to 47.5% in 2057 which is greater than 30% and 20% Emission Reduction Scenarios for the same year. The share of renewables reaches their maximum in the year 2037 as 54.7%. The decrease of coal-based generation was offset by natural gas fired generation in 2057 and it was observed a slight increase in the share of natural gas in total electricity generation by 2057.

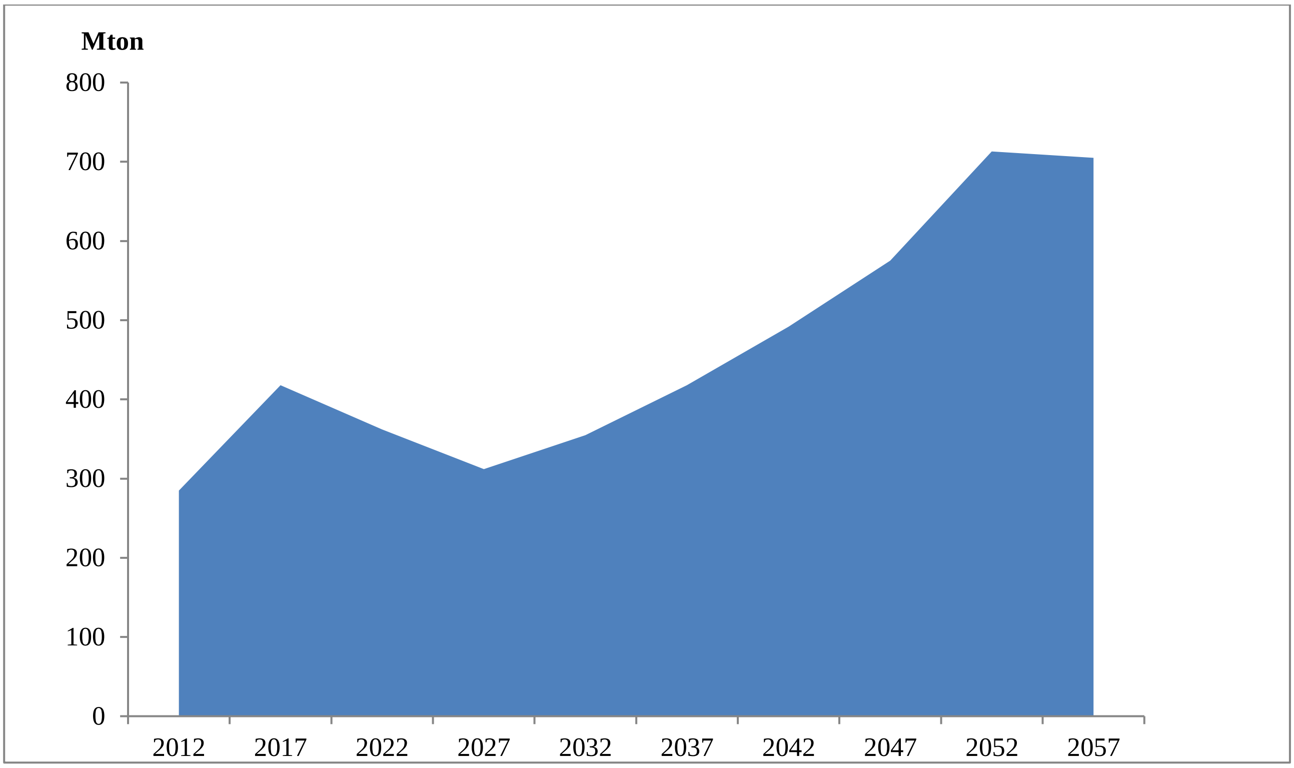


Figure 7.75. Total emissions in peak emission scenario.

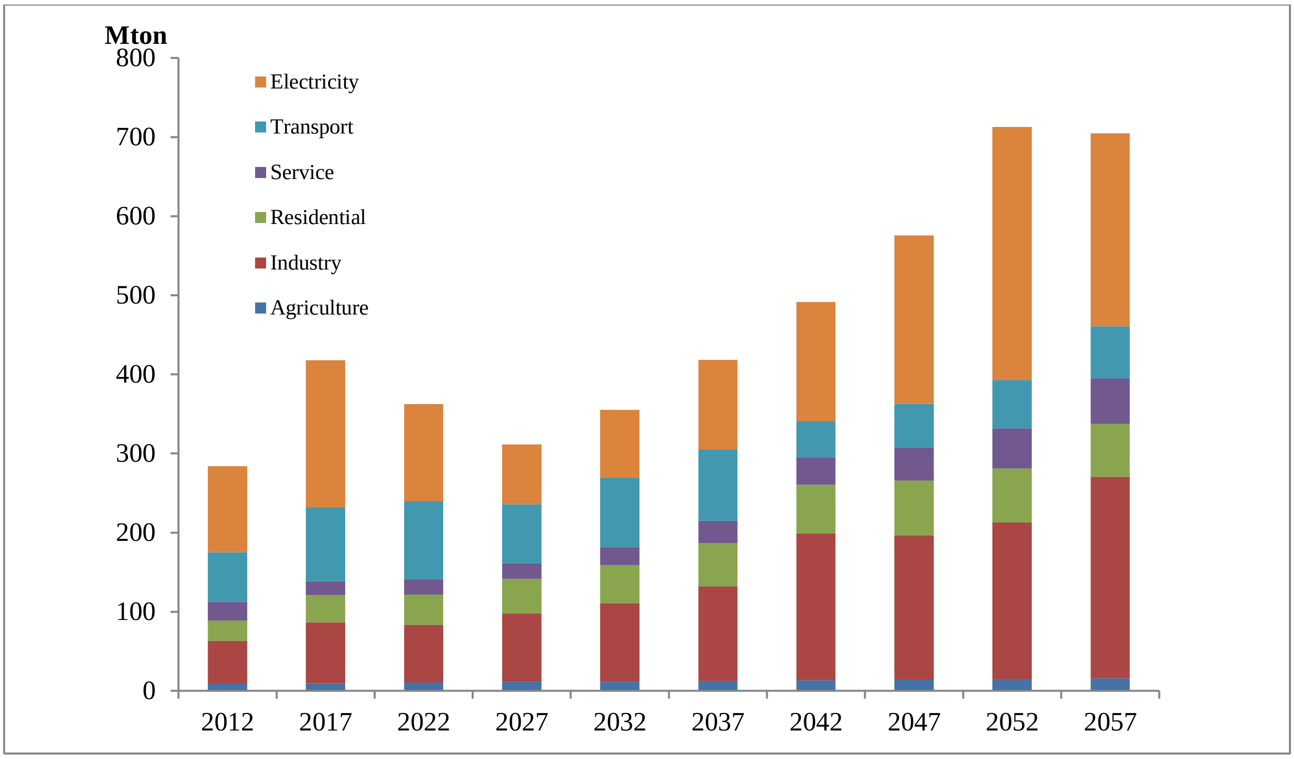


Figure 7.76. Total sectoral emissions in peak emissions scenario.

As shown in Figure 71. Total emissions plummeted to its lowest level in Peak Emission Scenario compared to Base, Tax and Emission Reduction Scenarios. After reaching its peak value of 713 Mton in 2052, it reduces to 705 Mton in 2057 corresponding to a fall by almost 39% compared to emission value of Base Scenario. Similarly, from electricity generation emissions perspective, in the year 2052 reaches its maximum value as 320 Mton and then decreases to 244 Mton in 2057 falling by more than 60% compared to emissions from electricity sector of Base Scenario for the year 2057. For the first time among all scenarios, as of 2057, emissions resulting from industry sector surpasses emissions from electricity generation becomes the largest source of emission in the year 2057 in Peak Emissions Scenario. This situation also justifies that electricity sector is much more flexible than any other sector to decarbonize.

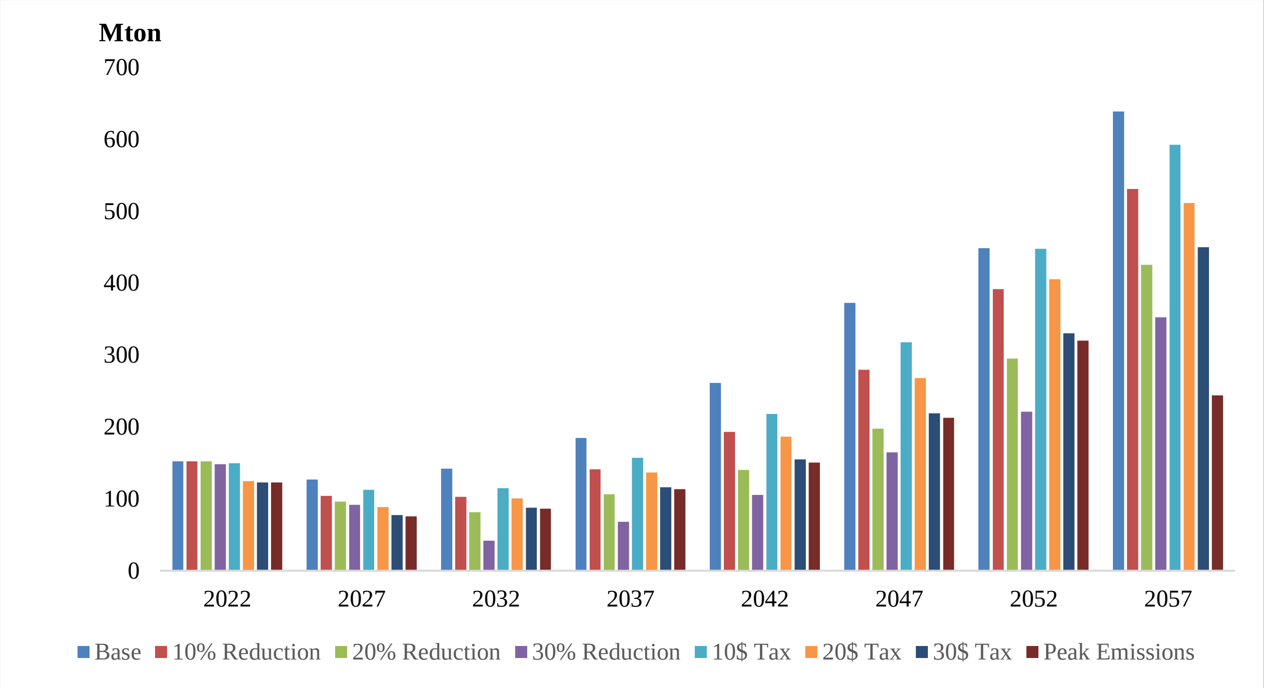


Figure 7.77. Emissions from electricity generation in all scenarios.

As expected, the lowest emission value resulting from electricity generation was obtained when 10% reduction target, 30$ of tax and emission restriction were applied together. Compared to Base Scenario emissions from electricity sector decreased by almost 61% and fell to 244 Mtons from 638.9 Mton in the year 2057.

It should be also noted that model was run under the assumption that by 2032 the total emissions would reduce to 1990 level. However, under this assumption model gave infeasible solution due to the fact that electricity demand could not be met without investing coal-based capacity.

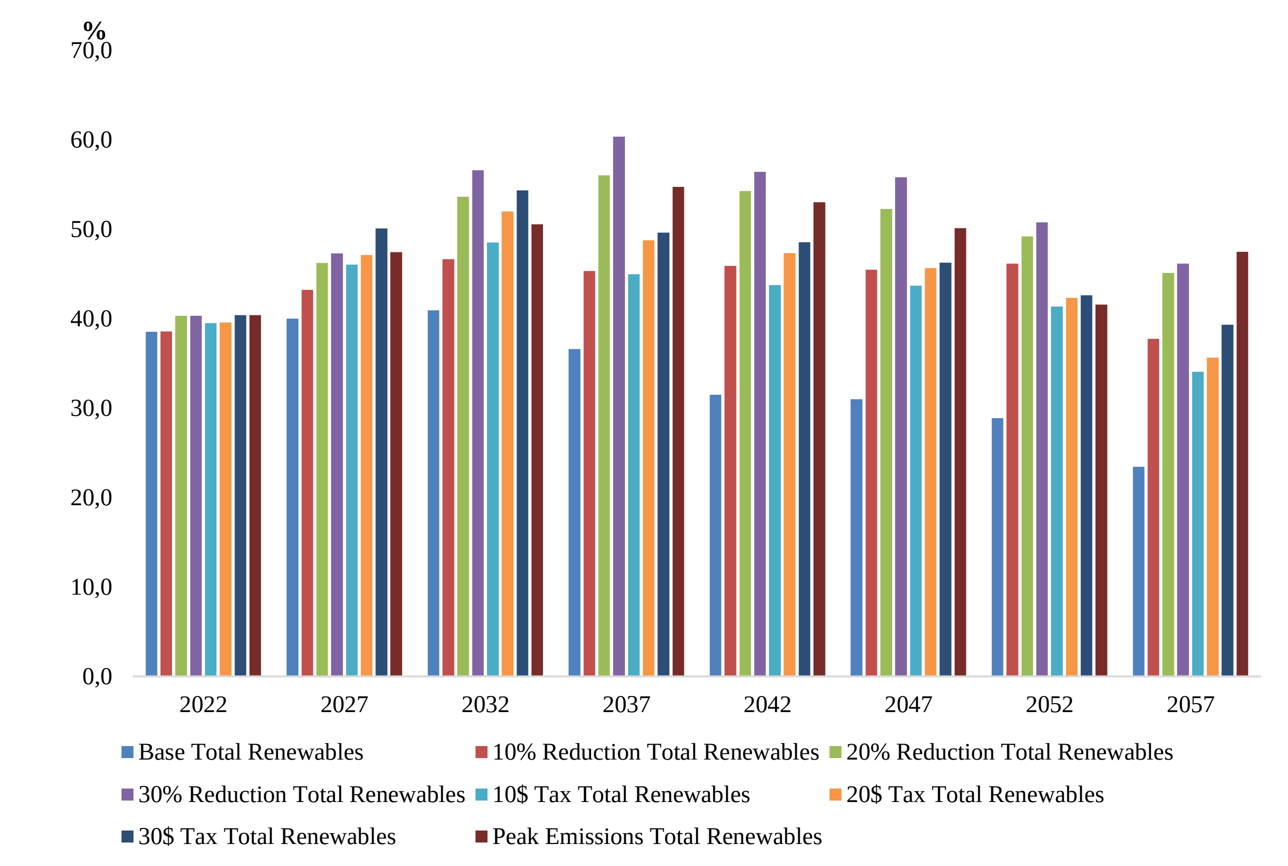


Figure 7.78. Share of renewables in electricity generation in all scenarios.

As can be seen from Figure 7.78 The share of total renewables in electricity generation has the highest level in Peak Emissions Scenario by the year 2057 with the share of 47.5% followed by 30% Reduction Scenario with 46.2%. Compared to Base Scenario, by 2057 the share of renewables in electricity generation increases by more than 100%. Wind based generation is the leading source by 21.2% among renewables and mostly all of technical capacity (48 GW) is used by the model. Wind is followed by hydro and solar generation with the share of 21% and 4.2% respectively for Peak Emissions Scenario. From cost perspective, the Table below summarizes the cost of all scenarios.

Table 7.8. Cost comparison of all scenarios million $.

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**	**2057**
Base (SP)	47292	76627	88575	97303	115000	131790	137920	164700	196590	235550
10%Reduction Scenario	47368	76657	88580	97669	116070	133260	140380	164300	196980	238850
20%Reduction Scenario	47392	76667	88770	98052	117000	134700	141960	166680	197400	237010
30%Reduction Scenario	47546	76701	88821	98087	119350	136470	146330	173530	206260	242080
10$ Scenario	47354	76639	92003	100780	119300	137080	145550	169390	203470	245120
20$ Scenario	47387	76645	95781	104170	123190	141520	151550	176000	210130	254210
30$ Scenario	47526	76686	99283	107310	126410	145080	157470	182940	217200	263550
Peak Emissions Scenario	47526	76715	99707	107260	126630	145540	163210	191940	227140	280610

As can be seen from the table, the highest cost belongs to Peak Emission Scenario, since 30$ tax and emission restriction are applied simultaneously. The total additional cost of Peak Emission Scenario compared to Base Scenario is 174931 Million$ throughout 2012-2057.

8. CONCLUSION

In this study, it has been aimed to make projections of Turkish electricity sector in terms of installed capacity, electricity generation and resulting CO_2 emissions by using latest energy policy, official papers and available data. For that purpose, BUEMS modelling framework was utilized to obtain reliable and realistic model outputs due to the fact that its modeling capacity has already been proven by Işık, (2016).

As explained in the sections above, BUEMS is a bottom-up approach economy-energy-environment model that uses least-cost options throughout the years between 2012-2057 by using GAMS linear programming. As any other bottom-up models in the same variety, the model requires considerable technological detail. Therefore, the model allows the modeler to build different scenarios configurations by applying set of constraints. The main advantage of the model is its ability to represent solely Turkish energy system.

In the model; Base, Tax, Emission Reduction and Peak Emission Scenarios are applied to monitor the evaluation of CO_2 emissions resulting from electricity generation. It should be noted that under Base and Tax scenarios total technical available onshore wind capacity was fixed to 37 GW. On the other hand, in Emission Reduction and Peak Emission Scenarios technical offshore wind potential, which is 11 GW, is also added and total wind capacity was fixed 48 GW. Under Base Scenario, Strategic Plan of MENR (2019-2023) was used. The installed capacity targets were introduced into the model. Besides, it has been assumed that by 2027 first and by 2037 second nuclear power plants of 4.8 GW will be operational and thus by 2037 total nuclear capacity was fixed to 9.6 GW. Under Base Scenario total system emissions reached to 1.138 Mton by 2057. Emissions from electricity generation was 108,6 Mton in 2012 and increased to 638,9 Mton by 2057 and it was still the main contributor to total emissions among all sectors. It has been observed that coal remains as main fuel for electricity generation and its share rose %60.2 in 2057. The share of total renewables was 23.4% in 2057. Total electricity installed capacity reaches almost to 180 GW.

After establishing Base Scenario, environmental tax was applied as 10-20 and 30$/t$CO_2$ to all sectors. Different from EU Emission Trading System, all emissions were subject to tax therefore, no free allowance was available. Under these Scenarios model tends to invest more on renewables as the amount of tax increases. For instance, total emissions were 1.076 Mton, 1.003 Mton and 932 Mton for 10-20 and 30$ tax application respectively.

Compared to Base Scenario emission from electricity generation fell to 450.2 Mton in 2057 when 30$ tax was introduced. Share of nuclear and renewables in total electricity generation rose to 10.8% and 39.3% respectively in 2057. Among renewables, the main contributor to electricity generation was hydro power plants, followed by wind and solar plants. In 30 $ tax Scenario, the share of coal in electricity generation plummeted to 36.9%, which was 60.2% in Base Scenario, for 2057. In tax scenarios the highest emission values were observed in electricity sector as in the case of Base Scenario.

Under Emission Restriction Scenarios, instead of environmental tax application, it was assumed that after the year 2032 the total emissions would be reduced by 10-20 and 30% compared to emission values of the Base Scenario. Under 30% emission reduction target, total emissions reduced to 798 Mton by 2057, representing the lowest emission value among Base, Tax and Emission Reduction Scenarios. Similarly, emissions from electricity generation decreased to 352.6 Mton by 2057 compared to same year of the Base Scenario. Emissions from electricity generation does not reach a peak value between 2012-2057. The share of renewables almost doubled compared to Base Scenario and rose to 46.2% in 2057.

Different from Base and Tax Scenarios, by 2057, the share of wind (20.6%) in total electricity generation surpasses the share of hydro based (20.4%) generation. Coal based generation decreases to 19.4% and it was offset by the addition of natural gas capacity. Emission Reduction Scenarios are more effective than Tax Scenarios from emission reduction perspective.

Lastly, in order to examine the peak emission effect, Peak Emission Scenarios was applied under 30$ Tax, 10% Emission Reduction Scenarios and it was assumed that by 2052 the total emissions reach peak value and start decreasing by 2057 The main aim of this scenario was to investigate cumulative effect of different scenarios. As a fact, the lowest total emission value was obtained under this scenario as 705 Mton. Emissions from electricity sector reached their maximum value in 2052 as 320 Mton and fell to 244 Mton by 2057. For the first time among all scenarios, by 2057, electricity sector becomes the second largest emission source and industry sector (254.9 Mton) become the main contributor to total emissions. The share of total renewables reached their maximum level with 47.5%, slightly higher than 30% Emission Reduction Scenario.

Among all scenarios the lowest value of emissions for electricity generation was obtained under Peak Scenario. It means that combination of different policies is more effective from environmental perspective. However, Peak Emission Scenario is a costly solution compared to any other scenario.

It was also observed that electricity sector responds more effectively to environmental restrictions than any other sector showing it is an easy-to-decarbonize sector compared to others.
Another important indicator is that nuclear power generation is a vital contributor for a decarbonized electricity system. In all scenarios it serves as a base load plant to stabilize intermittent renewable sources.

Apart from electricity sector, another important observation was that the model tends to invest on hydrogen for transport sector after 2042 as a novel technology.

In this study it was aimed to put forward of the result of different scenarios on the emissions resulting from electricity sector and to procure scientific knowledge for Turkey's climate policies. The model is also open to put additional mathematical formulations such as renewable energy support mechanism to analyze more accurately renewable capacity additions. Since energy sector is a dynamic process, the effect of new developments in Turkish energy sector, such as discovery of new gas fields in Black Sea as a potential game changer, needs to be investigated in the future studies.

Lastly, Turkey, as a developing country, is making an impressive effort in green growth and undoubtedly, will make significant contributions to a decarbonized world in the future.

REFERENCES

Ackerman, F., Decanio, S. J., Howarth, R. B., Sheeran, K., 2009. Limitation of integrated assessment models of climate change. Climate Change, 95, 297-315.

Barker, T., 1999. Achieving a 10% cut in Europe's carbon dioxide emissions using additional excise duties: Coordinated, uncoordinated and unilateral action using the econometric model E3ME. Economic System Research, 11, 401-422. http://dx.doi.org/10.1080/09535319900000029.

Bataille. C., Wolinetz. M., Peters. J., Bennett. M., Rivers. N., 2009. "Exploration of two Canadian greenhouse gas emissions targets: 25% below 1990 and 20% below 2006 levels by 2020" Prepared for: Pierre Sadik and Dale Marshall, representing the David Suzuki Foundation & Matthew Bramley, representing the Pembina Institute, Final Report. https://davidsuzuki.org/science-learning-centre-article/exploration-two-canadian-greenhouse-gas-emissions-targets-25-1990-20-2006-levels-2020/ (accessed April 2020).

Bernard, A. L., Vielle, M., 2003. Measuring the welfare cost of climate change policies: A comparative assessment based on the computable general equilibrium model GEMINI-E3. Environmental Modeling and Assessment, 8, 199-217.

Bhattacharyya, S. C., Timilsina, G. R., 2009, Energy demand models for policy formulation: A comparative study of energy demand models. The World Bank Development Research Group Environment and Energy Team.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. Witch a world induced technical change hybrid model. The Energy Journal, 27, 13-37.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2009. Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations. Resource and Energy Economics, 31, 123-137.

Böhringer, C., 1998. The synthesis of bottom-up and top-down in energy policy modeling. Energy Economics, 20, 233-248.

Böhringer, C., Rutherford, T. F., 2008. Combining bottom-up and top-down. Energy Economics, 30, 2, 574-596.

Böhringer, C., Rutherford, T. F., 2006, Combining bottom-up and top-down in energy policy analysis: A decomposition approach. ZEW Discussion Papers, No, 06-007.

Bruninx, K., Madzharov, D., Delarue, E., D’haeseleer, W., 2012. Impact of the German Nuclear Phase-out on Europe's Electricity Generation. TME Working Paper, Energy and Environment.

Burniaux, J. M., Nicoletti, G., Martins, J. O., Martin, J. P., 1991. Green: A Multi Region Dynamic General Equilibrium Model for Quantifying the Costs of Curbing CO_2 Emissions: A Technical Manual” OECD Economics Department Working Paper, No, 104.

Capros, P., Georgakopoulos, P., Zografakis, S., Proost, S., Van Regemorter, D., Conrad, K., Schmidt, T., Smeers, Y., Michiels, E., 1996. Double dividend analysis: First results of a general equilibrium model (GEM-E3) linking the EU-12 countries. Environmental Fiscal Reform and Unemployment, 193-227.

Capros, P., Georgakopoulos, P., Zografakis, S., Proost., 1996. Co-ordinated versus uncoordinated European carbon tax solutions analysed with GEM-E31 linking the EU-12 countries. Economic Aspects of Environmental Policy.

Catenazz, G., 2009. Advances in Techno-economic Energy Modeling Costs, Dynamics and Hybrid Aspects, Ph.D. Dissertation, Swiss Federal Institute of Technology.

Davies, E. G. R., Simonivic, S. P., 2011. Global water resources modeling with an integrated model of the social–economic–environmental system. Advances in Water Resources, 34, 684-700.

DG Energy, Market Observatory for Energy of the European Commission, 2020. Quarterly Report on European Electricity Markets, 13, 1.

Edenhofer, O., Bauer, N., Kriegler, E., 2005. The impact of technological change on climate protection and welfare: Insights from the model MIND. Ecological Economics, 54, 277-292.

Energy Market Regulatory Authority (EMRA), Natural Gas Market Sector Report 2019, https://www.epdk.gov.tr/Detay/Icerik/1-1275/natural-gasreports

Grtisevskyi, A., Nakicenovic, N., 2000. Modeling uncertainty of induced technological change. Energy Policy, 28, 907-921.

Grubb, M., Joe, E., Brick., P. T., Morrison., M., 1993. The cost of limiting fossil-fuel CO_2 emissions: A survey and analysis. Annual Review of Energy and the Environment, 18, 397–478.

Günel, G., 2018. Analysis of CO_2 Emission Reduction, Energy and Economy Interactions in Turkey Using BUEMS-MACRO, M.S. Thesis, Boğaziçi University.

Hamilton, L. D., Goldstein, G. A., Lee, J., Manne, A. S., Marcuse, W., Morris, S. C., Wene, C. O., 1992. MARKAL-MACRO: An Overview.

Heaps, C., Erickson, P., Kartha, S., Kemp-Benedict, K., 2009. Europe's Share of the Climate Challenge Domestic Actions and International Obligations to Protect the Planet. Stockholm Environment Institute.

Herbst, A., Toro, F., Reitze, F., Jochem, E., 2012. Introduction to energy systems modelling. Swiss Society of Economics and Statistics, 148, 111-135.

Hourcade, J. C., Jaccard, M., Bataille, C., Ghersi, F., 2006. Hybrid modeling: New answers to old challenges. Introduction to the Special Issue of the Energy Journal, 2, 1-12.

Ichisigu. Y., Masui. T., Karkour. S., Itsubo. N., 2019. Projection of National Carbon Footprint in Japan with Integration of LCA and IAMs. Sustainability, 11, 6875. doi:10.3390/su11236875

Işık, M., 2016. Energy Economy Energy Economy and Environment Integrated Large Scale Modeling and Analysis of the Turkish Energy System, Ph.D. Dissertation, Boğaziçi University.

IEA, 2020. International Energy Agency. Key World Energy Statistics 2020, Paris.

IEA, 2019, International Energy Agency, Nuclear Power in a Clean Energy System, Paris.

IPCC, 2018. Intergovernmental Panel on Climate Change, Special Report on Global Warming of 1.5°C (SR15), Chapter 2: "Mitigation pathways compatible with 1.5°C in the context of sustainable development", 2018, Geneva. https://www.ipcc.ch/sr15/ (accessed December 2019).

Jaccard, M., 2009. Combining Top Down and Bottom up in Energy Economy Models. In Evans, J., Hunt, L. C. (Eds.), International Handbook on the Economics of Energy, Edward Elgar Publishing Limited.

Kat, B., 2011. Mathematical Modelling for Energy Policy Analysis, Ph.D. Dissertation, Middle East Technical University.

Kelly, D. L., Kolstad, C. D., 1999. Integrated Assessment Models for Climate Change Control. In Folmer, H., Tietenberg, T., (Eds.), International Yearbook of Environmental and Resource Economics: A Survey of Current Issues Cheltenham, UK.

Köhler, J., Barker, T., Anderson, D., Haoran., P., 2006. Combining energy technology dynamics and macroeconometrics: The E3MG model. The Energy Journal Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down.

Kumbaroğlu, G. S., 2003. Environmental taxation and economic effects: A computable general equilibrium analysis for Turkey. Journal of Policy Modeling, 25, 795–810.

Kumbaroğlu, G. S., Madlener, R., 2003. Energy and climate policy analysis with the hybrid bottom-up computable general equilibrium model screen: The case of the swiss CO_2 act. Annals of Operations Research, 121, 1, 181-203.

Kumbaroğlu, G., Or, İ., Işık, M., 2017. Karbon vergisi ile sera gazı emisyonlarının azaltımı: Türkiye vakası. Uluslararası İlişkiler, 14, 54, 149-174.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL family models. https://www.iea-etsap.org/MrklDoc-I_StdMARKAL.pdf.

Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., Remme, U., 2016. Documentation for the TIMES model Part I. IEA-ETSAP.

Löschel, A., 2002. Technological change in economic models of environmental policy: A survey. Ecological Economics, 43, 105-126. https://www.econstor.eu/bitstream/10419/119613/1/NDL2002-004.pdf (accessed April 2020).

Manne, A. S., Richels, R. G., 2002. The Impact of Learning-By-Doing on the Timing and Costs of CO_2 Abatement. AEI-Brookings Joint Center for Regulatory Studies, Working Paper, 02-8.

Manne, A. S., Wene, C. O., 1992, Markal-macro: A linked model for energy-economy analysis. Technical Report, Brookhaven National Laboratory. doi:10.2172/10131857

Manne, A. S., Richels, R. G., 2004. Merge: An Integrated Assessment Model for Global Climate Change. Stanford University.

McCollum, D., Yang, C., Yeh, S., Ogden, J., 2012. Deep greenhouse gas reduction scenarios for California - Strategic implications from the CA-TIMES energy-economic systems model. Energy Strategy Reviews, 1, 19-32.

MENR Investor's Guide for Electricity Sector in Turkey, https://enerjiapi.etkb.gov.tr//Media/Dizin/DIGM/Belgeler/576588-investors_guide_for_electricity_-sector_in_turkey.pdf

Messner, S., Strubegger, M., 1995. User's Guide for MESSAGE III Working Paper. International Institute for Applied System Analysis.

Miller, R. E., Blair, P. D., 2009. Input-Output Analysis Foundation and Extensions. Second Edition. Cambridge University Press.

Morrow, W. S., Gallagher K. S., Collantes, G., Lee, H., 2010. Analysis of Policies to Reduce Oil Consumption and Greenhouse Gas Emissions form the U.S. Transportation Sector. Harvard University Belfer Center for Science and International Affairs.

Mundaca, L., Neij, L., 2009. Energy-economy models and energy efficiency policy evaluation for the household sector. The International Institute for Industrial Environmental Economics Reports, 2.

Mundaca, L., Neij, L., Worrell, E., McNeil, M., 2010, Evaluating energy efficiency policies with energy-economy models. Annual Review of Environment and Resources, 35, 1, 305-344.

Müller, B., Gardumi, F., Hülk, L., 2018. Comprehensive representation of models for energy system analyses: Insights from the Energy Modelling Platform for Europe (EMP-E) 2017. Energy Strategy Reviews, 21, 82-87.

Nakata, T., 2004. Energy-economic models and the environment. Progress in Energy and Combustion Science, 30, 417-475.

Nam, K.M., Selin, N.E., Reilly., J.M., Paltsev, S., 2010. Measuring welfare loss caused by air pollution in Europe: A CGE analysis. Energy Policy, 38, 5059–5071.

Nathani, C., 2006. Materials use and induced energy demand: An input-output analysis. Paper to be presented at the intermediate international input-output meeting on sustainability. Trade and Productivity, Japan.

Nordhaus, W. D., Boyer, J., 2000. Warming the World Economic Models of Global Warming. MIT Press.

Nordhaus, W. D., Yang, Z., 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. American Economic Review, 86, 4, 741-765.

Ortiz, R. A., Markandya, A., 2009. Integrated Impact Assesment Models of Climate Change with an Emphasis on Damage Functions: A Literature Review. Technical report, Basque Centre for Climate Change Working Paper Series. https://ideas.repec.org/p/bcc/wpaper/2009-06.html (accessed May 2020).

Park, N. B., Yun, S. J., Jeon, E. C., "An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector". *Energy Policy*, vol. 52, pp, 288-296, 2013.

Poncelet, K., Duerinck, J., Six, D., D'haeseleer, W., 2014. The Importance of Integrating the Variability of Renewables in Long-term Energy Planning Models. Leuven Energy Institute, TME Working Paper.

Proença, S. A., Aubyn, M. S., 2009. A hybrid Top-down/Bottom-up model for energy policy analysis in a small open economy - the Portuguese case" Centro de Estudos da União Europeia (CEUNEUROP), Discussion Paper No. 52.

Sasai. Y., Imagawa. T., Hasegawa. T., Ono. M., 2010. The prediction of CO_2 emissions up to 2020 in Japanese economic activities", 18th INFORUM World Conference, Japan, 2010. http://www.inforum.umd.edu/~infweb/organization/international/japan_iti.php (accessed May 2020).

Seebregts, A., Smekens, K., Goldstein, G. A., Energy/Environmental Modeling with the MARKAL Family of Models. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.198.6929&-rep=rep1&type=pdf (accessed May 2020).

Subramarian, A. S. R., Gundersen, T., Adams, T. A., 2018. Modeling and simulation of energy systems: A review. Processes, 6, 12, 238. doi:10.3390/pr6120238.

Turkish Electricity Transmission Corporation (TEİAŞ), 2020. https://www.teias.gov.tr/tr-TR/turkiye-elektrik-uretim-iletim-istatistikleri

Turkish Statistical Institute, 2020. "Turkish Greenhouse Gas Inventory 1990-2018", National Inventory Report for Submission under the United Nations Framework Convention on Climate Change.

Van Beeck, N., 1999. "Classification of Energy Models". Internal Report no. FEW 777. Technical Report, Faculty of Economics, Tilburg University.

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Richels, R., Rotmans, J., Shukla, P., Cline, W., Fankhauser, S., Tol. R., 1996. Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results. In Bruce J. et al. (Eds.)), Climate Change 1995-Economic and Social Dimensions of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge: Cambridge University Press. Forthcoming.

Vennemo, H., 1994. Welfare and the Environment Implications of a recent tax reform in Norway. Statistics Norway Research Department, 94, 1.