

ANALYSIS OF CO₂ EMISSIONS AND ECONOMIC IMPACTS FOR TURKEY
USING TIMES-MACRO ENERGY MODELING SYSTEM

by

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ABSTRACT

ANALYSIS OF CO₂ EMISSIONS AND ECONOMIC IMPACTS FOR TURKEY USING TIMES-MACRO ENERGY MODELING SYSTEM

There has been growing consideration about the intensity of greenhouse gases in the atmosphere as a trigger of climate change. This issue has resulted in the need to define targets for abating carbon emissions. Turkey's CO₂ emissions have tripled in the period 1990-2012. It is therefore needed to examine Turkey's energy sector to understand the leading cause of skyrocketing emissions and elaborate the policy options to reduce emissions. The costs associated with emission reductions are also influential on the national economy. In order to be able to analyze these interactions, this thesis defines a model to examine the economic impacts of emission constraints and presents a baseline for policy makers. The TIMES-MACRO modeling framework has been employed in this thesis which is a hybrid energy system and economic growth model. Using this modeling framework, Turkey's energy sector and CO₂ emissions have been evaluated together with the economic implications. Following an overall overview of the model, the behavior of the Turkey energy sector under a business-as-usual scenario, under carbon constraints and under carbon taxes have been comparatively evaluated. The main focus of this thesis is to assess the effects of emission constraints on the energy sector, evaluate costs and the subsequent impacts on the entire economy. The model is calibrated under a reference scenario along with various policy scenarios considering the same resource availability, macroeconomic assumptions and technological characteristics, but applying different emission targets and policy tools. Results suggest various useful policy implications for an environmentally and economically sustainable development of the country and provide long-term prospects for effective and applicable energy policy solutions to foster investment into new technologies.

ÖZET

TIMES-MACRO ENERJİ MODELLEME SİSTEMİ İLE TÜRKİYE İÇİN CO₂ EMİSYONLARI VE EKONOMİK ETKİLERİN ANALİZİ

Atmosferdeki sera gazlarının yoğunluğu, iklim değişikliğinin tetikleyicisi olarak giderek artmakta. Bu konu, karbon emisyonlarını azaltmaya yönelik hedefleri belirleme ihtiyacını doğurmuştur. Türkiye'nin CO₂ emisyonları 1990-2012 döneminde üç katına çıkmıştır. Bu nedenle, gökdelen emisyonlarının önde gelen nedenini anlamak ve emisyonları azaltmak için politika seçeneklerini detaylandırmak amacıyla, Türkiye'deki enerji sektörünü incelemek gerekmektedir. Emisyon azaltımları ile ilgili maliyetler de ekonomide etkilidir. Bu etkileşimleri analiz edebilmek için, bu tez, emisyon kısıtlamalarının ekonomik etkilerini incelemek için bir model tanımlamaktadır. TIMES-MACRO modelleme çerçevesi, hibrit bir enerji sistemi ve ekonomik modeli olan bu tezde kullanılmıştır. Modelin genel görünümünü takiben, Türkiye enerji sektörünün olağan bir senaryo altında, karbon kısıtlamaları ve karbon vergileri altında davranışları karşılaştırmalı olarak değerlendirilmiştir. Bu tezin ana odak noktası, CO₂ kısıtlarının enerji sektörü üzerindeki etkilerini değerlendirmek, maliyetleri ve tüm ekonominin sonraki etkilerini değerlendirmektir. Model, aynı kaynak mevcudiyeti, makroekonomik varsayımlar ve teknolojik özellikler göz önünde bulundurularak çeşitli politika senaryoları ile birlikte bir referans senaryosu altında kalibre edilmekte, ancak farklı emisyon hedefleri ve politika araçları uygulanmaktadır. Sonuçlar, ülkenin çevresel ve ekonomik açıdan sürdürülebilir bir kalkınması için çeşitli yararlı politika çıkarımları ortaya koymakta ve yeni teknolojilere yatırımları teşvik etmek için etkili ve uygulanabilir enerji politikası çözümleri için uzun vadeli beklentiler sunmaktadır.

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1. INTRODUCTION

CO₂ emissions are considered to be the largest contributor to global warming. The challenge in energy modeling is to show in which way and to what degree the switch to carbon-free fuels could be acquired and to recognize efficient policy decisions. Therefore, the models that evaluate the energy system based on inelastic energy demands projections, are not sufficient anymore. As a result, it is of upmost importance to be able to adjust demands to price changes and also determine the economic indications of environmental or supply constraints at the same time. This is why the TIMES-MACRO model has been implemented in this thesis study. The TIMES-MACRO model is a proper framework which enables to examine partial and general equilibrium in the energy markets together with the effects of emission abatement policies. The primary advantage of TIMES-MACRO is being able to deal with energy demand, supply and various conversion technologies as well as emission constraints and conservation alternatives, through the general equilibrium structure. The efficiency gap between the top-down and bottom-up models has also been solved in the TIMES-MACRO modeling framework and it is possible to take into account the economic effects of emission constraints in both aggregated and disaggregated levels. In general, there are two main modeling techniques for evaluation of economic effects caused by different policies: bottom-up models and top-down models. The primary difference in these two modeling frameworks is degree of the technological details of the energy system. Bottom-up models like TIMES describe the energy sector through partial equilibrium. In this modeling frameworks, several distinct technologies are used to enable switching between energy carriers on both primary and final consumption levels, substitution between various processes, and energy efficiency improvements. However, in these models the macroeconomic impacts of different energy policies such as emission abatement policies are not taken into account. Bottom-up models are generally optimization models that determine the least-cost mixture of the technologies engaged in the energy system to satisfy a specified demand for end-use sectors subject to technical and environmental constraints. On the other hand, top-down models are not able to capture the technological details of the energy sector and cannot represent future

technologies with the required details. However, these models are capable of obtaining macroeconomic impacts of different energy policies. As a result, top-down models tend to neglect the details on the energy side which may be useful for a proper evaluation of energy policy options. By considering the pros and cons associated with each of these models, there is the need to combine them. This is why TIMES-MACRO has been developed which enables new techniques for modeling that is flexible in adjusting demands to changes in prices and also determining economic impacts of emission constraints. By combining bottom-up and top-down modeling techniques in a single model, TIMES-MACRO compensates the weaknesses in each technique, while maintaining the built-in credits of each of the approaches.

2. LITERATURE SURVEY

Different approaches are used to study cost-effective strategies for greenhouse gas mitigation in energy system analysis with the main purpose of improving the quality and efficiency of these approaches. Furthermore, different models have their own properties which are important to take into account while interpreting the results obtained from each of them. Energy system models are used to understand the energy system better and to evaluate the optimal combination of technologies or examine the impacts of some particular measures. Several models exist at the international level. Two generally accepted approaches for energy modeling based on their level of aggregation, are bottom-up and top-down models. Bottom-up models focus on the energy sector without any further interactions with other economic entities. On the other hand, top-down models are macroeconomic models that depict the energy system in an aggregated way. Considering the shortcomings of both bottom-up and top-down modeling approaches, hybrid modeling approaches have emerged recently that combines these two models.

2.1. Top-Down Models

In Top-down models, each sector is represented by a production function designed to simulate the potential substitutions between the main factors of production (energy, capital, and labor) in the production of each sector's output. In this model category are found a number of models of national or global energy systems. Top-down models represent the whole economy through a relatively small number of aggregate variables and equations. In these models, production function parameters are calculated for each sector such that inputs and outputs reproduce a single base historical year. Various top-down models have been employed in energy and environmental policy with little technological detail such as: input-output models (IO), integrated assessment models (IA), computable general equilibrium models (CGE), and macro-econometric models. However, conventional top-down models are mostly based on the general equilibrium framework (Nakata, 2004). The pioneering approach to combine a single-sector top-down model of the macroeconomy, called MACRO, with an energy technology as-

assessment model including bottom-up detail, called ETA, dates back to 1977 (Manne, 1977).

2.2. Bottom-Up Models

Bottom-up models are detailed, technology rich models that focus on the energy sector of an economy. In these models, each energy-using technology is identified by a detailed description of its inputs, outputs, unit costs, and several other technical and economic characteristics. In these models, a sector is constituted by a number of technologies, linked together by their inputs and outputs. Some bottom-up models compute a partial equilibrium via maximization of the total surplus (consumer and producer). In bottom-up models, one unit of sectoral output is produced using a mix of individual technologies' outputs. Thus the production function of a sector is implicitly constructed, rather than explicitly specified as in top-down models. Bottom-up models are not capable of observing the interactions of the energy sector with the rest of the economy. In these models, only the specific cost elements of economic agents are represented in this kind of models. An extensive review addressing the strengths and weaknesses of existing approaches is carried out by Müller *et al.*, (2018). Bottom-up models, such as TIMES, are used to construct the transition paths for energy systems. However, these models can have misleading outcomes, because they only take into account the technological and cost measures and determine minimum-cost transition paths in order to satisfy the demand. In these models, it is assumed that the behavior of consumers in the energy system is economically rational and also that small changes in prices induce immediate variations in the technology profile, which is an important problem encountered in bottom-up models such as TIMES. Some recent examples of TIMES model applications are as follows: The long-term decarbonization of the Danish transport sector have been analyzed and determined the optimal technology mix by minimizing total costs, while environmental and policy constraints have also been taken into account (Tattini *et al.*, 2018). In another study, the TIMES energy system model has been used to evaluate several emission abatement scenarios in the residential sector in the province of Quebec and have shown that peak demand rises while trying to abate

emissions, but can be reduced by interventions in the residential sector (Astudillo *et al.*, 2017).

Li *et al.*, have pointed out that the decarbonisation transitions by most energy system models are too optimistic and that they tend to only minimize cost and do not take households' preferences into account. So, they have proposed a framework to integrate heterogeneous households' preferences into the modeling process of the UK TIMES model (Li *et al.*, 2018).

Shi *et al.* have analyzed the impact of technological improvement and renewable energy use in residential sector by using China TIMES model. They have measured the emission abatement potential of the residential sector in China and have showed this sector is able to obtain a low-carbon path (Shi *et al.*, 2016). Postic *et al.* have used TIMES to evaluate the impact of national contributions to the UNFCCC and analyzes decarbonizing the power sector in the absence of emission constraints through long-term economic optimization (Postic *et al.*, 2017).

2.3. Hybrid Models

As mentioned before, bottom-up models use partial equilibrium representation with highly detailed technology information, while top-down models have an economy-wide approach. Conventional top-down models are criticized with limited representation of the energy system while investigating the energy-economy interactions. Top-down models lack in technological options that are crucial for the accurate assessment of energy policy options. Besides, bottom-up models fail to capture the macroeconomic feedbacks that occur as a result of different energy-climate policy instruments. Due to the shortcomings of bottom-up and top-down models, recent studies have revealed the necessity of combining the two modeling approaches. To satisfy the shortcomings associated with each approach, hybrid models that contain rich technological structure of bottom-up models with the economic aggregation of top-down models were developed.

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

The ETA-MACRO framework links the energy sector and the rest of the economy (Manne, 1977). The ETA model is a technologically detailed energy model and the MACRO submodel is a single sector representation of the macroeconomy that deploys a constant elasticity of substitution production function which allows substitution between capital, labor, and energy. The aim of this linked model is to maximize the discounted utility subject to a set of constraints such as economic growth rates, limits to capital dynamics, and energy supply (Dowlatabadi and Oravetz, 2006; Jaccard *et al.*, 2003).

Combining the MARKAL framework with the MACRO submodel, which maximizes the utility function, results in a new modeling framework, called the MARKAL-MACRO (Manne and Wene, 1992). MARKAL-MACRO is a hybrid non-linear optimization framework which aims at maximizing consumer utility over the planning horizon, while providing least-cost energy system configurations to meet the endogenously determined energy demands.

TIMES-MACRO (Kypreos and Lehtila, 2013) is a hybrid model combining the technological detail of TIMES with a succinct representation of the macro-economy consisting of a single producing sector in a single region. To the best of my knowledge, there are no modeling applications using TIMES-MACRO published in peer-reviewed international scientific journals yet.

3. THE TIMES MODELING FRAMEWORK

TIMES is a dynamic linear programming model that provides a technology-rich basis for representing energy dynamics over a multi-period time horizon. It is usually employed in studying the energy sector. End-use energy demand estimations are provided exogenously to drive the base scenario. Along with demand estimations, present and future sources of primary energy supply and their potentials, the characteristics of available future technologies and the existing stocks of energy related equipment should be provided. TIMES uses these as inputs and aims to supply energy services at the lowest possible cost (minimizing cost is equivalent to minimizing loss of total surplus), while deciding on optimal investment and operation. In TIMES the quantities and prices of the various commodities are in equilibrium. In other words, prices and quantities in each time period are in a way that the suppliers produce exactly the quantities demanded by the consumers. The total economic surplus is maximized through this equilibrium (Loulou *et al.*, 2016). TIMES is a technologically based linear programming model of the energy system. The model is mostly used for studying the national energy systems in most countries. All the possible routes from each primary energy source through different transformation alternatives to the end-use demand sectors can be represented in the TIMES modeling framework. Furthermore, the emissions (in the case of converting energy forms to one another or emitting sectors) can also be depicted in TIMES. This model distinguishes the paths and technologies that best satisfy the objectives of the entire system. The typical parameters used in TIMES are energy efficiency, availability factor, operating and maintenance cost, investment cost and emissions. The main goal is to satisfy the end-use demands at a minimum system cost. There are different types of constraints in TIMES. Most of the constraints define commodity balances. The balance constraint defaults to an equality in the case of materials (i.e. the quantity produced and imported is exactly equal to that consumed and exported), and to an inequality in the case of energy carriers, emissions and demands (thus allowing some surplus production). For those commodities for which time-slices have been defined, the balance constraint must be satisfied in each time-slice. (Loulou *et al.*, 2016). There are other constraints related to capacity requirements which guar-

antee that sufficient capacity will be built to supply the demands for energy carriers.

The main category of required data in TIMES is divided into four categories:

- technology classification
- Primary energy sources
- useful energy demands
- environmental constraints

4. CONCEPT OF THE TIMES-MACRO MODEL

The TIMES-MACRO model links the Bottom-Up energy system TIMES with the Top-Down model MACRO. Bottom-Up models like TIMES illustrate the energy system with detailed technological structure but fail to consider the interaction between this technology-rich energy system with the remaining economy. At the same time, top-down models such as MACRO that represent the economic interactions, allow to analyze the connection between economic growth and energy demand. Considering that this connection in top-down models is done based on an aggregate level and hence cannot deliver the detailed technology of the energy sector, there is the need to merge the bottom-up TIMES and top-down MACRO model. TIMES-MACRO expresses the interaction between the energy system and the economy subject to a set of constraints. Figure 4.1 provides a general review between the two submodels in the TIMES-MACRO framework. The primary inputs capital, labor, and energy

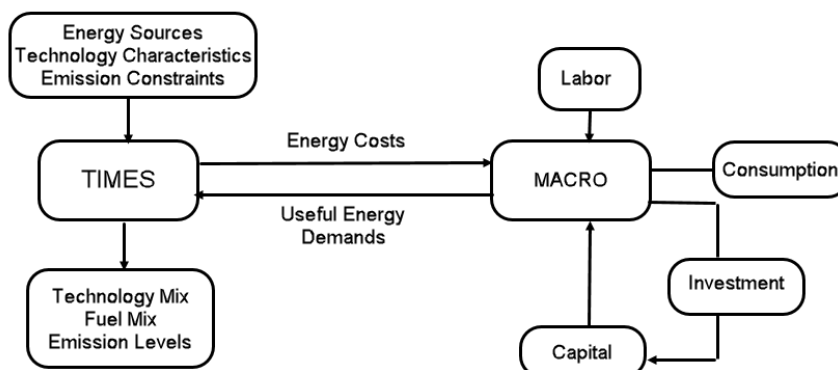


Figure 4.1. TIMES-MACRO Interactions

form the economic output that is allocated to consumption, investments and energy requirements and also for satisfying the environmental constraints. The useful energy demands are defined exogenously in the TIMES model but become endogenous in the MACRO submodel. The primary linkage between these two models is done through a production function that enables TIMES-MACRO to form a direct relation between

the energy system and a long-term macroeconomic growth model.

4.1. The MACRO Model

The main characteristic of the MACRO model is the production function. The production function used in the MACRO submodel has a nonlinear form and thus a small price change results in a small change in the composition of inputs or outputs. In linear models, a small change in price leads either to no change or to a large change in the mix of inputs or outputs (Manne and Wene, 1992). The primary inputs to the production function are capital, labor and useful energy demands. At the top level, the aggregate of capital-labor can substitute the energy aggregate and at the lower level, capital and labor can be substituted for each other. At the end, all of the three production factors can substitute each other. This is how the model involves price-driven conservation for energy (The term “conservation” is defined as the steps taken to decrease the total final energy consumption to satisfy a certain demand). Besides, autonomous energy efficiency improvement (AEEI) is also possible. AEEI factors are price-independent factors that could reduce energy demands per unit of gross output (Y). The long-run growth of an economy is determined by the growth of labor force and its productivity (labor efficiency unit) and is defined as the economy’s potential growth rate. The potential growth rate is also an important determining element of the utility discount factor in the objective function that will be discussed in the next section. If there is an increase in energy costs, it would be optimal to decrease consumption and investment. In the case where there is a decrease in capital formation, the actualized growth rate will not be the same as the potential growth rate.

4.1.1. Mathematical Formulation of the MACRO model

4.1.1.1. The MACRO objective function.

$$Max \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t) + \frac{dfact_{T-1} \cdot dfactcurr_{T-1}^{\frac{d_{T-1}+d_T}{2}}}{1 - dfactcurr_T^{\frac{d_{T-1}+d_T}{2}}} \cdot \ln(C_t)$$

The MACRO model maximizes the discounted utility. The utility is represented by the logarithm of consumption. The utility function is a concave function, so the utility rises when consumption increases, but the amount of increase in utility becomes smaller and smaller, representing diminishing marginal utility. In this utility function, since it is assumed that the utility of the last period will be taken into account for the infinite time horizon after the last period, the discount factor of the last period has a greater influence and is defined in the following way:

$$dfactcurr_{r,t} = 1 - \left(\frac{kpvs_r}{kgdp_r} - \frac{depr_r}{100} - \frac{growv_{r,t}}{100} \right)$$

where:

- $dfactcurr_{r,t}$: annual discount rate of the utility function,
- $kpvs_r$: capital value share,
- $kgdp_r$: initial capital to GDP value,
- $depr_r$: annual depreciation rate,
- $growv_{r,t}$: percentage growth rate in period t.

The capital value share is defined as the share of capital in the sum of all of the production factors (capital, labor, and energy), it may also be interpreted as the optimal share of capital in the value added aggregate. The first term in the parenthesis $\frac{kpvs_r}{kgdp_r}$ denotes the share of capital that is allocated to GDP divided by the initial capital stock $kgdp_r$. Therefore, $\frac{kpvs_r}{kgdp_r}$ can also be defined as the rate of return on capital. As can be seen from the expression, the rate of return on capital is reduced both by the depreciated capital and the labor growth. The depreciation rate value is selected approximately close to the general discount rate of the TIMES model. The discount factors for the first period is equal to 1:

$$dfact_{r,0} = 1$$

The discount factor for periods $1, \dots, T - 1$ (except the last period) is defined as:

$$dfact_{r,t} = dfact_{r,t-1} \cdot dfactcurr_{r,t-1}^{\frac{d_{t-1}+d_t}{2}} \quad \forall t \in 1, \dots, T - 1$$

and the discount factor for the last period with the greater influence continuing until the infinite horizon after the last period of the model taking into account an infinite geometric sequence ($\sum_{n=0}^{\infty} q^n = \frac{1}{1-q}$) is expressed as:

$$dfact_{r,T} = \frac{dfact_{r,T-1} \cdot dfactcurr_{r,T-1}^{\frac{d_{T-1}+d_T}{2}}}{1 - dfactcurr_{r,T}^{\frac{d_{T-1}+d_T}{2}}}$$

4.1.1.2. The MACRO Production Function. The production function is expressed as:

$$Y_t = \left(akl \cdot K_t^{kpvs \cdot \rho} \cdot l_t^{(1-kpvs) \cdot \rho} + \sum_{dm} b_{dm} \cdot DEM_M_{t,dm}^\rho \right)^{1/\rho}$$

where:

- Y_t : annual production in period t ,
- K_t : total capital in period t ,
- l_t : annual labor index in period t ,
- $DEM_M_{t,dm}$: annual demand in the MACRO submodel for commodity dm in period t ,
- akl : production function constant,
- b_{dm} : demand coefficient,
- $kpvs$: capital value share,
- ρ : substitution constant ($\rho = 1 - \frac{1}{\sigma}$), and
- σ : elasticity of substitution.

The production function is a nested, constant elasticity of substitution (CES) function that defines the gross (aggregate) output Y as a function of three primary production

factors capital, labor and energy. The production factors capital K_t and labor l_t build an aggregate A_{KL} together and can be substituted by each other through a Cobb-Douglas function. The second term in the production function indicates that each of the useful energy demand forms can be substituted for the others such that if the price of one of these end use energy forms increases, the other ones become more attractive to use. Furthermore, there is the possibility of substitution between the aggregate of energy forms and the aggregate of capital-labor, e.g. allowing energy conservation due to price changes through substituting more capital and labor per unit of output (the energy efficiency improvement in economic terms has two sources: first, substitution of energy by other inputs and second, technical changes). The parameter ρ is defined through ESUB (the elasticity of substitution between the aggregate of energy and capital-labor aggregate) by this equation: $\rho = 1 - \frac{1}{ESUB}$. In TIMES-MACRO the demand for energy services becomes an endogenous model variable (DEM_M) that enters the production function. By applying the first order optimality condition for maximizing utility (i.e. maximizing profit), the dual equation of the production function is obtained that links the demand for energy services to their prices.

A model that optimizes utility maximizes also the profit function. The profit function is defined as the production value minus the cost of production. Thus, in order to maximize the profit function π , subject to a simplified production function:

$$\begin{aligned} \text{Max } \pi &= Y.P_Y - A_{KL}.P_{KL} - E.P_E \\ \text{s.t. } Y &= [a.A_{KL}^\rho + b.E^\rho]^{\frac{1}{\rho}} \end{aligned}$$

where:

- A_{KL} : aggregate of capital-labor
- E : energy
- P_{KL} : price of the capital-labor aggregate
- P_E : price of energy

By using the Lagrange function of the stated problem:

$$\nabla = \pi - Y.P_Y + A_{KL}.P_{KL} + E.P_E + \lambda \left[Y - (a.A_{KL}^\rho + b.E^\rho)^{\frac{1}{\rho}} \right]$$

and equating all the partial derivatives to zero, the prices for the aggregate of capital-labor and energy will be determined as follow:

$$P_{KL} = P_Y.a \left(\frac{Y}{A_{KL}} \right)^{1-\rho}$$

$$P_E = P_Y.b \left(\frac{Y}{E} \right)^{1-\rho}$$

And by manipulating these equations, equations defining the demand for energy and for the capital-labor activity as a function of their prices will be obtained:

$$E = Y. \left(\frac{P_E}{b.P_Y} \right)^{\frac{-1}{1-\rho}}$$

$$A_{KL} = Y. \left(\frac{P_{KL}}{A_{KL}.P_Y} \right)^{\frac{-1}{1-\rho}}$$

The elasticity of substitution between the capital-labor aggregate and the energy aggregate (that is the proportion of the relative changes in the ratio between the production factors (A_{KL} and E) and the relative changes in their prices (P_{KL} and P_E)) can be determined by using these equations:

$$\frac{E}{A_{KL}} = \left(\frac{a.P_E}{b.P_{KL}} \right)^{\frac{-1}{1-\rho}}$$

$$\sigma = \frac{\frac{\partial \left(\frac{A_{KLE}}{E} \right)}{\frac{A_{KLE}}{E}}}{\frac{\partial \left(\frac{P_{KLE}}{P_E} \right)}{\frac{P_{KLE}}{P_E}}} = \frac{\partial \ln \left(\frac{A_{KLE}}{E} \right)}{\partial \ln \left(\frac{P_{KLE}}{P_E} \right)}$$

Thus, elasticity of substitution (ESUB) is derived as: $\sigma = \frac{1}{1-\rho}$. The elasticity of substitution between labor, capital and the aggregate of energy expresses the elasticity of energy demand services, and their quantities and prices. Furthermore, it is an aggregate used to determine the reaction of all demands to changes in their prices. Thus, it is difficult to calculate the exact value. Reasonable interval for the elasticity of substitution is estimated to be in the 0.2-0.5 range. It is recommended that if the variety of technological alternatives is high in TIMES, the value of ESUB should be selected from the lower bound in this interval (0.2-0.5), in order to prevent magnifying the reaction of the combined demand. Thus, the value selected here is ESUB=0.25 for the calibration procedure. The higher the value of ESUB is, the less expensive it would be to decouple energy demand from GDP growth in case of having energy prices increasing.

The production function constant akl and the demand coefficients b_{dm} are determined by taking the partial derivatives of the production function with respect to the energy demands which is the equilibrium energy price:

$$\left. \frac{\partial Y_t}{\partial D_{t,dm}} \right|_{t=0} = pref_{0,dm} = \left(\frac{Y_0}{DEM_{-}M_{0,dm}} \right)^{1-\rho} \cdot b_{dm}$$

The reference prices $pref_{0,dm}$ (marginal costs of the demand commodities in the initial period) are taken from the TIMES-LP run. After computing the demand coefficient, the akl constant can be calculated from the production function for the first period.

4.1.1.3. The Economic Output Equation. The gross output of economy is distributed between consumption C , investment INV which is used to form capital stock, and

energy cost EC that is the total cost of requirements of the energy system.

$$Y_t = C_t + INV_t + EC_t$$

In this equation, it is assumed that the gross domestic production (GDP) is the sum of consumption and investment. In other words: $Y = GDP + EC$ In the case of resource exhaustion or emission constraint, energy will be substituted by capital and labor through the production function, while the economic output Y and energy demand will decline.

4.1.1.4. The capital dynamics equation. This equation implies that the capital of a period comes from the capital surviving from the previous period and investments that are made in both current and the previous periods:

$$K_{t+1} = tsrv_t \cdot K_t + \frac{1}{2} (d_t \cdot tsrv_t \cdot INV_t + d_{t+1} \cdot INV_{t+1})$$

Since, capital is depreciated over time, the capital survival factor $tsrv_t$ is introduced that represents the capital share in a period that has survived until the next period. This survival rate is based on the depreciation rate and is expressed as:

$$tsrv_t = (1 - depr)^{\frac{(d_{t+1} + d_t)}{2}}$$

The duration $\frac{(d_{t+1} + d_t)}{2}$ is the duration between the end of the middle year of period t and the middle year of the period $t + 1$. The second term of the equation describes the weighted average of investments in t and $t + 1$.

4.1.1.5. Investment equation in the initial period. It has been assumed that the capital of the first period grows with the labor growth rate of the first period $growv_0$. Since the investment must cover both the growth and the deprecation of the capital,

investment in the initial period can be expressed as:

$$INV_0 = K_0 \cdot (depr + growv_0)$$

4.1.1.6. The terminal conditions. This equation is defined to ensure that after the end of the model horizon (which is infinite), the capital stock is not depleted:

$$K_T \cdot (growv_T + depr) \leq INV_t$$

4.1.1.7. The production factor labor. Labor is exogenously defined in MACRO by the labor growth rate $growv_t$ (labor increases with this potential growth rate) and has an efficiency indicator of 1 for the initial period:

$$l_0 = 1 \quad \text{and} \quad l_{t+1} = l_t \cdot (1 + growv_t)^{\frac{d_t + d_{t+1}}{2}}$$

4.1.2. Linkage of the TIMES and MACRO models

TIMES is formulated by the following LP model:

$$\text{Min} \sum_t dfact_t \cdot COST_T_t(x)$$

$$\text{s.t.} \quad E \cdot x = DEM_T_t \quad (1)$$

$$A \cdot x = b \quad (2)$$

where:

- x : the vector of TIMES variables,
- $dfact_t$: discount factor of period t,

- *Constraints* (1): express demand satisfaction in TIMES,
- *Constraints* (2): other constraints in the TIMES model,
- $COST_T_t(x)$: annual undiscounted cost in TIMES and is expressed as:

$$\begin{aligned}
COST_T_t(x) = & \sum_k \{ Annualized_INV \cos t(t, k) * INV(t, k) \\
& + Fixom(t, k) * CAP(t, k) \\
& + Varom(t, k) * \sum_{S,S} CT(t, k, s) \\
& + \sum_c [Delivcost(t, k, c) * Input(t, k, c) * \sum_s ACT(t, k, s)] \} \\
& + \sum_{c,s} \{ Miningcost(t, c, l) * Mining(t, c, l) \\
& + Tradecost(t, c) * TRADE(t, c, s, i/e) \\
& + Importprice(t, c, l) * Import(t, c, l) \\
& - Exportprice(t, c, l) * Export(t, c, l) \} \\
& + \sum_c \{ Tax(t, p) * ENV(t, p) \}
\end{aligned}$$

that is the summation over all technologies k , all demand elements d , all pollutants, and all input fuels, of the various costs accrued such as: annualized investments, annual operating costs (which includes fixed and variable technology costs, fuel delivery costs, costs of extracting and importing energy carriers), minus revenue from exported energy carriers, plus taxes on emissions.

Demand satisfying constraint in TIMES is such that for each time period, the total activity of end-use technologies that are used to supply that demand must be at least equal to that demand.

Linking TIMES with MACRO is done by two sets of variables:

- the energy demand variables $DEM_T_{dm,t}$, and
- the energy costs $COST_T_t$.

The useful energy demands that are inputs of the production function used in MACRO, are obtained by applying the autonomous energy efficiency improvement factor ($aeefac_{t,dm}$) through this equation:

$$DEM_T_{t,dm} = aeefac_{t,dm} \cdot DEM_M_{t,dm}$$

The energy demand in TIMES can be lower than the energy requirement of the MACRO model due to demand reductions, which are caused by autonomous energy efficiency improvements and come in addition to those captured in the energy sector of the TIMES model. The autonomous energy efficiency improvement factor $aeefac_{t,dm}$ is calculated in the calibration process (Louolou *et al.*, July 2016). The second link between TIMES and MACRO is the energy cost EC_t flow, that is the payments made in the energy system and is equal to the annual undiscounted energy system cost of the TIMES model, $COST_T_t$, magnified with some additional terms:

$$COST_T_t + \frac{1}{2}qfac \sum_p \frac{cstinv_{t,p}}{expf_t \cdot capfy_p} \cdot XCAP_{t,p}^2 = EC_t$$

where:

- $XCAP_{t,p}$: fraction of the capacity expansion of technology p in period t that is penalized. It is also used in a constraint in MACRO $CAP_{t+1,p} \leq (1+expf_t) CAP_{p,t} + XCAP_{t+1,p}$, which is defined as the fraction surpassing a predefined acceptable expansion rate $expf_t$ used to reduce the speed of the penetration of technologies.
- EC_t : costs for the production factor in the MACRO model,
- $qfac$: trigger to activate penalty (1 for activating and 0 for deactivating),
- $cstinv_{t,p}$: specific annualized investment costs of technology p in period t,
- $capfy_p$: maximum level of capacity for technology p,
- $expf_t$: acceptable expansion between two periods,
- $CAP_{t,p}$: total installed capacity of technology p in period t.

On the condition that the total installed capacity in period $t+1$ is less than $(1 + \text{expf}_t)CAP_{p,t}$, there is no penalty cost placed. If the capacity level $XCAP_{t+1,p}$ goes beyond the acceptable capacity level, penalty costs will be computed in addition to the regular costs of the TIMES model.

The useful energy demands are defined exogenously in TIMES. The TIMES model presents how the demands are satisfied while minimizing cost, but the level of energy demanded from the energy system in TIMES, is independent of the price that the consumers must pay for these energy services and shows that there is no demand-price interaction which is inconvenient in modeling where changes in relative prices are expected. In contrast, the useful energy demands in TIMES-MACRO are calculated endogenously in the model and are based on the economic growth rate, the autonomous energy efficiency improvement factors (AEEI), the elasticity of substitution and the also the changes in energy prices.

The production function,

$$Y_t = \left(akl.K_t^{kpv_s.\rho}.l_t^{(1-kpv_s)\rho} + \sum_{dm} b_{dm}.DEM - M_{t,dm}^\rho \right)^{\frac{1}{\rho}}$$

the output equation,

$$Y_t = C_t + INV_t + EC_t$$

and the capital formation equation,

$$K_{t+1} = tsrv_t.K_t + \frac{1}{2}(d_t.tsrv_t.INV_t + d_{t+1}.INV_{t+1})$$

capture the feed-back between the energy system and the rest of the economy by employing capital and labor to substitute for energy. Labor is defined exogenously. The energy cost EC is computed in TIMES and by maximizing the utility function (which is the logarithm of annual consumption), the optimal share of economic output

between consumption and investment is determined.

4.1.3. The Autonomous Energy Efficiency Improvement Factor, AEEI

There exists a conventional technique for considering technological changes that influence energy efficiency in long-run energy forecasts. In this technique, an exogenous element, autonomous energy efficiency improvement factor (AEEI), is introduced that decreases the energy that is required to provide the same level of output in each sector, while all other measures are being held constant (not changing). Thus, AEEI can be referred to as a diminished-level assessment of the advancement price-independent changes in demand. The AEEI factor is generally interpreted as technical changes, but it represents more than only technical changes and a more comprehensive definition could be that AEEI represents other changes as well, for instance, structural changes of production on the aggregated level (Babiker *et al.*, 2001).

Technically advanced economies depend on energy resources and at the same time, there are policies that restrict energy supply alternatives. On this basis, industrialized countries feel the urge to study their energy system and also the complicated interaction among various parts of this system. One of the most important topics to study in this field is analyzing the elements that influence energy consumption. Originally, the research has shown that energy consumption is strongly associated with the level of economic activity. As the level of economic activity increases, the more energy will be demanded. By considering this link, future energy consumption could be predicted from GDP estimations, yet since the economy is non-homogenous, a more accurate technique might be used to link energy consumption to particular indicators of each sector that are necessarily dependent on monetary measures. For instance, in transportation sector, the sector-specific indicator could be linked to person-kilometers traveled. In addition, after the energy crisis of the 1970s, another measure was added to be studied in the energy demand area and it was the price changes. Thus, it is important to study the degree of susceptibility (response) of energy consumption to price for a given level of economic activity. Gradually, studies were done to examine past and future price elasticities and reactions in the level demanded by considering

the price changes. As a result, energy demand was being studied as a function of the energy price and the economic activity, yet, since the level of energy demanded is based on the demand for energy using technologies, the overall result of changes in price cannot be grasped in the energy system at once. Another factor in measuring energy consumption is the impact of technological improvements on the level of energy demanded. The demand for technologies that consume energy is dependent on the price of energy to a degree, but mostly is dependent on technology improvements. The improvements in technologies are mostly independent of price effects are based on many factors that hard to recognize. Despite these difficulties, if the rate of technological improvement over the past periods reveals consistency to a degree, it might be effective for evaluating energy demand. AEEI expresses the changes in the economy (without any price changes) that reduce the energy intensity per unit of output (Luciuk, 1996).

The AEEI factor reflects technological progress in the energy system, however it can be clarified more precisely. The most important definition is that AEEI expresses efficiency improvement that is independent of price changes. An alternative definition is that this factor adapts for the non-unitary income elasticity of demand. As a result AEEI can be connected to the structural changes in the economy (S. Kypreos, 1996).

The increase in energy prices is not the only reason in demand reductions. There are also autonomous energy efficiency improvement factors that affect the demand for energy. The AEEI factor can be interpreted as changes in energy consumption that are not induced by price changes, such as, increase in the efficiency of end-use demands, or structural changes in the economy, such as moving toward less or more energy-intensive industries (Manne and Richels, 1992).

In the TIMES modeling framework, final energy demands are exogenously estimated and hence, efficiency measures like decreased electricity transmission and distribution losses, limits on using inefficient electrical appliances and restrictions on coal power plants along with other policy plans for renewable energy use, induce different technology mixes while minimizing the total system cost and resulting in reduced energy consumption. In other words, the TIMES demand forecasts take into account

implicit assumptions on decoupling GDP and demand growths. Whereas, TIMES-MACRO considers this as an instance of autonomous energy efficiency improvement and explains it by the AEEI parameter.

In TIMES-MACRO, the demand for energy services turns into an endogenous variable, since the demand projections in the TIMES model are disaggregated, and it is not reasonable to develop disaggregated demand projections according to aggregate levels of economic activity, sectors with high or low demand growths should be differentiated (because it affects economic growth). This is the reason that TIMES-MACRO is being calibrated through the time-dependent projections, in which time and sector dependent demand decoupling factors are introduced. Accordingly, various scenarios can be defined and simulated by introducing various parameters for each scenario. In this way, energy demand turns into a variable only under emission constraint. The overall procedure for the calibration in which ddf factors are specified as follows: for the purpose of defining ddf factors, these technological improvements are explicitly inserted in the production function:

$$Y_t = \left[akl \cdot K_t^{kpv_s \cdot \rho} \cdot L_t^{(1-kpv_s) \cdot \rho} + \sum_{dm} b_{dm} \cdot (\exp^{ddf_{dm} \cdot \Delta t} \cdot DEM_{dm,t})^\rho \right]^{1/\rho}$$

The so called demand decoupling factors augment the production factor energy in a way that less energy is used for the same amount of economic output. By taking the partial derivative of the production function with respect to the energy demand $\frac{\partial Y_t}{\partial DEM_{t,dm}} = P_{t,dm}$, the price of energy is related to its demand:

$$DEM_{t,dm} = \exp^{-ddf_{dm} \cdot \Delta t \cdot (1-\sigma)} \cdot Y_t \cdot \left(\frac{P_{dm,t}}{b_{dm}} \right)^{-\sigma}$$

By introducing a time period index k, this equation is reformulated as:

$$DEM_{t,dm} = \exp\left[\sum_{k=1}^t -ddf_{dm,k} \cdot \delta t (1-\sigma)\right] \cdot Y_t \cdot \left(\frac{P_{dm,t}}{b_{dm}} \right)^{-\sigma}$$

where:

- δt : the time step per period,
- σ : the elasticity of substitution,
- $P_{dm,t}$: are the shadow prices of each useful energy demand that come from TIMES, and
- $DEM_{dm,t}$: the exogenous demand projections entering the TIMES model.

By having these parameters and variables, demand decoupling factors can be estimated for each time period by applying these relations:

$$\left\{ \begin{array}{l} dd f_{dm} = 0 \quad \text{for } k = 0 \text{ (first period)} \\ F_{dm,k} = \frac{DEM_{dm,k}}{Y_t \cdot P_{dm,k}^{-\sigma}} \quad \text{for } k = 2, 3, \dots, t \\ dd f_{dm,k} = \ln \left(\frac{F_{dm,k}}{F_{dm,k-1}} \right) \cdot \frac{(\rho-1)}{\delta t \cdot \rho} \end{array} \right.$$

Demand decoupling factors are parameters that account for existing demand decoupling from GDP growth, for instance, in the case where air transport is growing faster than GDP. The demand decoupling equation links the energy demand of the MACRO model with the energy demand of the Times model, for each demand commodity. In this way, the demand parameter of the TIMES model (energy demand is defined exogenously in the TIMES model) becomes the demand variable of the TIMES model. The AEEI factor is responsible for demand reductions. These reductions in demand are caused by autonomous energy efficiency improvement that are not being considered in the energy sector of the TIMES model. The AEEI factors are price-independent factors that are able to cut down energy demands per unit of gross output.

5. MODEL CALIBRATION

The calibration process has two goals: the first goal is that the demand decoupling factors should be calculated during this process such that the demand variables of the TIMES model decouple with the exogenously entered demand parameters, and the second goal is that the calculated (during the MACRO calibration) GDP growth rates are matched with the specified GDP growth rate projections (gr_t). Therefore, at the end of the calibration process, the results in the energy part of the TIMES model are equivalent to the ones in the TIMES-MACRO model, since as mentioned earlier the purpose of the calibration is coupling (matching) the exogenous demand of the TIMSE model with the endogenous demand of the TIMES-MACRO model and then the results of this calibrated model are used as a base scenario to evaluate the influences of policy scenarios, like GDP loss, that will be added to the base scenario after calibration.

The results of the TIMES model are the inputs for the calibration procedure and based on these results, the annual energy system cost, the marginal costs of the demand commodities for the first period, and the ddf factors are calculated. The purpose of the demand decoupling equation is linking the energy demand of the MACRO submodel $VAR_D_{t,dm}$ with the energy demand entering the TIMES model $VAR_DEM_{t,dm}$, for each demand commodity (exogenously specified energy demand parameters in TIMES ($com_proj_{t,dm}$) are replaced by the energy demand variables $VAR_DEM_{t,dm}$). The autonomous energy efficiency improvement factor $aeefac_{t,dm}$ captures the reductions in energy demand that are resulting from these factors and were not being taken into account in the energy sector of TIMES. The demand decoupling equation is expressed as:

$$VAR_DEM_{t,dm} = \frac{1}{scale_nrg} \cdot (aeefac_{t,dm} \cdot VAR_D_{t,dm} + VAR_SP_{t,dm})$$

$$aeefac_{t+1,dm} = aeefac_{t,dm} \cdot (1 - aeenv_{t+1,dm})^{\frac{d_t + d_{t+1}}{2}}$$

$$aeiv_{t,dm} = \frac{ddf_{t,dm}}{100}$$

where:

- $aeefac_{t,dm}$: period-wise autonomous energy efficiency improvement factor,
- $aeiv_{t,dm}$: annual autonomous energy efficiency improvement factor,
- $ddf_{t,dm}$: demand decoupling factor,
- $VAR_SP_{t,dm}$: a dummy variable and is fixed to value of zero. The shadow prices associated with this variable are used in the computation of the marginal costs of the demand commodities in the calibration procedure.

In order to run the calibration process, the elasticity of substitution between the capital-labor aggregate and the energy aggregate should be specified. In this calibration procedure, the useful energy demands of TIMES enter into the energy aggregate of the production function. The other required MACRO input parameters are: GDP in the base year and projected GDP growth rates that were accessible from statistical sources. For the base year, the useful energy demands are taken from the TIMES model and prices are also taken from the shadow prices of the dual solution of the TIMES model. The results of the LP TIMES model are used as inputs for the calibration process, such that:

- The annual energy system cost of the first period in MACRO is equal to the result parameter of the objective value of TIMES in the first period adjusted by the associated cost scaling factor: $ec0 = objv0.scale_cst$
- The marginal costs of the demand commodities for the initial period are obtained from the marginal costs of the commodity balance equations in TIMES.

In TIMES, commodity balance equation requires that at each period and time-slice, the total procurement (import, production, etc.) of a commodity balances its total disposition (export, consumption, etc.). In the case of energy carriers and emissions, this constraint ensures that disposition (consumption) of each commodity (energy car-

riers or emissions) may not exceed its supply. If the commodity balance represents an inequality constraint, the primal value equals the obtained value while all terms that include variables are on the left-hand-side of this equation, and all constants are on the right-hand-side. Thus, the primal value is the value of the left-hand-side. Therefore, commodity balance is binding (consumption=production), when its primal value equals its RHS constant, and is non-binding (production is greater than consumption) when the primal value is greater than the constant on the RHS.

The dual variable or shadow price of the balance equation defines the internal value of the corresponding commodity. In the case where the constraint is binding, that is when consumption is equal to production, the shadow price defines the cost change in the objective function caused by an increase in the commodity demand by one unit. Given that the left-hand-side of the balance equation is the difference between production and consumption, this extra demand can be satisfied by either an increase in production or a decrease in consumption. The undiscounted shadow prices of the demand commodities obtained from the TIMES model are then used as reference prices for useful energy demands in the MACRO model.

$$ddatpref_{dm} = \sum_s yrfr_s \frac{COMBAL.M_{0,dm,s}}{disc_0}$$

where:

- $ddatpref_{dm}$: the shadow price of demand commodity dm in first period,
- $COMBAL.M$: shadow price coming from the commodity balance equation in TIMES,
- $disc$: the discount factor used in TIMES that converts annual undiscounted costs in period-wise discounted costs, and
- $yrfr$: duration of time-slice s that is defined as a fraction of a year.

Besides, the partial derivative of the production with respect to the energy demand in the initial period is equal to the reference price of the energy demand adjusted by cost

and energy scale factors:

$$\frac{\partial VAR_Y_t}{\partial VAR_D_{t,dm}} = ddatpref_{dm} \cdot \frac{scale_cst}{scale_nrg}$$

The shadow prices for satisfying the energy demand of commodity dm in TIMES is computed as:

$$ddf_mc_{t,dm} = -\frac{VAR_SP.M_{t,dm}}{EQ_COSTNRG.M_t} \cdot \frac{scale_nrg}{scale_cst}$$

where:

- $ddf_mc_{t,dm}$: is the undiscounted marginal cost of demand commodities dm in period t ,
- $scale_nrg$: is the demand scaling parameter from TIMES demand units to the MACRO submodel demand units, and
- $scale_cst$: is the cost scaling parameter from TIMES costs units to MACRO units.

The marginal cost $VAR_SP.M_{t,dm}$ explains the change in utility by increasing the energy demand by one unit. The marginal cost (shadow price) $EQ_COSTNRG.M_t$ defines the change in utility by changing the costs by one unit. By considering these definitions, this equation can be examined as a conversion factor between the utility and the energy system cost. Then, in order to estimate the demand decoupling factors $ddf_{t,dm}$, these parameters are calculated as:

$$ddf_sp_{t,dm} = \frac{\sum_{s \in com_{dm,s}} yrfr_s \frac{COMBAL.M_{t,dm,s}}{disc_t}}{ddatpref_{0,dm}}$$

$$ddf_dm_{t,dm} = \frac{com_proj_{t,dm}}{com_proj_{0,dm}}$$

$$ddf_y_0 = 1$$

$$ddf_{-y_t} = ddf_{-y_{t-1}} \cdot \left(1 + \frac{yr_{t-1}}{100}\right)^{\frac{d_{t-1}+d_t}{2}}$$

$$ddf_{0,dm} = 0$$

$$ddf_{t,dm} = 100 \cdot \left\{ 1 - \left[\frac{\frac{ddf_{-dm_{t,dm}}}{ddf_{-y_t} \cdot ddf_{-sp_{t,dm}}^{-esub}}}{\frac{ddf_{-dm_{t-1,dm}}}{ddf_{-y_{t-1}} \cdot ddf_{-sp_{t-1,dm}}^{-esub}}} \right]^{\frac{\rho-1}{d_{t-1}} \cdot \rho} \right\}$$

where:

- $ddf_{-sp_{t,dm}}$: is the normalized shadow prices for the demand commodities,
- $ddf_{-dm_{t,dm}}$: is the normalized demand,
- yr_t : is the annual production growth rate,
- ddf_{-y_t} : is the normalized GDP growth projection, and
- $ddf_{t,dm}$: is the normalized demand projection.

Then the normalized projections are used to calculate a new set of demand decoupling factors $ddf_{t,dm}$:

$$ddf_{-y_0} = 1$$

$$ddf_{-y_t} = ddf_{-y_{t-1}} \cdot \left(1 + \frac{gr_{t-1}}{100}\right)^{\frac{d_{t-1}+d_t}{2}}$$

$$ddatpref_{dm} = ddf_{-mc_{0,dm}}$$

$$ddf_{-sp_{t,dm}} = \frac{ddf_{-mc_{t,dm}}}{ddatpref_{r,dm}}$$

$$ddf_dm_{t,dm} = \frac{com_proj_{t,dm}}{com_proj_{0,dm}}$$

$$ddf_{0,dm} = 0$$

$$ddf_{t,dm} = 100. \left\{ 1 - \left[\frac{\frac{ddf_dm_{t,dm}}{ddf_y_t \cdot ddf_sp_{t,dm}^{-esub}}}{\frac{ddf_dm_{t-1,dm}}{ddf_y_{t-1} \cdot ddf_sp_{t-1,dm}^{-esub}}} \right]^{\frac{\rho-1}{d_t-1} \cdot \rho} \right\}$$

This procedure is repeated until the exogenously defined energy demand of the TIMES model $com_proj_{t,dm}$ is sufficiently converged to the demand that has been calculated during the calibration process $VAR_DEM_{t,dm}$ as well as the GDP growth rates estimated by the MACRO calibration $grgdp_t$ that should match the previously specified GDP growth projections gr_t . In this calibration procedure, after each run a new labor growth rate is obtained by adjusting the previous one by the difference between the projected growth rate and the actualized growth rate that has been calculated in the model run:

$$growvn_t = growv_t + gr_t - gdp_t$$

$$growvn_T = gr_T$$

$$growv_t = growvn_t$$

where:

- $growvn_t$: new labor growth rate,
- $growv_t$: previous growth rate,
- gr_t : projected GDP growth rate, and
- gdp_t : actual GDP growth rate in the model run.

6. MODEL RESULTS

The CO₂ emission control costs can be analyzed by defining different scenarios. A scenario is a collection of social, political and environmental assumptions that is defined to achieve a development in a country. Various scenarios have been defined in TIMES-MACRO to study the results of CO₂ control policies. By applying proper bounds on emission levels, it is possible to evaluate the policy targets. In the reference scenario there is no constraint on CO₂ emissions, while there are other scenarios in which carbon emission tax and carbon emission bounds have been defined. There are two emission bound scenarios defined: 10% and 21%. In emission bound scenarios, emission constraints are imposed on the total emission levels obtained from the reference scenario. Emission tax scenarios are analyzed under 4 different tax levels: \$10, \$20, \$50 and \$80 per ton CO₂ and enables to study the model behavior under taxation. The energy system is modeled in such a way that the demands for five demand sectors are met. These sectors are defined as agriculture, residential, commercial, industry and transportation sector. Each of these sectors are modeled with technologies specific to their own in order to be able to recognize the reaction of the demand technologies. In the reference scenario, the existing trend is assumed to be valid in agriculture, residential, commercial, industry and transportation and also in electricity generation sector and regulations of the Turkish Energy System have been taken into account for the whole planning period until 2050.

6.1. The Advantages of TIMES-MACRO

TIMES-MACRO is a technology-rich, energy-environment model that is linked to a long-term neoclassical growth model. If considerable abatement levels in CO₂ emissions are needed in the long run, both energy demand and energy prices are two significant measures that might be influenced. The emission abatement costs to the national economy are expected to be considerably large to be evaluated as a percentage of GDP. In TIMES, both demand projections and resource energy costs are inputs to the model, and do not change under certain situations. However, in TIMES-MACRO,

energy demand and energy prices are calculated endogenously as a result of the interaction between the energy system and the economy. In this way, the abatement costs are computed in terms of GDP.

In TIMES, there are no technological options to capture price-induced conservations in the demand-side, however there are various alternatives for inter-fuel substitutions. For many of the demand commodities, the TIMES framework consists both autonomous conservation and price-driven conservation technologies. The following model results will show how this influences the impression of conservation when TIMES and MACRO are linked.

The differences between results of TIMES and TIMES-MACRO are shown in this chapter for a 21% emission reduction from 2018 until the end of the model horizon, since in TIMES-MACRO, energy demand become a model variable only under emission constraints. In TIMES, energy related emissions are reduced mainly from fossil fuel shares. However, in TIMES-MACRO, emissions are reduced through reductions in both GDP growth rates, and reductions in useful energy demands per unit of GDP.

The TIMES-MACRO modeling framework considers conservation through the production function. This is how the impact of higher prices on demanded energy is considered. Every useful energy demand is handled by the same approach, although there are no technological details. In TIMES, energy conservation is not considered in such an inclusive way, however the present TIMES-Turkey database has a very detailed demand-side representation.

6.1.1. Primary Energy

The primary energy consumption levels in TIMES-MACRO and stand-alone TIMES model runs under 21% emission reduction from BAU levels are compared in Figures 6.1 and 6.2. The composition of energy consumption is similar in both runs. Most of the differences are due to variations in useful energy demand levels that tend to be higher in the TIMES stand-alone model. The primary difference is that in TIMES-

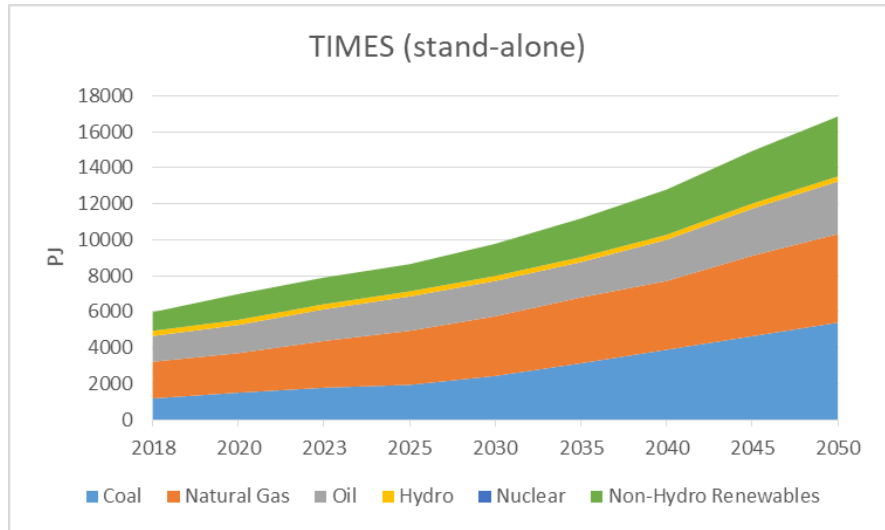


Figure 6.1. Primary Energy Consumption Levels estimated in TIMES stand-alone run

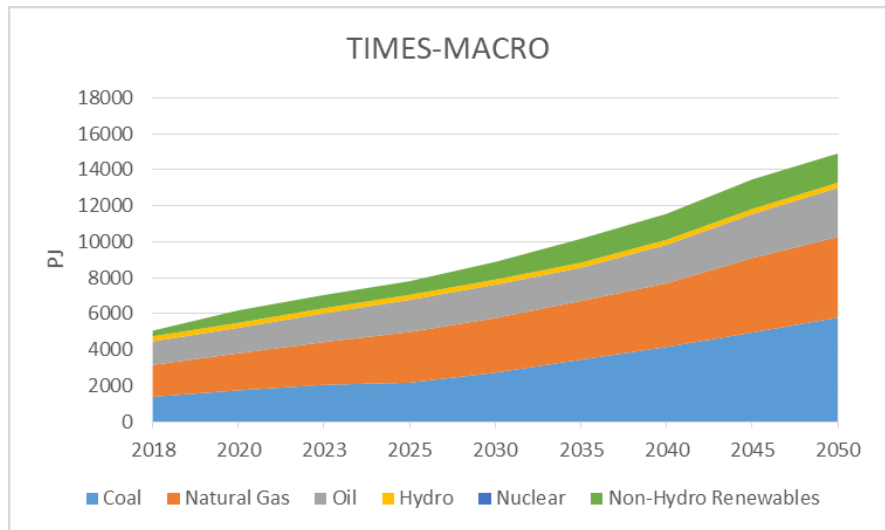


Figure 6.2. Primary Energy Consumption Levels estimated in TIME-MACRO run

MACRO, the changes in the remaining economy are being considered. For instance, under the same reduction amount, technological changes are lesser in TIMES-MACRO compared to the stand-alone TIMES. In order to meet the applied emission constraints, there will be an increase in energy costs that leads to a reduction in GDP together with a decline in energy demand per unit of GDP, which is caused by substituting energy by the other production factors in the production function of TIMES-MACRO through the elasticity of substitution.

6.1.2. Electricity Generation

As mentioned before, TIMES-MACRO has the potential to reduce emissions resulting from a decline in GDP growth and also a reduction in energy demand per unit of GDP. These joint reductions are the reasons that comparatively expensive non-fossil energy supplies are not required, which might be the reason solar energy is used less in TIMES-MACRO in electricity generation sector compared to stand-alone TIMES, that is used more for generating electricity. The variations in electricity generation levels in stand-alone TIMES and TIMES-MACRO are illustrated in Figures 6.3 and 6.4.

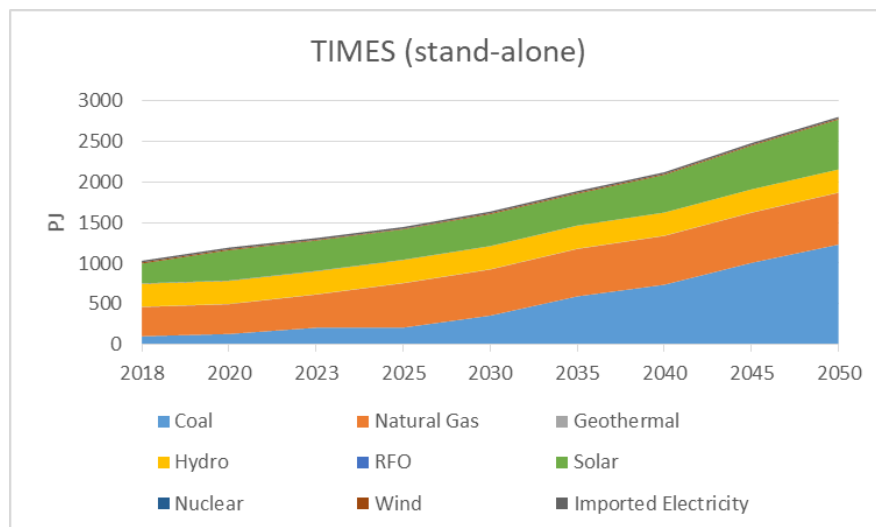


Figure 6.3. Electricity Generation estimated in TIMES stand-alone run

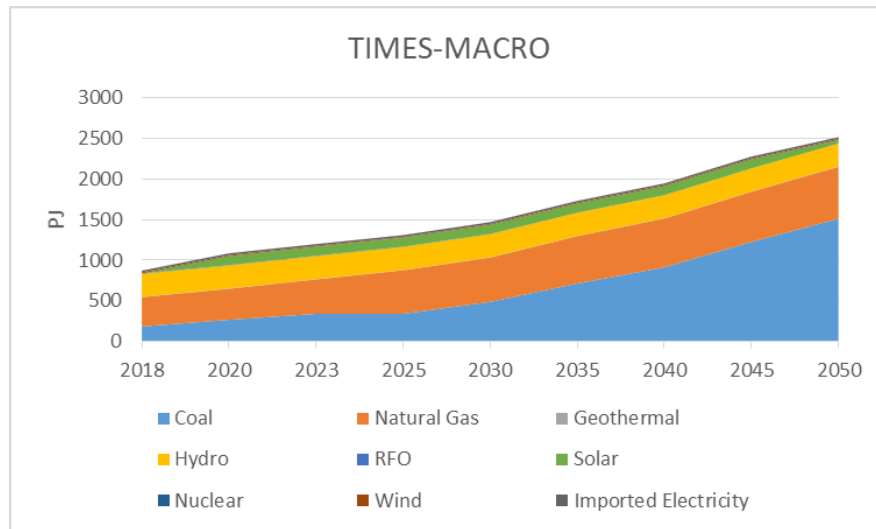


Figure 6.4. Electricity Generation estimated in TIMES-MACRO run

6.1.3. Industry Sector

Figures 6.5 and 6.6 show the composition chosen in TIMES stand-alone and TIMES-MACRO that satisfy the useful energy demands in industry sector under 21% emission bound applied from 2018 until 2050. The combination of energy use is similar in both model runs. However, as can be seen in the figures, in the TIMES-MACRO run, conservation technologies are realized to reduce the demand for end-use technologies and as a result, consumption levels are lower in the TIMES-MACRO model.

6.1.4. Residential and Commercial Sector

Figures 6.7 and 6.8 depict the consumption levels in residential and commercial sector under 21% emission constraint applied from 2018 until 2050. Since in TIMES-MACRO, price changes are taken into account and useful energy demands are calculated endogenously and responsive to these changes, by introducing an emission bound in 2018 to the model, the system will respond by reducing demand which in turn will lead to reduction in consumption levels. For instance, in 2040, consumption is 13% lower in TIMES-MACRO compared to stand-alone TIMES.

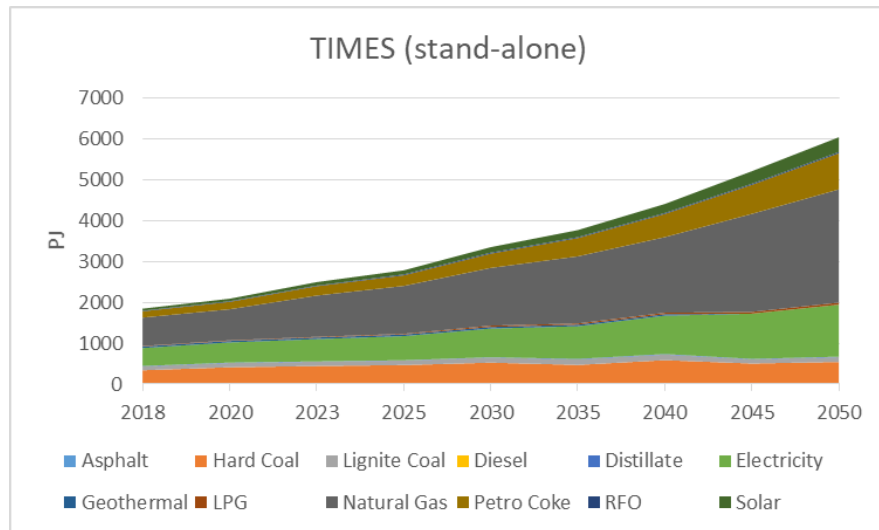


Figure 6.5. Energy Consumption in Industry Sector in TIMES stand-alone

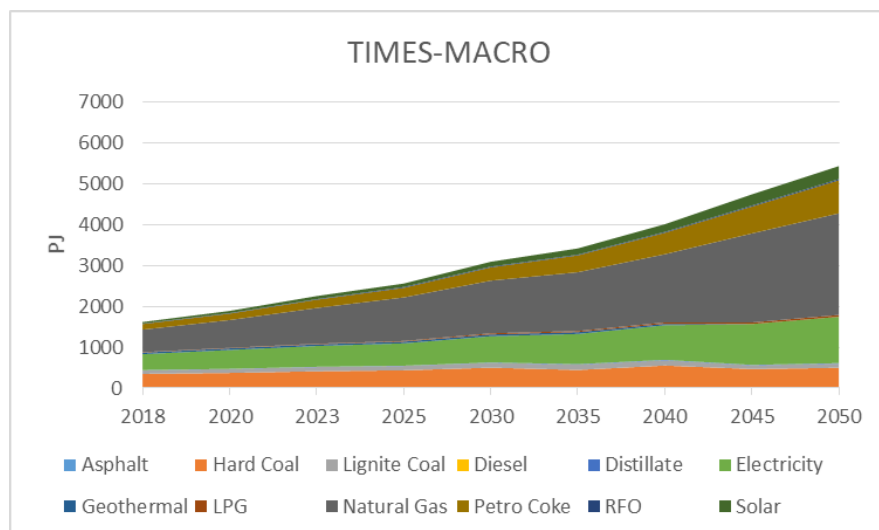


Figure 6.6. Energy Consumption in Industry Sector in TIMES-MACRO

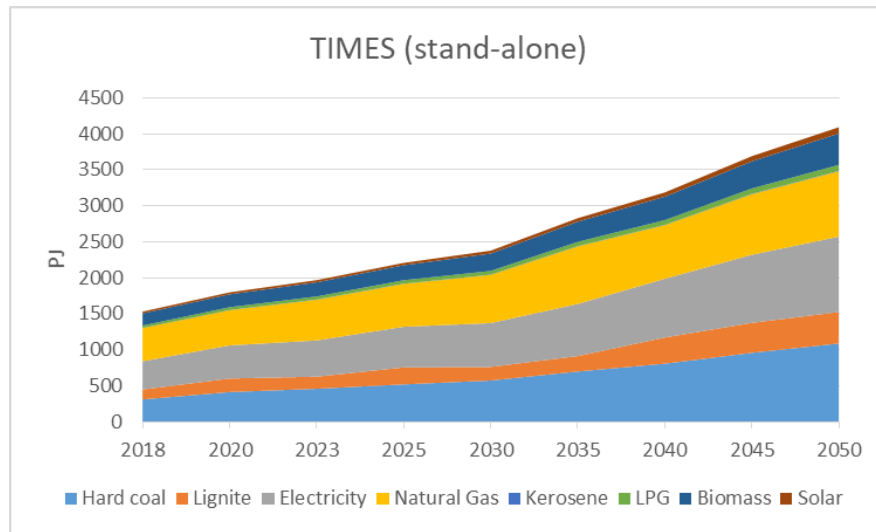


Figure 6.7. Energy Consumption in Residential and Commercial Sector in stand-alone TIMES Model

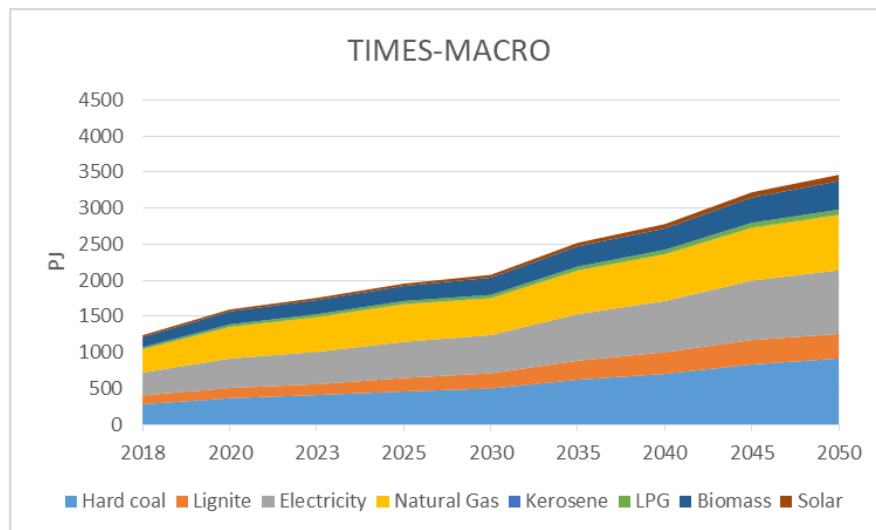


Figure 6.8. Energy Consumption in Residential and Commercial Sector in TIMES-MACRO Model

6.1.5. Transport Sector

In TIMES-MACRO, the respond from demand-side is a significant factor which lets the model to lower costs by reducing the level of energy demanded by consumers instead of investing in expensive technologies. This demand response is also observed in the transport sector but at lower levels. By applying 21% emission constraint from 2018 until 2050, the difference in consumption levels between TIMES and TIMES-MACRO is only 4% in the 2030-2050 period. One reason might be the inelastic demand in this sector, which can be caused by the high variety of end-use technologies in the transport sector. Consumption levels in transport sector, in TIMES and TIMES-MACRO, are seen in Figures 6.9 and 6.10.

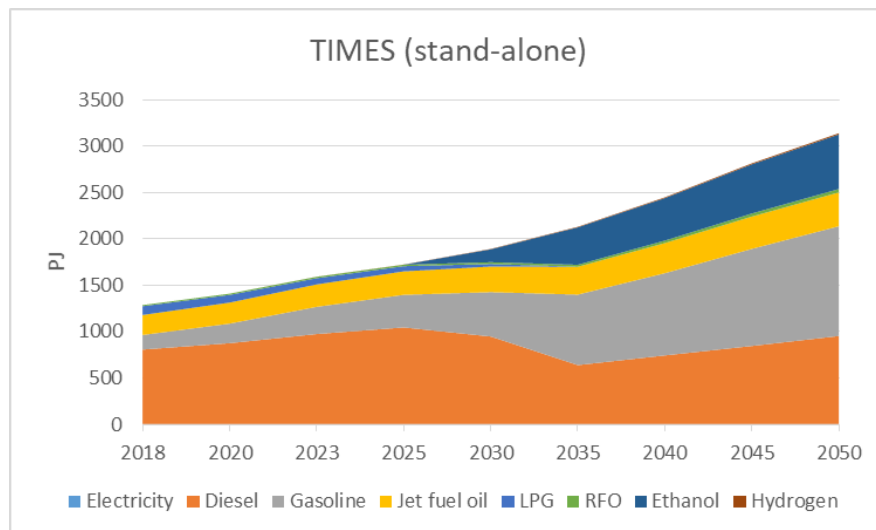


Figure 6.9. Energy Consumption Levels in Transport Sector in stand-alone TIMES

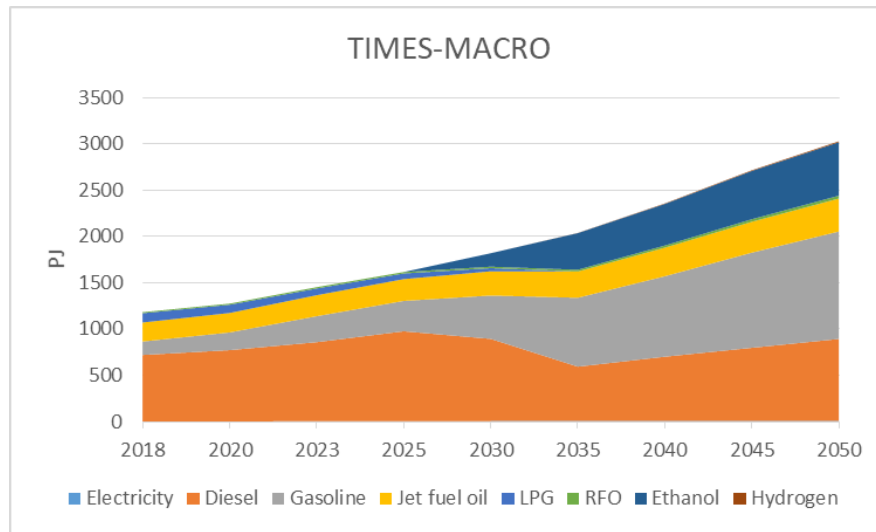


Figure 6.10. Energy Consumption Levels in Transport Sector in TIMES-MACRO

7. REFERENCE SCENARIO RESULTS

In the reference scenario the CO₂ emissions are not constrained at all and it has been assumed that the existing conditions will be valid until the end of the modeling horizon for all sectors.

7.1. Reference Assumptions

In addition to the laws and regulations of the Turkish Energy System, the following assumptions (Table 7.1) are made for every sector in the reference scenario.

7.1.1. Reference Scenario Results

In the reference scenario, electricity generation increases which is the result of GDP growth and also a rise in energy intensity, from 241.19 TWh in 2012 up to 809.65 TWh in 2050, while the primary energy consumption increases from 5773.86 PJ in 2012 to 21215.64 PJ in 2050. Primary energy is dominantly supplied by natural gas, coal and oil followed by renewable sources. From 2012 until 2018, primary energy is mainly supplied by natural gas, while from 2018 until the end of the model horizon, primary energy is dominantly provided by coal. That is why the CO₂ emissions reach to 1783.53 Mton in 2050 from the emission levels of 402.13 Mton in 2012. As can be seen in Table 7.2, by 2050, the primary energy consumption is expected to reach 21215.64 PJ with coal share increasing from 23% in 2012 to 36% in 2050 and renewable share decreasing from 7.67% in 2012 to 4.68% in 2050.

7.1.1.1. Agriculture Sector. As can be seen in Figure 7.1, total consumption in 2015 was 90.21 PJ in agriculture sector and is projected to be 280.93 PJ in 2050. Diesel is the dominant source in this sector with an average share of 51% and is followed by electricity (25% share). There is 7% efficiency improvement in diesel consuming technologies until 2030 and 14% increase in energy efficiency through 2030-2050.

Table 7.1. Reference scenario assumptions.

Sector	Assumption
Electricity Generation (Coal, Natural gas and Hydro)	Power plants that are declared to be licensed in the TEIAS 2013 Capacity Projection Report are added to the total installed capacity. The related production costs are applied according to the delegated legislation with Law no:5346 (Date:29 December 2010 No.6094)
Electricity Generation (Solar, Wind, and Geothermal)	Power plants that are declared to be licensed in the TEIAS 2013 Capacity Projection Report are added to the total installed capacity. The related production costs are applied according to the delegated legislation with Law no:5346 (Date:29 December 2010 No.6094)
Electricity Transmission and Distribution	Electric leakage loss ratio is assumed to remain unchanged. The ratio of leakage losses for the base year and 2015 is assumed to be 14.7% as given in IEA statistics and 17% from 2018 until the end of 2050.
Transportation Sector	Resource usage and capacity investment decisions are made in accordance with the minimum cost objective function.
Industry Sector	Resource usage and capacity investment decisions are made in accordance with the minimum cost objective function. Production levels are obtained from the reports published by TUIK. Demands are projected by considering the GDP change declared by OECD.
Residential and Commercial Sector	It is assumed that existing building stock has no energy saving resulted from insulation.
Agriculture Sector	Demands are projected by considering the GDP change provided by OECD.

Table 7.2. Energy Consumption in BAU-PJ.

	2015	2018	2020	2023	2025	2030	2035	2040	2045	2050
Asphalt	22	26	29	33	35	42	50	57	65	71
Hard Coal	979	1282	1562	2022	2298	3074	3360	3637	4065	4409
Lignite	679	742	976	1034	1054	1048	1611	2309	3165	3984
Electricity	769	864	975	1089	1204	1375	1587	1832	2143	2419
Natural Gas	1672	1965	2182	2459	2861	3076	3372	3696	4160	4537
Nuclear	0	0	0	0	0	0	0	0	0	0
Diesel	729	858	938	1041	1118	1026	733	851	971	1093
Distillate Oil	4	5	6	7	7	12	13	13	11	12
Gasoline	72	157	211	293	352	479	760	886	1048	1184
Jet Fuel Oil	194	216	227	252	272	306	350	389	433	469
Kerosene	2	2	2	3	3	3	4	5	5	6
LPG	148	140	136	127	123	113	90	103	119	134
RFO	43	44	43	48	49	48	47	49	51	59
Petro coke	142	154	181	228	260	350	447	567	711	883
Biomass	126	131	132	121	119	91	78	63	52	41
Ethanol	0	0	0	0	0	139	404	458	531	589
Geothermal	93	96	98	101	103	109	114	115	87	93
Hydrogen	0	0	0	0	0	0	0	0	0	0
Hydro	203	283	283	283	283	283	283	283	283	283
Solar	33	36	38	41	44	51	60	68	72	88
Wind	18	14	12	10	9	12	12	12	12	12
Crude Oil	1035	2538	2775	3081	3280	3051	2196	2543	2887	3249

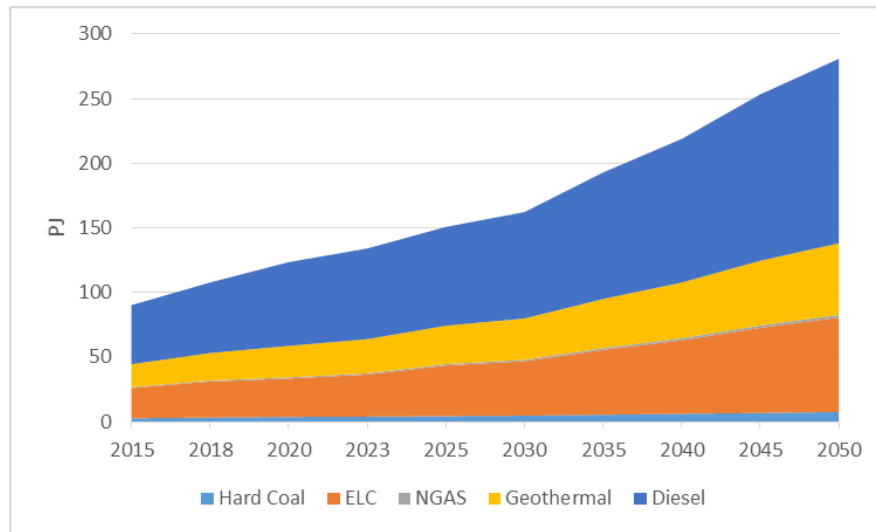


Figure 7.1. Energy Consumption by carrier in Agriculture Sector-BAU Scenario

7.1.1.2. Industry Sector. The industry sector is the largest energy consumer in Turkey. As can be seen in Figure 7.2, total final energy consumption was 1591.44 PJ in 2015 and is expected to reach 6074.67 PJ in 2050 (almost 4 times the level in 2015). The highest share in fuel consumption belongs to coal and remains the highest in the model horizon. The second most consumed fuel is natural gas with 32.68% share in 2015 and the share grows throughout the period with 33.56% share in 2045.

7.1.1.3. Residential and Commercial Sector. The energy consumption mix in residential and commercial sector is illustrated in Figure 9.5. The residential and commercial sectors are mainly dependent on natural gas, electricity and coal. The energy mix in this is approximately the same throughout the modeling horizon. The share of coal consumption increases from 31.9% in 2015 to 38.65% in 2050. The share of natural gas also increases throughout the horizon from 26.46% in 2015 to 30.48% in 2050. Electricity share is projected to decrease from 27% in 2015 to 25.59% in 2050.

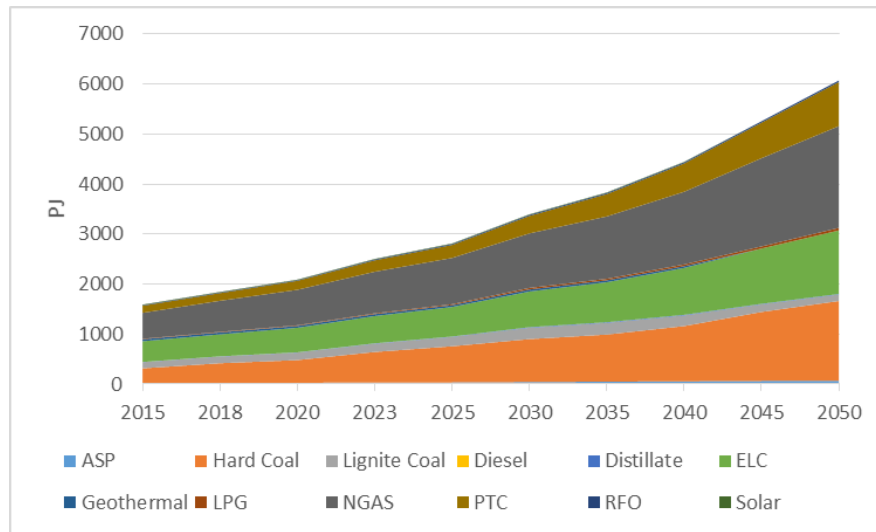


Figure 7.2. Energy Consumption by Carrier in Industry Sector-BAU Scenario

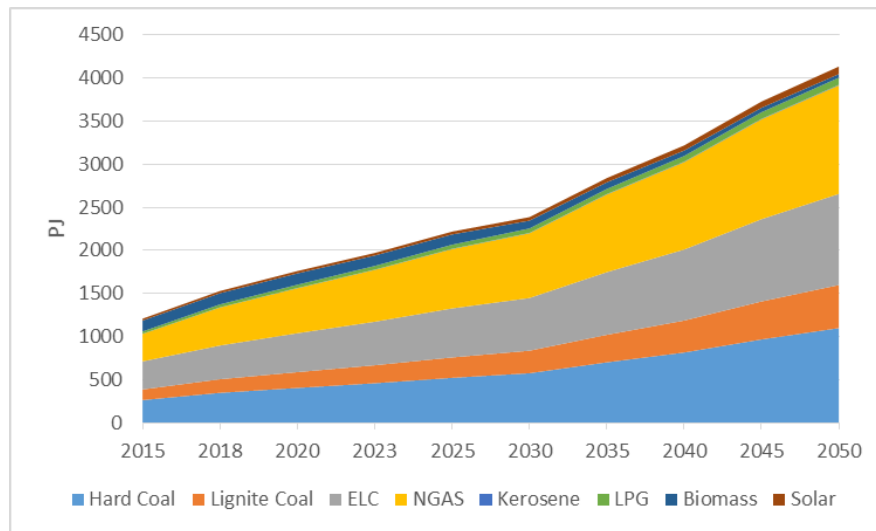


Figure 7.3. Energy Consumption by Carrier in Residential and Commercial Sector-BAU Scenario

7.1.1.4. Electricity Generation. In BAU scenario, electricity generation reaches 1656.1 PJ in 2030 and 2914.7 PJ in 2050 (almost 3 times the base year). In 2015, natural gas was the main source of electricity generation (39% share), while other sources like coal, hydro and oil accounted for 33%, 22.65% and, 0.59%, respectively. However, as can be

seen in Figure 7.4, starting from 2020, this trend starts to change, by coal becoming the dominant source of electricity generation. This change is because of the low price of coal supply. There is a peak in hydroelectricity generation in 2018 and from this year onwards, it remains constant. This is because hydroelectricity generation technologies are more expensive than coal electricity generation technologies and annual available capacity of hydroelectricity generation technologies is lower than that of coal generation technologies. Other renewable energy sources like solar and wind decrease until the end of model horizon, except hydro and geothermal energy, that remain constant and maintain their maximum potential throughout the planning horizon.

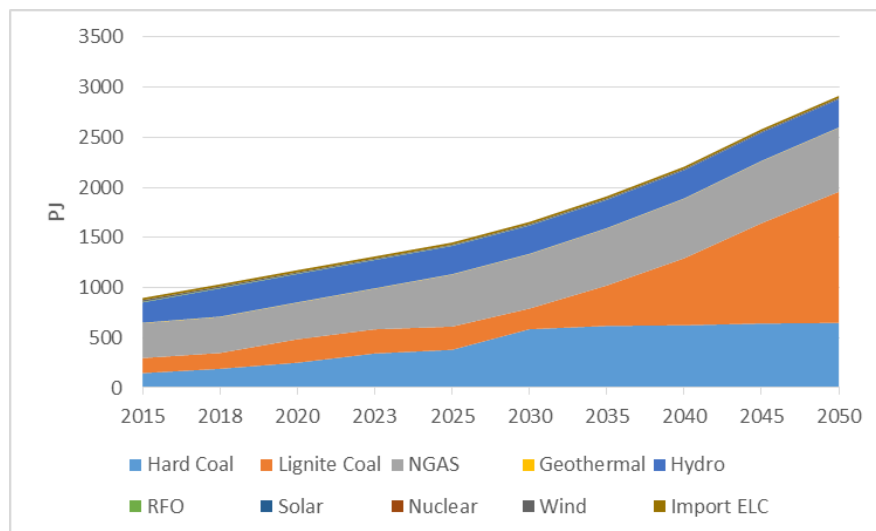


Figure 7.4. Electricity Generation w.r.t. type of Resource-BAU Scenario

7.1.1.5. Emissions. Sectoral CO₂ Emissions are illustrated in Figure 7.5. CO₂ emissions are expected to reach 1783.53 Mton in 2050, approximately four times higher than 2015 levels. The largest CO₂ emitters in the base year are electricity generation and industry sector with 36% and 21% shares, respectively. Steel and cement production are the main emitters in the industry sector. This is a result of high coal consumption in these industries. Power sector will continue to be the largest emitter by 42% share in 2050 followed by the industry sector as the second most emitter by a 26% share of CO₂ emission in 2050.

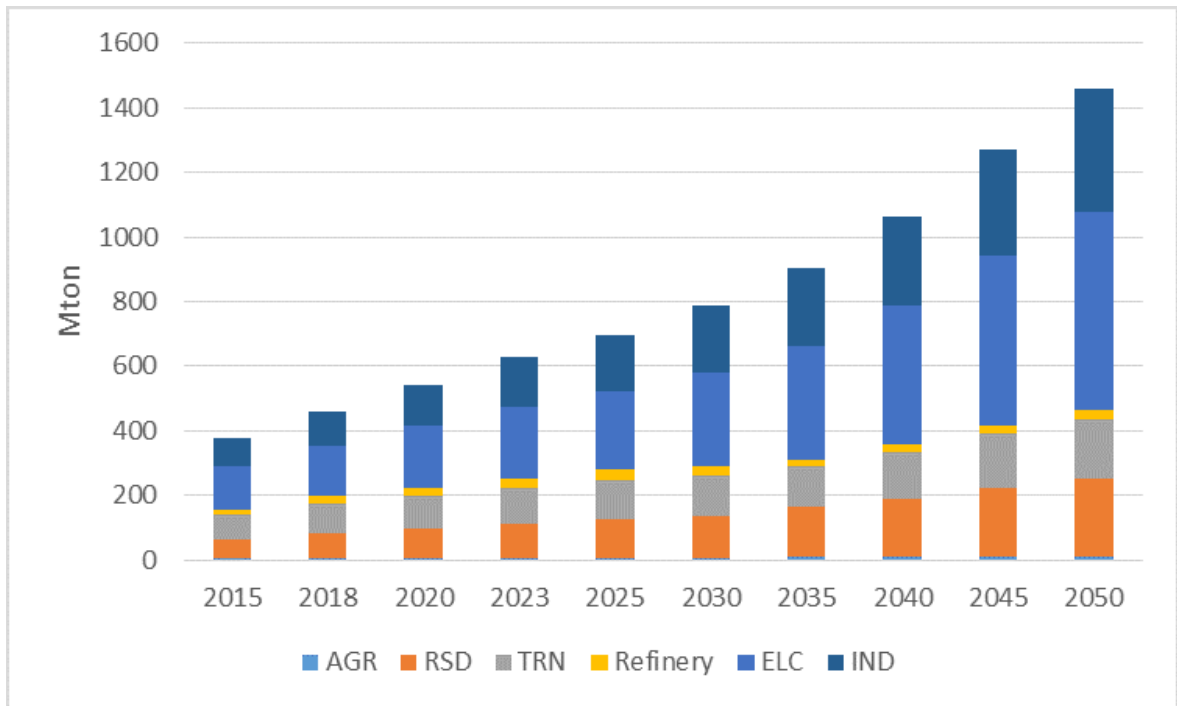


Figure 7.5. Sectoral CO₂ Emissions-BAU Scenario

8. EMISSION BOUND SCENARIO RESULTS

Two emission reduction scenarios have been defined, 10% reduction and 21% reduction (the INDC of Turkey) with respect to the base scenario starting from 2018. In this section, results of the emission reduction scenarios are compared with the reference scenario.

8.1. Primary Energy Consumption

Emission constraints cause considerable reductions in the primary energy consumption levels. As can be seen in Figure 8.1, primary energy consumption starts to decrease from 2018 in both emission reduction scenarios, for instance, in 10% emission reduction scenario, there is 7.27% reduction in energy consumption compared to the reference scenario in 2018 and under 21% emission reduction scenario, model achieves to reduce energy use to 15.42% lower than the reference scenario in 2018. As can be seen from the structural variations in primary energy consumption, it is obvious that coal (mostly lignite) is eliminated mainly and is substituted by renewable sources, while natural gas and oil keep on providing almost the same fractions of primary energy consumption. In 2018, coal share drops from 34% in the reference scenario to 27% in the 21% bound scenario. There is a slight increase in the share of natural gas in the 21% bound scenario, for instance, in 2018, natural gas share increases from 33% in the base scenario to 35% in the 21% bound scenario and in 2045, the same share increases from 28% to 31%. The share of oil remains nearly the same at the BAU levels. Consequently, the shares of renewable energy sources are increased over the base scenario. Introducing emission constraints causes significant reductions in primary energy consumption, since the energy system shifts towards using more efficiently and consuming lower energy levels by increasing conservation levels and also through endogenous demand response. Reductions in primary energy consumption get higher as the emission constraints get more stringent. By imposing CO₂ constraints in 2018 onwards, the response of the energy system is to use more efficient technologies which in turn needs lower energy level. There is another reason that energy consumption is reduced in

emission reduction scenarios and it is the response of demand in end-use sectors by reflecting the increase in energy prices. Figure 8.1 shows how the decline in primary energy consumption increases as emission bounds get tighter; under 21% emission constraint primary energy is decreased by 12% in 2050, while under 10% constraint, the reduction is nearly 7%. The same behavior is observed in final energy consumption.

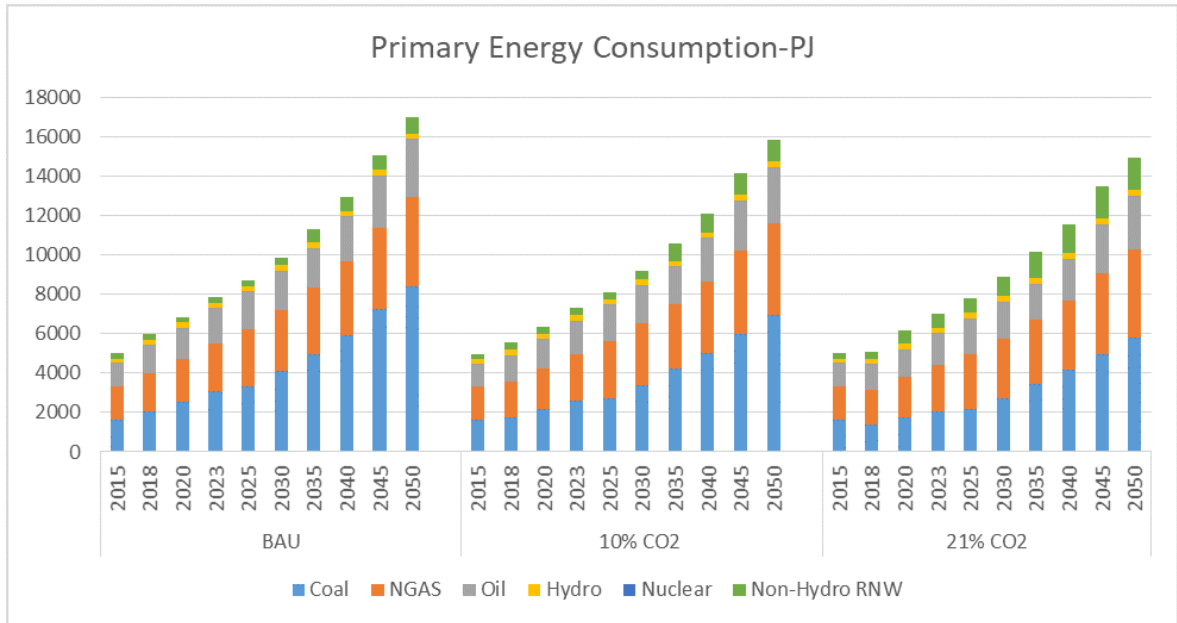


Figure 8.1. Primary Energy Consumption estimated in BAU and Emission Bound Scenarios

Coal has the highest carbon emission factor and this is the reason that in both emission reduction scenarios, coal consumption has the highest percentage drop among the fuels. As can be seen in Figure 8.2, coal share increases in both emission reduction scenarios, even in 21% bound scenario coal share increases throughout the model (although at a lower rate), except the severe fall in 2018 in which the CO₂ bound is imposed, and in 2025 that there is a slight decrease in coal share, which is due to the imposed activity bounds on coal power plants.

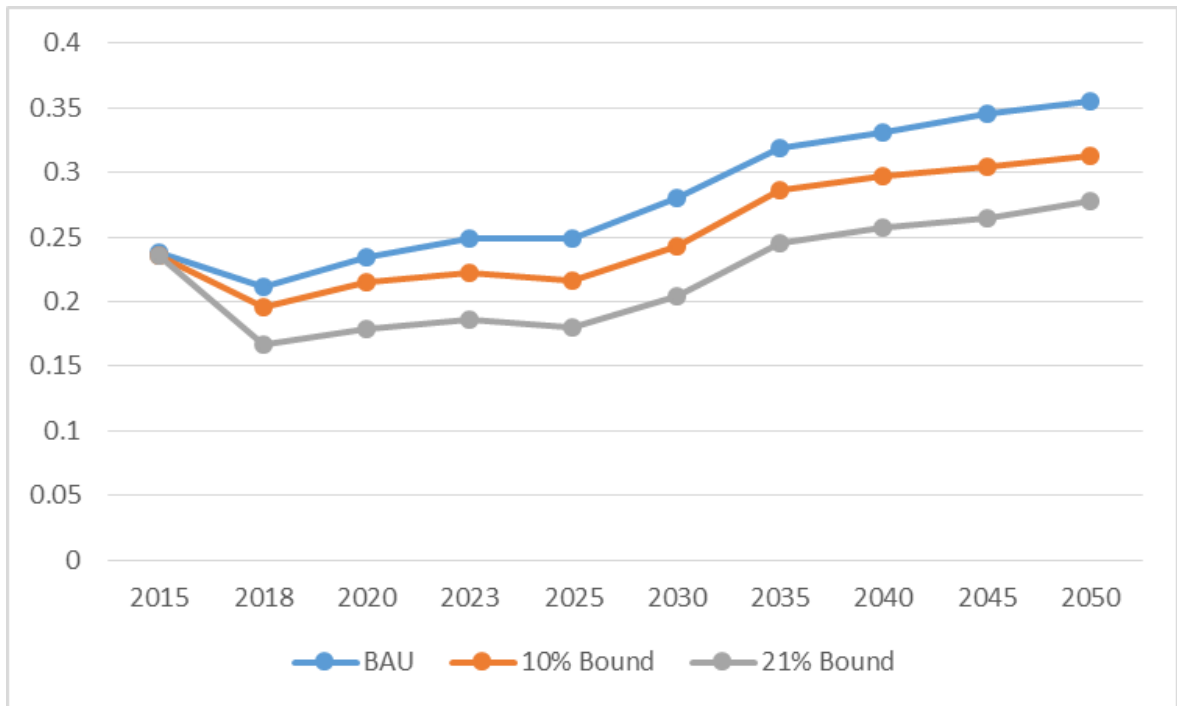


Figure 8.2. Coal Share in Primary Energy Consumption

Under 10% emission reduction scenario, coal consumption is partly replaced by natural gas that has lower emission factor compared to coal and partly by biomass. While, in 21% emission bound, the model tends to use biomass and solar energy instead of coal. The share of renewable energy use in emission reduction scenarios is depicted below. As can be seen in Figures 8.3 and 8.4, under both of emission bound scenarios, there is a peak in the renewable share in 2035. This peak is the result of new biomass (wood-based biomass technology in residential heating) investment. Under 21% reduction, there is an additional peak in renewable share in 2020. This peak is due to an investment in solar PVs in this year.

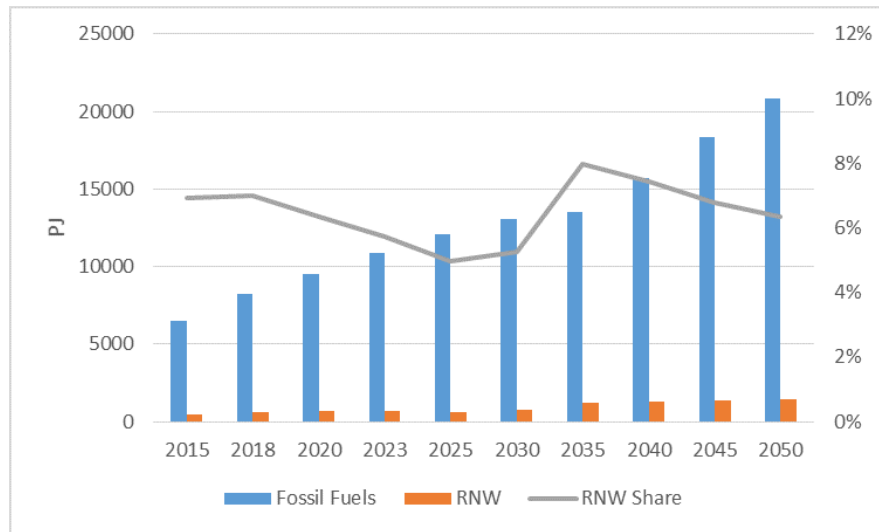


Figure 8.3. Fossil fuel and renewable energy consumption under 10% CO₂ Bound

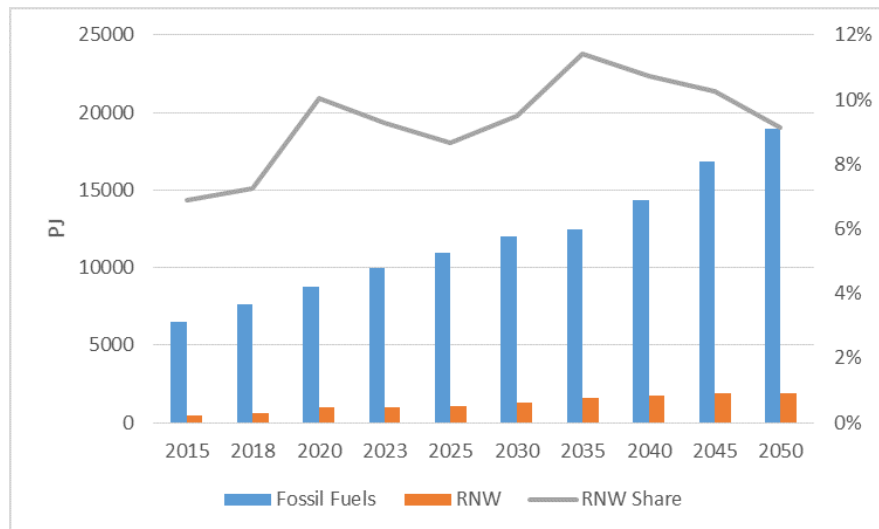


Figure 8.4. Fossil fuel and renewable energy consumption under 21% CO₂ Bound

As depicted in the Figure 8.5, both of the emission reduction scenarios have lower energy intensities (higher efficiencies) compared to the base scenario. Among these two scenarios, 21% emission bound scenario is more efficient. Energy intensity decreases throughout the planning horizon except the 2015-2025 period.

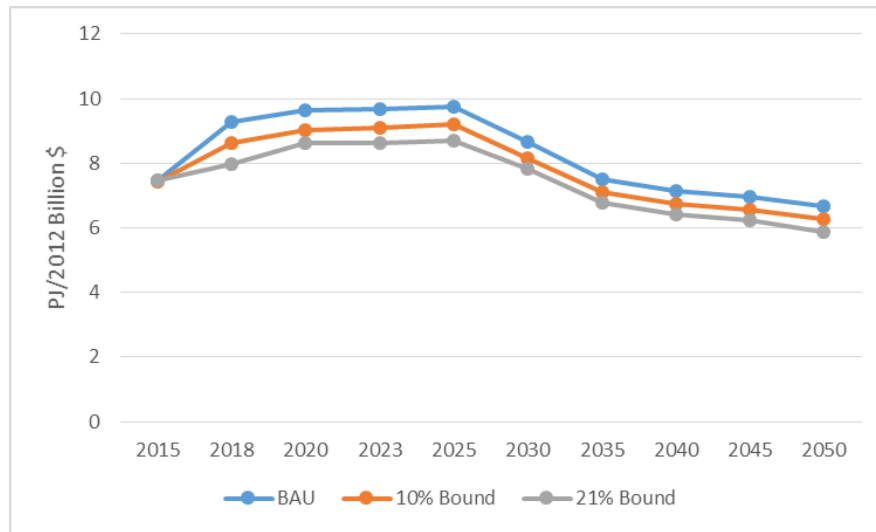


Figure 8.5. Energy Intensities in BAU and Emission Bound Scenarios

8.2. Electricity Generation

Emission constraints limit the alternatives for electricity generation. This limitation leads to an increase in electricity prices and decreases demand. The effect of emission constraints on the level of electricity generation is depicted in Figure 8.6. Under 21% emission bound, the model manages to decrease electricity generation by 15% compared to the reference scenario in 2018. The structural mix of electricity generation is almost the same between the BAU and the emission reduction scenarios. As can be seen in the figure, lignite starts decreasing significantly by introducing emission bounds in 2018 in both scenarios. In 2018, model manages to lower lignite coal by 90% under 21% bound scenario compared to the base scenario, although this percentage is volatile and decreases throughout the model horizon except in 2035 (due to activity bounds that are fixed until 2030 according to the policy assumptions related to lignite use). In the reference scenario, electricity generation from solar power is not preferred. Also, under 10% emission bound, solar power is not favored, although by introducing 21% emission bound, electricity generation from solar power is promoted and provides nearly 31.18 TWh annually from 2020 until 2045.

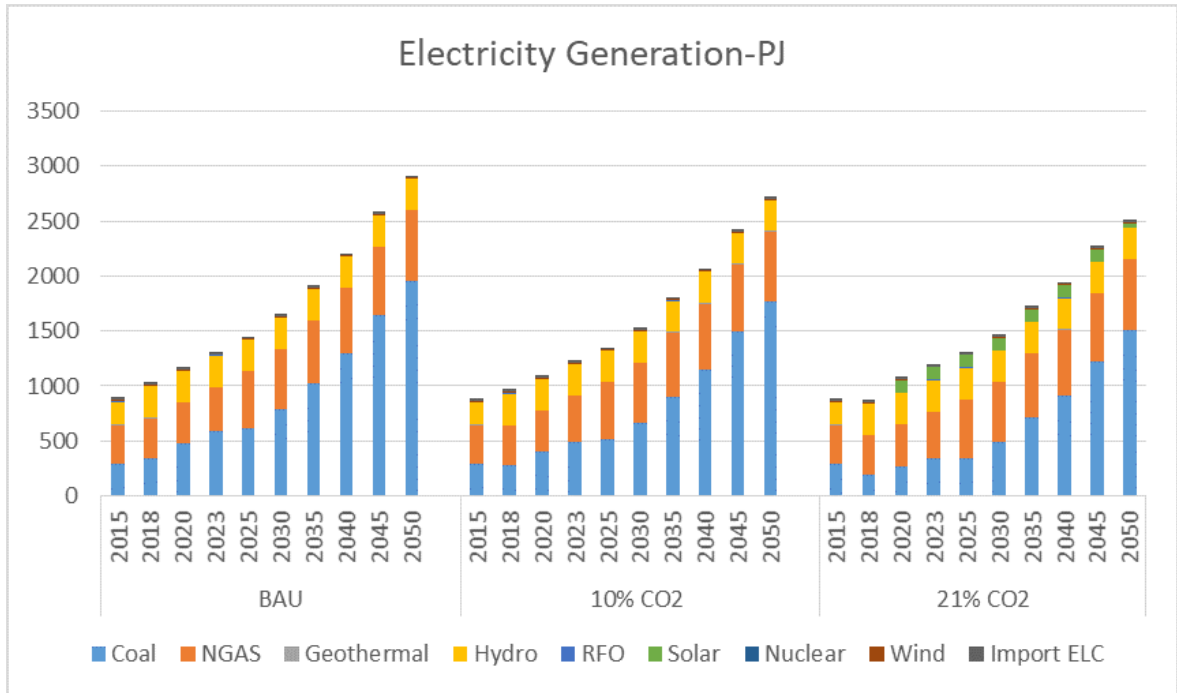


Figure 8.6. Electricity Generation under Emission Reduction Scenarios

As depicted in Tables 8.1 and 8.2, total installed capacity of coal electricity generation technologies are mainly replaced by solar electricity generation technologies under 21% emission reduction scenario.

8.3. Demand Response

Demand response is the primary factor in the TIMES-MACRO model that enables the model to lower costs by reducing the demand for energy instead of having to invest in low carbon technologies with higher costs. As emission reduction constraints get stricter, demand response becomes even more influential to help minimize the marginal abatement costs.

By introducing CO₂ constraints in the energy system, there will be responses from the end-use demand sectors.

Table 8.1. Total Installed Capacity in BAU Scenario (GW).

	2015	2018	2020	2023	2025	2030	2035	2040	2045	2050
Coal	26.9	29.2	37.5	39.3	39.2	36.3	48.4	63.3	81.9	99.4
Natural Gas	25.4	26.9	27.8	24.8	25.5	24.9	24.6	24.2	23.8	22.5
Oil	1.31	1.39	1.31	1.18	1.09	0.87	0.6	0.4	0.2	0
Hydro	20.1	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6
Wind	2.3	2.3	2.3	2.3	2.3	2.3	1.2	1.2	1.2	1.2
Solar	0.01	0.01	0.01	0	0	0	0	0	0	0
Geothermal	0.7	0.7	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.1
Biomass	0.2	0.21	0.2	0.18	0.17	0.13	0.1	0.07	0.03	0
MSW	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0	0
Total	77	86.4	95.6	94.1	94.4	90.7	101	115.1	132.9	148.8

Table 8.2. Total Installed Capacity in 21% Emission Reduction Scenario (GW).

	2015	2018	2020	2023	2025	2030	2035	2040	2045	2050
Coal	26.9	28.6	31.5	30.2	29.6	26.8	30.7	41.4	57.8	73.7
Natural Gas	25.3	26.9	33.2	31.3	31	25.9	29.6	26.6	23.7	22.4
Oil	1.3	1.4	1.3	1.2	1.1	0.8	0.6	0.4	0.2	0
Hydro	20.1	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6
Wind	2.3	2.3	2.3	2.3	2.3	2.3	1.2	1.2	1.2	1.2
Solar	0.01	0.01	17.8	17.8	17.8	17.8	17.8	17.8	17.8	7.1
Geothermal	0.67	0.69	0.65	0.58	0.54	0.43	0.33	0.22	0.12	0.12
Biomass	0.2	0.21	0.2	0.18	0.17	0.13	0.1	0.07	0.03	0
MSW	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0	0
Total	76.9	85.8	112	109	108	99.9	106.1	113.4	126	130.1

Reducing emissions from the demand side can be obtained by:

- switching to low-carbon fuels,
- using more efficient end-use demand devices,
- using conservative measures that need lower demand for energy (high-efficiency oil burners are examples of conservation measures), and
- price-induced (endogenous) reductions in the overall demand levels.

The MACRO submodel captures the demand response endogenously and reflects the response to the price changes. As mentioned before, although only one aggregated elasticity of substitution is being used in the TIMES-MACRO model, it can influence different useful energy demands by considering their marginal costs, such that sectors that have lower marginal costs, are reduced more when emission constraints are applied. Low marginal costs are mainly an indication of the limited technological substitution alternatives. The level of response from different sectors is based on demand decoupling factors (DDFs) that represent the link between the trends in the aggregate economy (being represented by GDP) and the activity of each demand sector. As mentioned before, through the calibration procedure, DDFs are used to assure that GDP and demands converge to a reasonable level with the projected GDP growth rates and exogenous demands of the TIMES model. By analyzing the changes in sectoral demand responses, it can be seen that the largest reductions occurs in the residential and commercial sector followed by industry and agriculture sectors, while transport sector is the least responsive sector. As emission constraints get stricter, the importance of demand response also becomes higher, since it helps to lower the marginal abatement costs. For instance, under 21% constraint, demands are reduced by 13% in 2050, while under 10% constraint demands are decreased by 6% which indicates while the cost of low carbon alternatives are higher, demand reductions are even greater as the system is trying to minimize the costs. Additionally, the behavior of demands is similar to the marginal abatement cost trends. This can indicate that the level of marginal costs is an important driver of the demand response.

In order to be able to better examine the impact of emission constraints, the results of 21% emission reduction that reflects the effects more significant, are compared with BAU.

8.3.1. Industry Sector

The industry sector is the second sector that has the deepest reductions in response to the 21% emission constraint applied in 2018. A 21% reduction in CO₂ emissions leads to changes in resource and technology usage in this sector. Low demand growth, reductions in demand, switching fuel usage, and energy efficiency are responsible for emission reduction in this sector. Under the 21% emission reduction scenario, changes in the industry sector lead to an increase in geothermal and solar energy use and a significant decrease in coal consumption. As illustrated in Figure 8.7, coal consumption is decreased by 21% in 21% emission bound scenario compared to the base scenario in 2018 and continues to decrease until the end of model horizon such that in 2050, coal consumption is reduced by 66%. Coal consumption is partially substituted by natural gas.

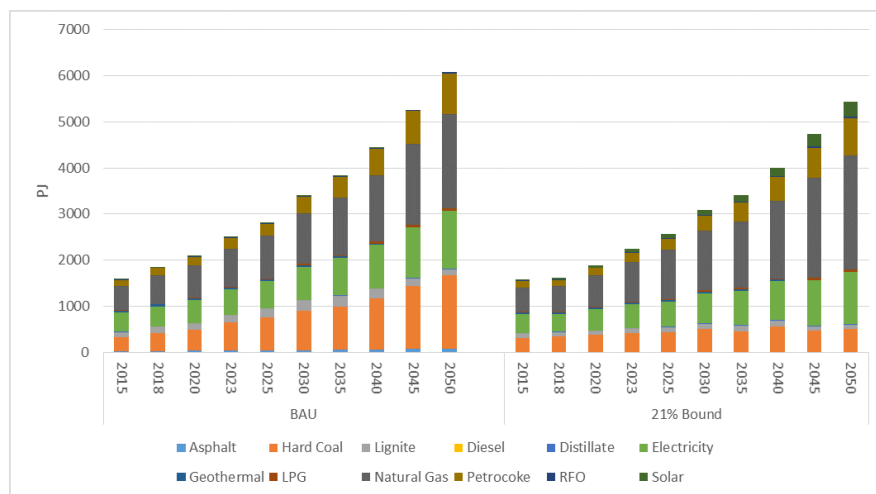


Figure 8.7. Energy Consumption in Industry Sector estimated in BAU and 21% Emission Bound Scenario

8.3.2. Residential and Commercial Sector

Energy Consumption in Residential and Commercial Sector in BAU and 21% emission bound scenario is shown in Figure 8.8. Under 21% emission constraint, hard coal and lignite consumption decrease by 20% in 2018 compared to the base scenario. Natural gas consumption also is reduced under 21% bound scenario throughout the model horizon, for instance, in 2018 natural gas is reduced by 27% and in 2050, by 39% compared to the base scenario. Electricity use also is reduced in this sector by introducing 21% emission bound. Electricity consumption starts decreasing in 2018 by 19% compared to the base scenario, continues decreasing and reaches 882.45 PJ in 2050 which is 17% lower than the electricity consumption level in the base scenario. Under 21% emission bound that is introduced in 2018, biomass becomes a source of energy for the residential sector, such that while it covers 11% in 2045 under 21% emission constraint, the same share is 1% in the base scenario.

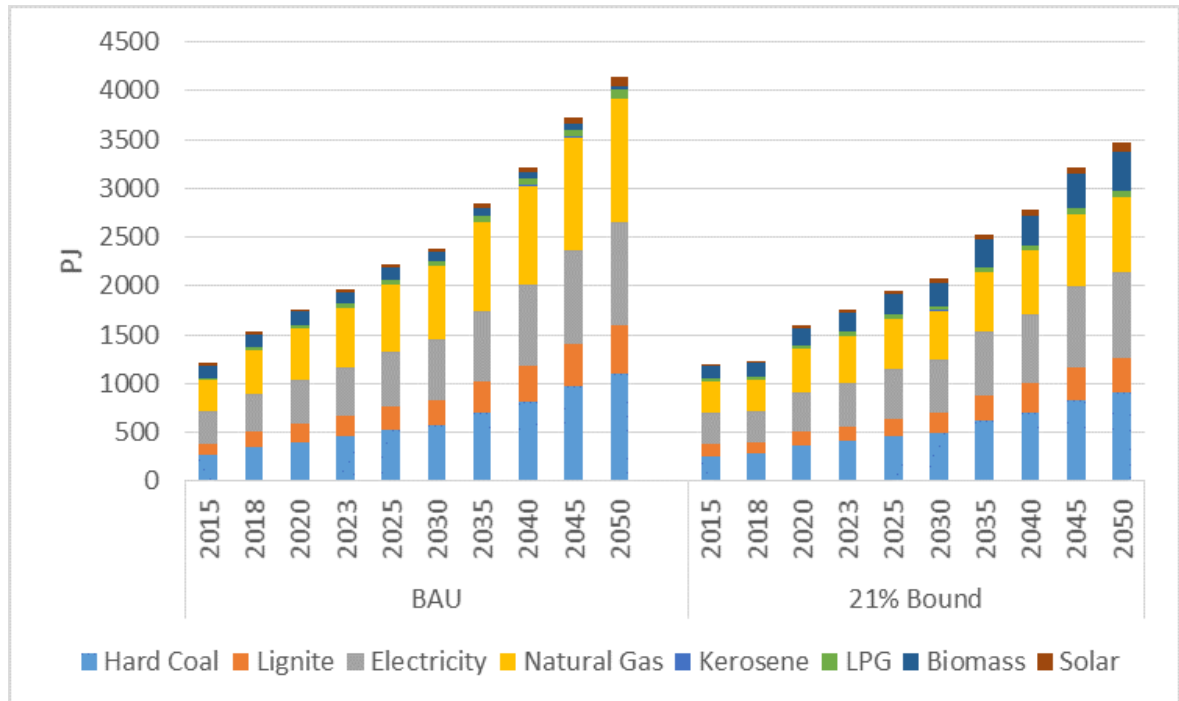


Figure 8.8. Energy Consumption in Residential and Commercial Sector in BAU and 21% Emission Bound Scenario

8.3.3. Transport Sector

As can be seen in Figure 8.9, the 21% emission constraint leads to overall energy demand decrease in the transport sector that is the result of two effects: first, vehicles become more efficient and second, higher energy prices trigger the demand reduction. In 2018, under 21% emission bound, diesel consumption is reduced by 11% and gasoline usage decreases by 7% compared to the reference scenario. The decline in diesel consumption is more severe than gasoline, since the emission factor of diesel is higher than that of gasoline. Consumption of jet fuel oil in air transport is also decreased throughout the model horizon and is substituted by hydrogen. In the transport sector, emission reductions already become available in the reference scenario without any emission restrictions as the system moves to more efficient vehicles. This might be the reason that transport sector is not very responsive to emission constraints. The other reasons can be the inelastic demand response, and the relatively high variety of technologies that neutralize the requirement of high demand responses.

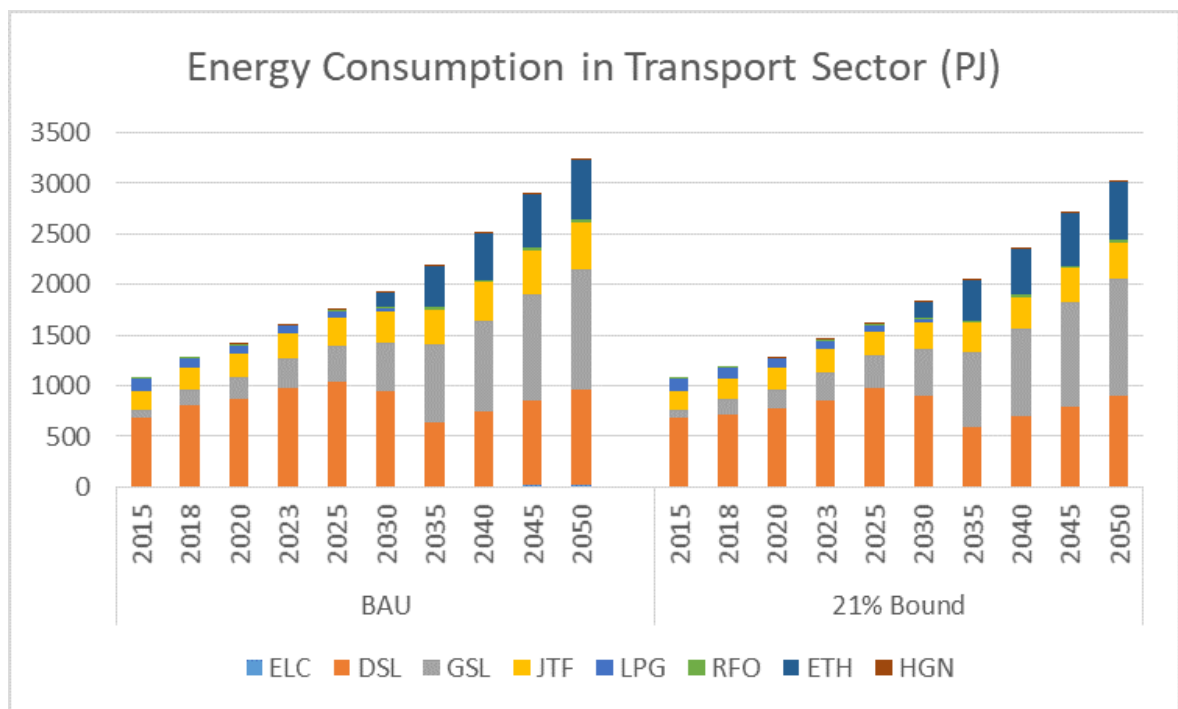


Figure 8.9. Energy Consumption in Transport Sector in BAU and 21% Emission Bound Scenario

8.3.4. Renewable Sources

As can be seen in Figure 8.10, the share of renewable energy sources tend to increase in years in which investments will be made in renewable technologies but is not able to keep the high shares and drops throughout the planning horizon. As mentioned previously, renewable consumption levels increase under emission reduction scenarios. But, their share decreases because renewable energy sources cannot keep up with the increasing demand.

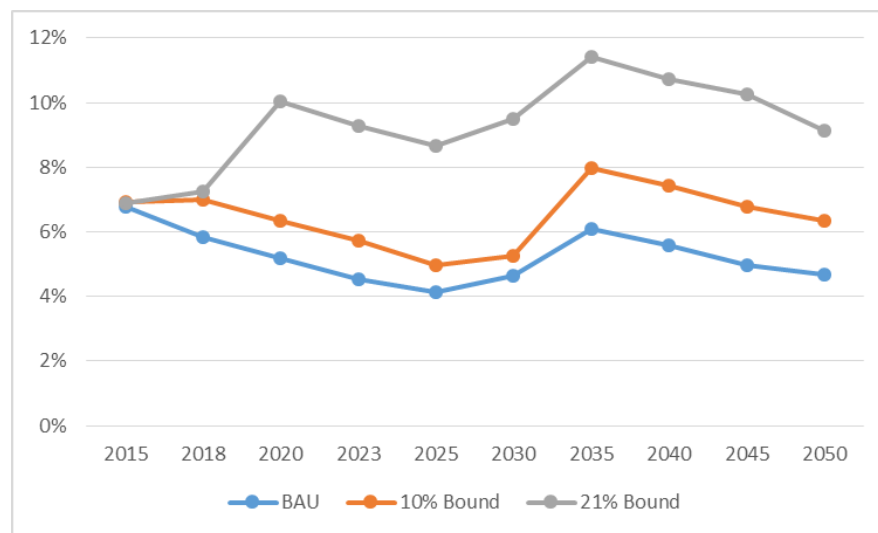


Figure 8.10. Renewable Shares in BAU and Emission Bound Scenarios

8.3.5. Emissions

As can be seen in Figure 8.11, there are significant reductions in emission levels starting from 2018 compared to the base scenario. The decline in CO₂ emission levels under reduction bound scenarios follows the similar pattern that emerges in the base scenario. As can be seen in Figure 8.11, electricity generation sector is the most responsive sector to reduce emissions and is followed by industry and residential sectors that are less efficient in cutting down on their carbon emissions.

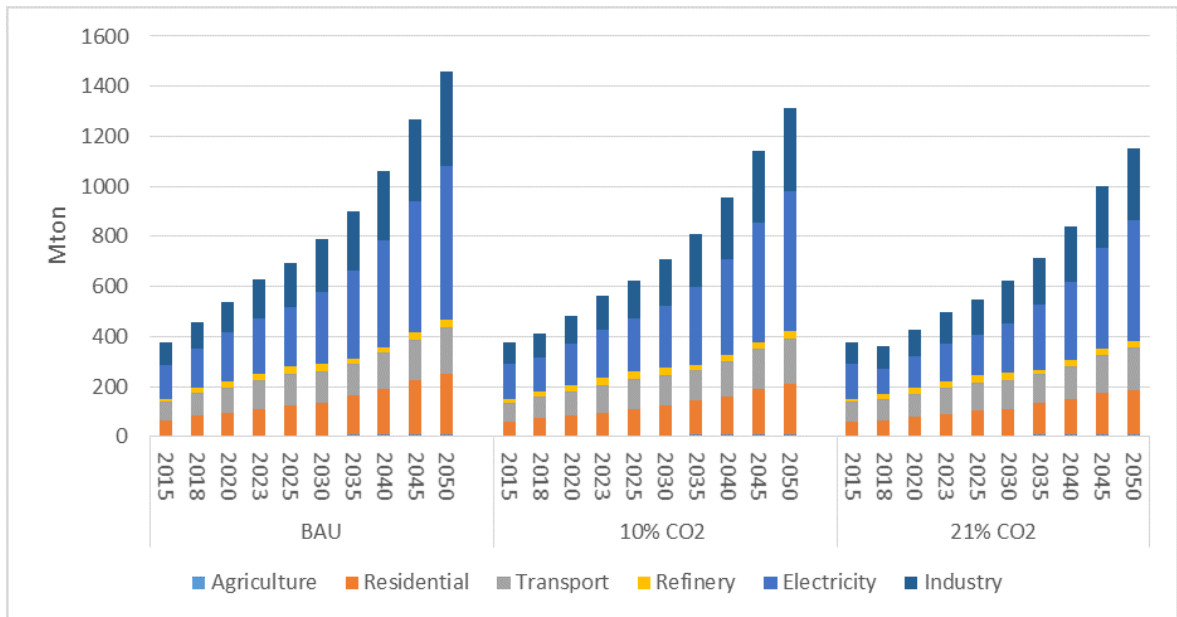


Figure 8.11. CO₂ Emissions estimated in BAU and Emission reduction scenarios

8.3.6. Energy System Cost

In both emission reduction scenarios, the energy system cost is decreased by introducing the emission constraints throughout the planning horizon. As can be seen in Figure 8.12, the annualized energy cost decreases by 4% in 21% emission bound scenario in 2018 compared to the base scenario. The reduction in the energy cost is the result of two effects working against each other: on one hand, the unit cost of the energy sector is increased, due to using more expensive technologies and higher fuel costs to meet the applied emission bounds. On the other hand, the decrease in energy demand due to behavioral changes, leads to a shrinkage in energy systems under the emission constrained scenarios. Thus, in both emission bound scenarios, the reduction in demand outweighs the higher unit costs. Since the price effects are stronger in 21% emission constraint than the 10% emission constraint (the carbon constraint makes the unit cost of energy expensive), the demand for energy and fuel costs are lower in the 21% constraint scenario.

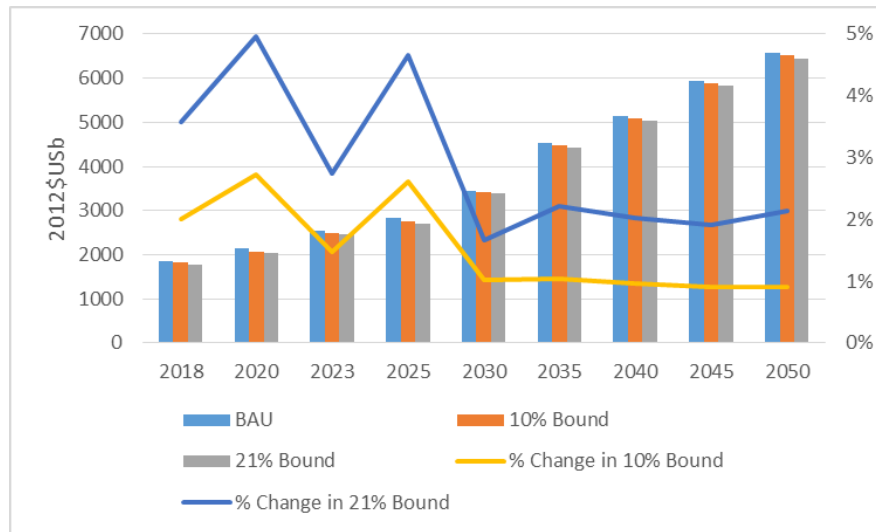


Figure 8.12. Energy System Cost Levels and Percent Changes relative to BAU Scenario

8.3.7. Economic Impacts

To assess the unit cost of emission reductions, the GDP difference between a scenario and the reference scenario is divided by the level of emission reduction obtained in the same scenario. The resulting change in GDP per unit reduction for emission reduction scenarios is illustrated in Figure 8.13. The abatement costs get higher when emission constraints are stricter or technologies needed to reduce emissions are more expensive. Abatement costs do not get progressively higher over time as expected, for instance in 21% emission bound scenario the abatement cost in 2030 is lower than the cost in 2025. This can be an indication that the system has low carbon technologies available at a lower cost in 2030 (more cost-effective low carbon technologies).

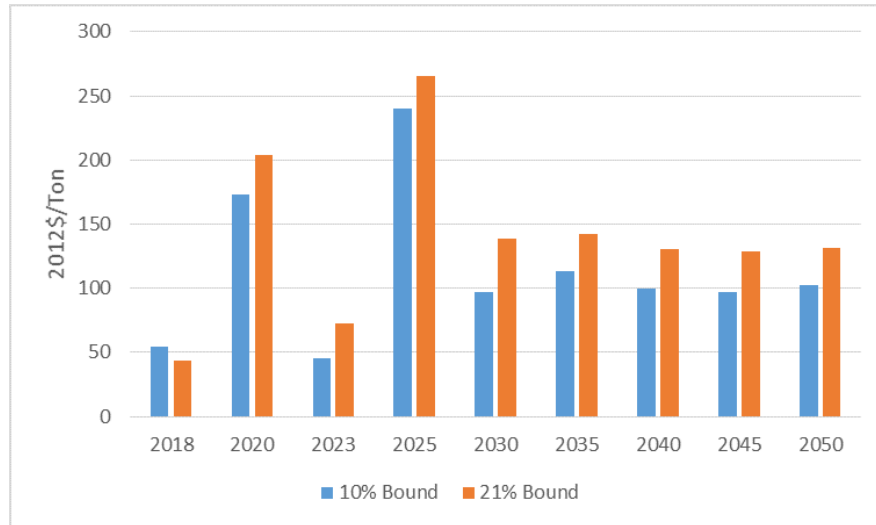


Figure 8.13. Abatement costs of emission bound scenarios

As emission constraints get more strict, GDP loss rates also tend to increase. As can be seen in Figure 8.14 under 10% emission constraint, GDP decreases by 0.47% in 2050, while under 21% constraint it decreases by 1.24% compared to the base scenario.

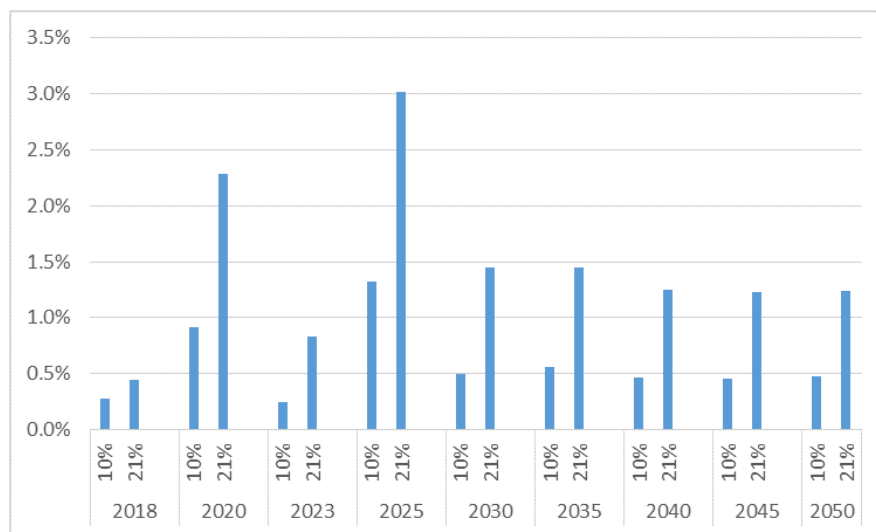


Figure 8.14. Percentage GDP Loss w.r.t. the Base Scenario

9. TAX SCENARIO RESULTS

In all tax scenarios, the value of tax is applied from 2018 until the end of the model horizon.

9.1. Industry Sector

The response of the industry sector, when per ton tax is imposed under four different tax scenarios, is explained in this section. As can be seen in Figure 9.1, In industry sector, under 10\$ tax, hard coal consumption starts to decline from 2025 and continues to decrease until 2050 and is substituted by natural gas (lower price) that increases from 2025 until the end of planning horizon. Lignite coal use declines throughout the model horizon when compared to the base scenario. The consumption of geothermal is slightly increased under 10\$ tax, and there is no change in solar energy and it remains constant. Under 20\$ tax, hard coal consumption declines from 2020 until the end of the planning horizon compared with the base scenario, and lignite coal decreases throughout the model horizon. Electricity consumption also declines from 2018. Natural gas usage declines through the 2015-2018 period and increases in 2018-2050, mostly as a substitution of hard coal. There is also a slight increase in solar energy compared to the reference scenario.

The response of industry sector under 50\$ and 80\$ taxes is shown in Figure 9.2. Under 50\$ tax, industry sector manages to reduce coal (hard coal+ lignite coal) consumption from 2015. The share of coal consumption under 50\$ tax, is almost 27% in 2015 and decreases to 15% in 2050, whereas in the base scenario, the share of coal consumption remains at an average share of 29.5% throughout the model horizon. Compared to the base scenario, natural gas consumption declines in the 2015-2020 period and increases from 2023 until 2050. Electricity consumption declines from 2018 with respect to the base scenario. The consumption of solar energy under 50\$ tax, reaches to 74.28 PJ in 2030, while in the reference case, it is 10.77 PJ in 2030.

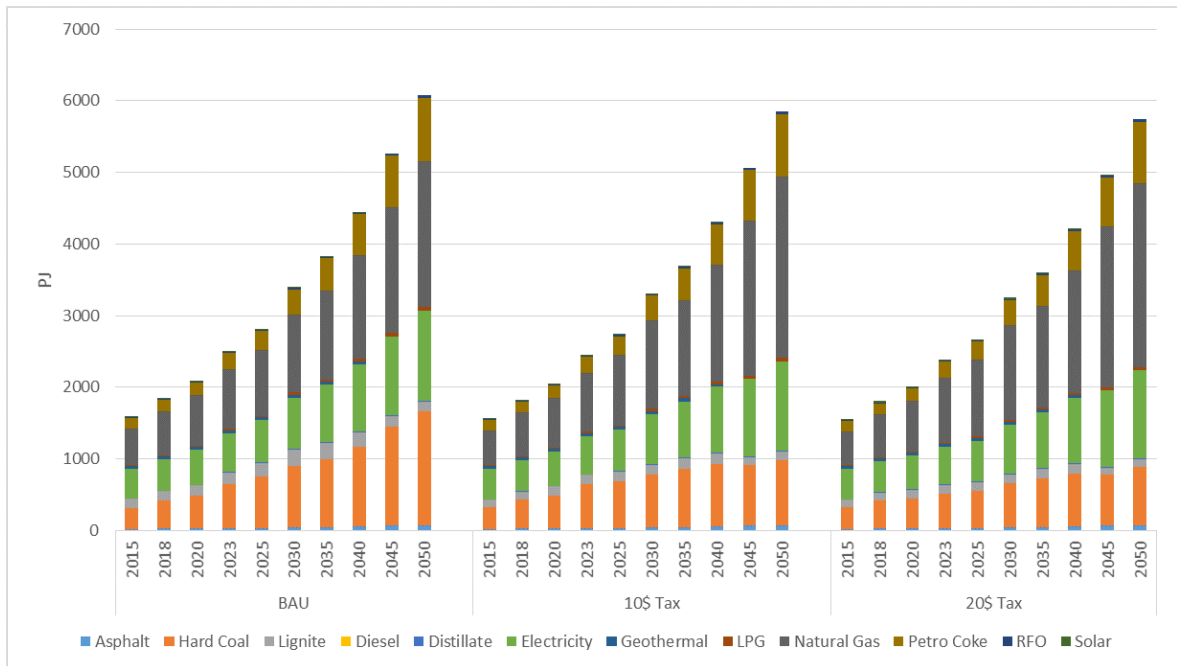


Figure 9.1. Industry Sector Energy Consumption in BAU, 10\$ and 20\$ Tax Scenarios

The response of the industry sector under 80\$ tax is similar to the 50\$ tax scenario, although with higher levels of differences with respect to the reference scenario. For instance, in both 50\$ and 80\$ tax scenarios, coal consumption declines throughout the model horizon compared to the base scenario, while the difference between the value of consumed coal in the reference case and the 50\$ tax case is 310.3 PJ in 2030, the similar difference for coal usage is 478.58 PJ under 80\$ tax. Under 80\$ tax, solar consumption reaches to 268.84 PJ in 2045, while under 50\$ tax, it is 46 PJ.

9.2. Transport Sector

Energy consumption in transport sector shows a slight reduction by applying tax values less than 50\$ per ton. As can be seen in Figures 9.3 and 9.4, even under 50\$ tax, there is a small reduction in electricity, diesel and gasoline consumption. Jet fuel oil consumption also decreases slightly in comparison with the base scenario and is substituted by hydrogen that is less carbon intensive.

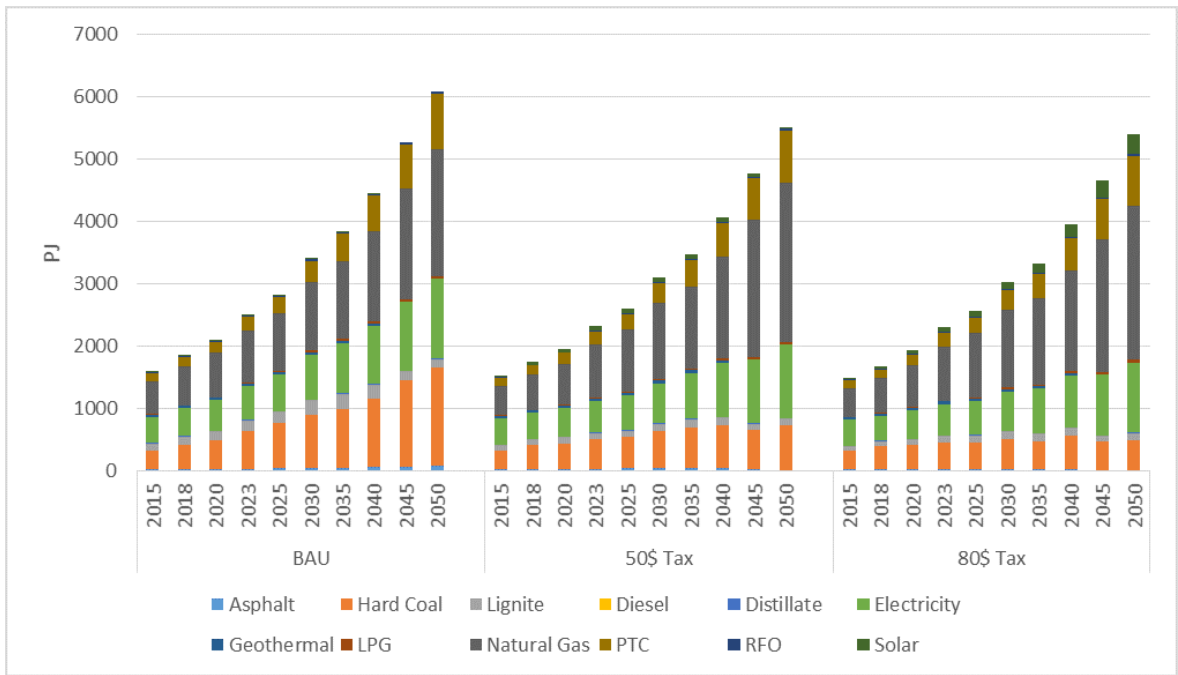


Figure 9.2. Industry Sector Energy Consumption in BAU, 50\$ and 80\$ Tax Scenarios

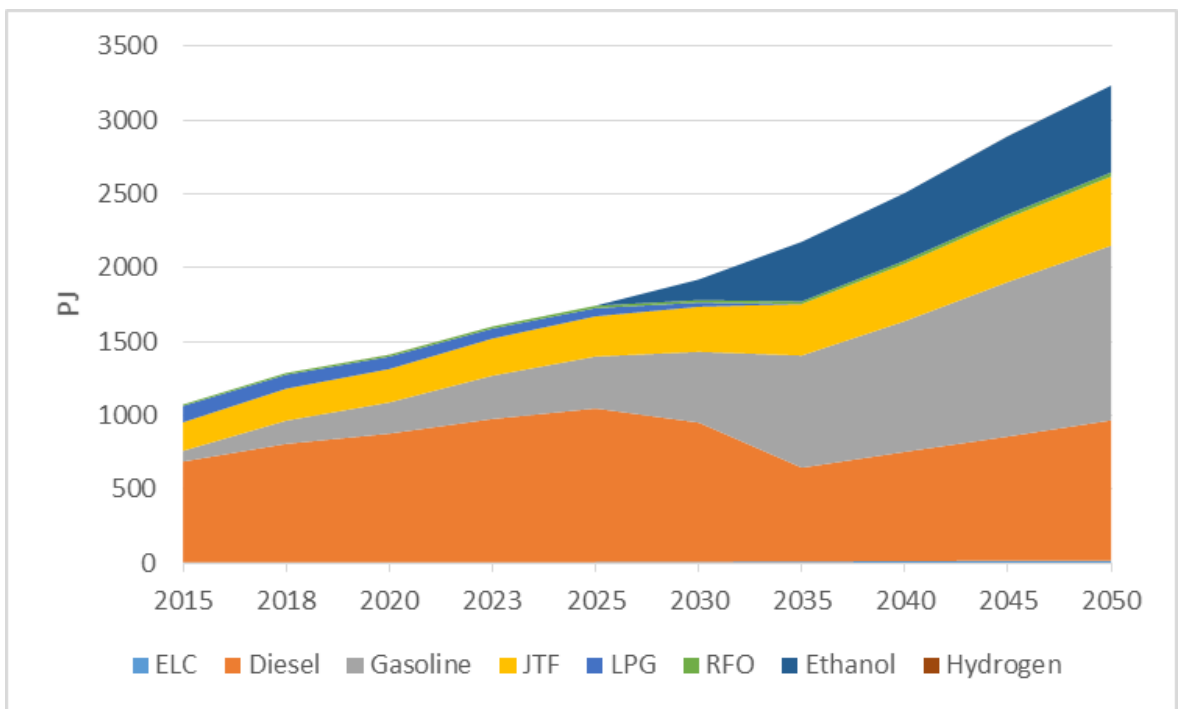


Figure 9.3. Transportation Sector Total Consumption-BAU Scenario

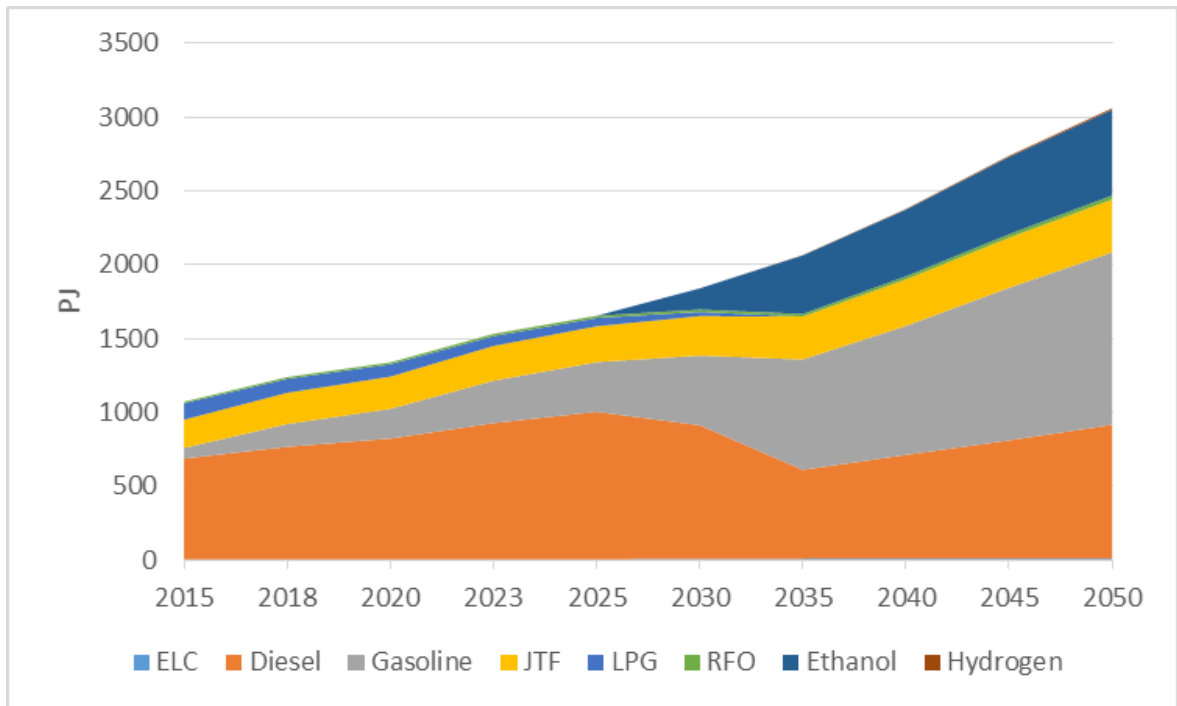


Figure 9.4. Transportation Sector Total Consumption under 50\$ Tax Scenario

9.3. Residential and Commercial Sector

By imposing tax levels less than 50\$ per ton of CO₂ in residential and commercial sector, the consumption levels of coal, electricity, and natural gas, are all predicted to decrease. As can be seen in Figures 9.5 and 9.6, under 50\$ tax, coal consumption levels decrease that is for instance, in the reference case coal consumption is predicted to be 1019.8 PJ in 2035, while in the 50\$ tax scenario, it is predicted to be 905.18 PJ. Natural gas share also drops compared to the reference case, for example, the share of natural gas in the reference case is 31.77% in 2035, while it is 23.96% in the 50\$ tax scenario. There is no change regarding solar energy consumption under 50\$ tax and it is similar to the base scenario, but biomass consumption starts increasing from 2018 until the end of model horizon.

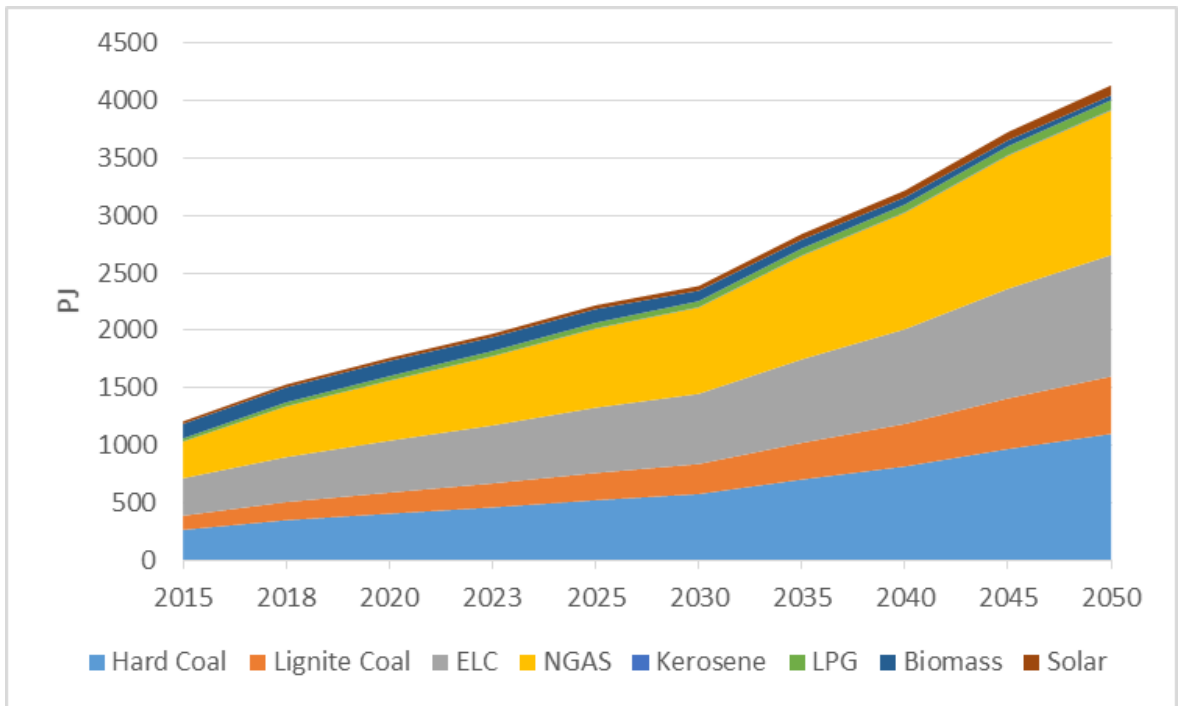


Figure 9.5. Residential and Commercial Energy Consumption-BAU Scenario

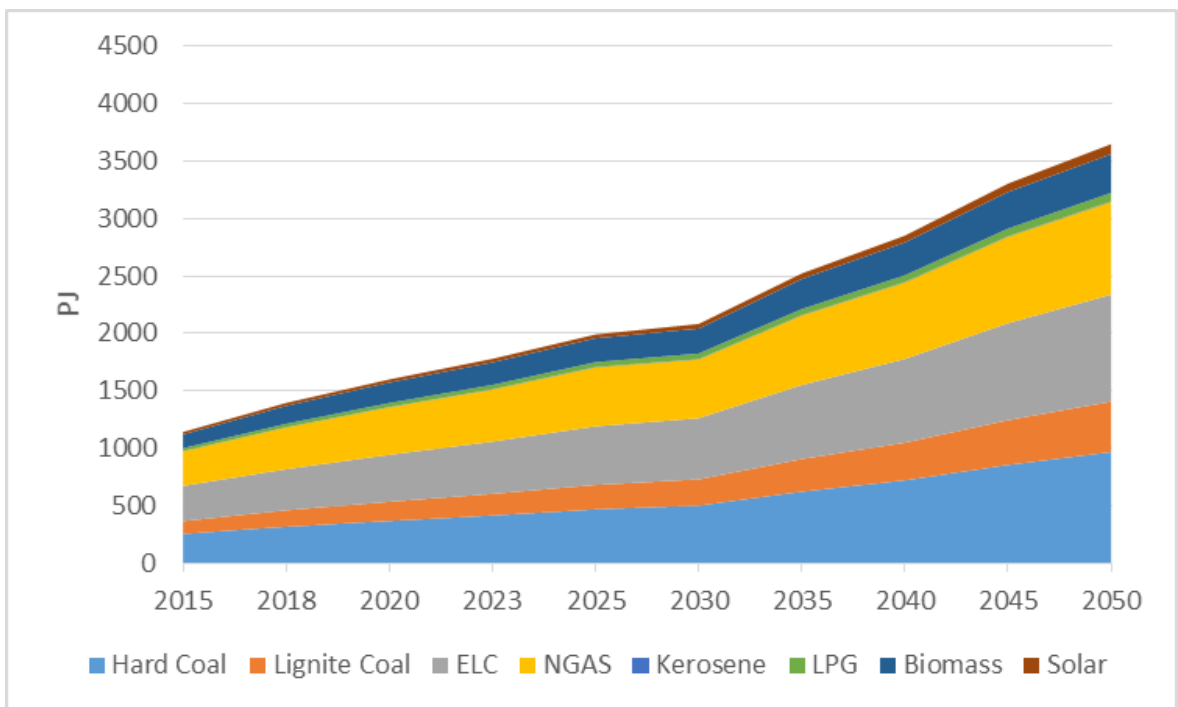


Figure 9.6. Residential and Commercial Energy Consumption-50\$ Tax Scenario

9.4. Electricity Generation

Electricity generation levels decrease under all tax scenarios. Electricity generation is mainly dependent on coal (hard coal and lignite coal), hydroelectric and natural gas. By increasing the variable costs of electricity generated from fossil fuels by imposing tax, there will be incentives inducted to switch to less carbon intensive or zero carbon technologies. By applying 10\$ tax per ton of CO₂, there is no significant decrease in CO₂ emissions. The significant emission reduction starts by applying 20\$ tax per ton. As can be seen in Figures 9.7 and 9.8, under 20\$ tax, electricity generation from lignite coal starts to decline from 2020. In 2020, lignite coal decreases by 20.24% compared to the base scenario, while in 2040, this value drops to 14.55%. Under 20\$ tax, electricity generation from natural gas and hydro also remains the same as the base scenario.

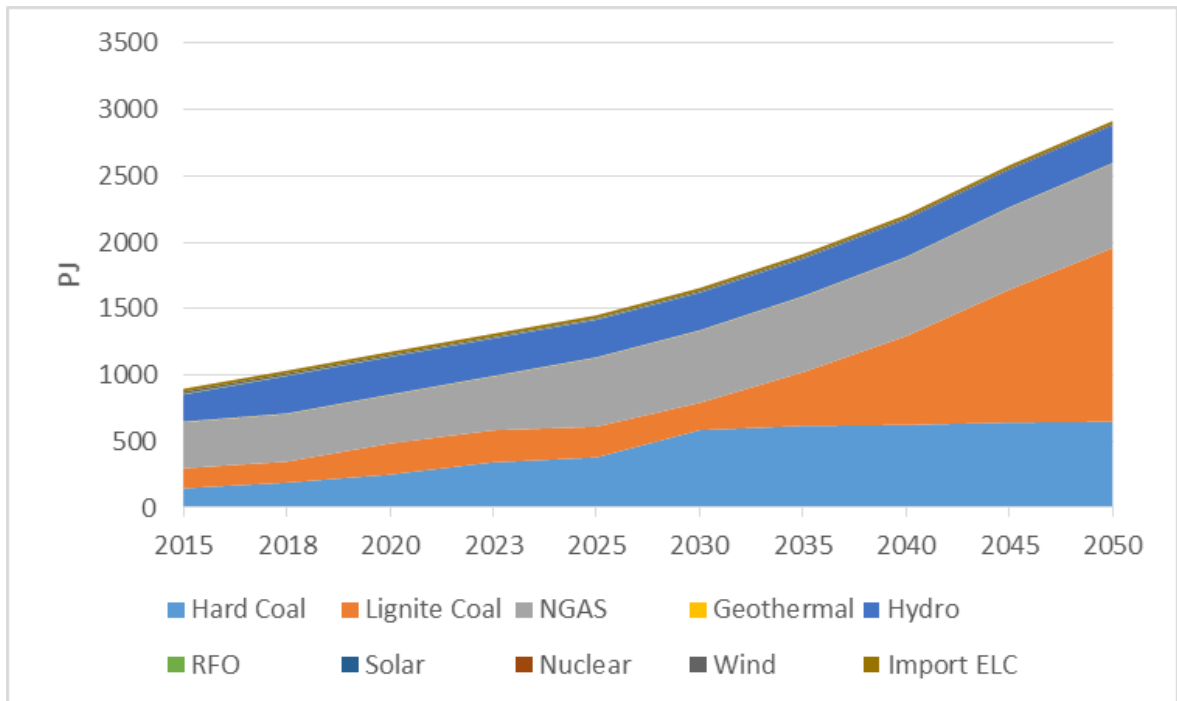


Figure 9.7. Electricity Generation w.r.t. type of resource-BAU Scenario

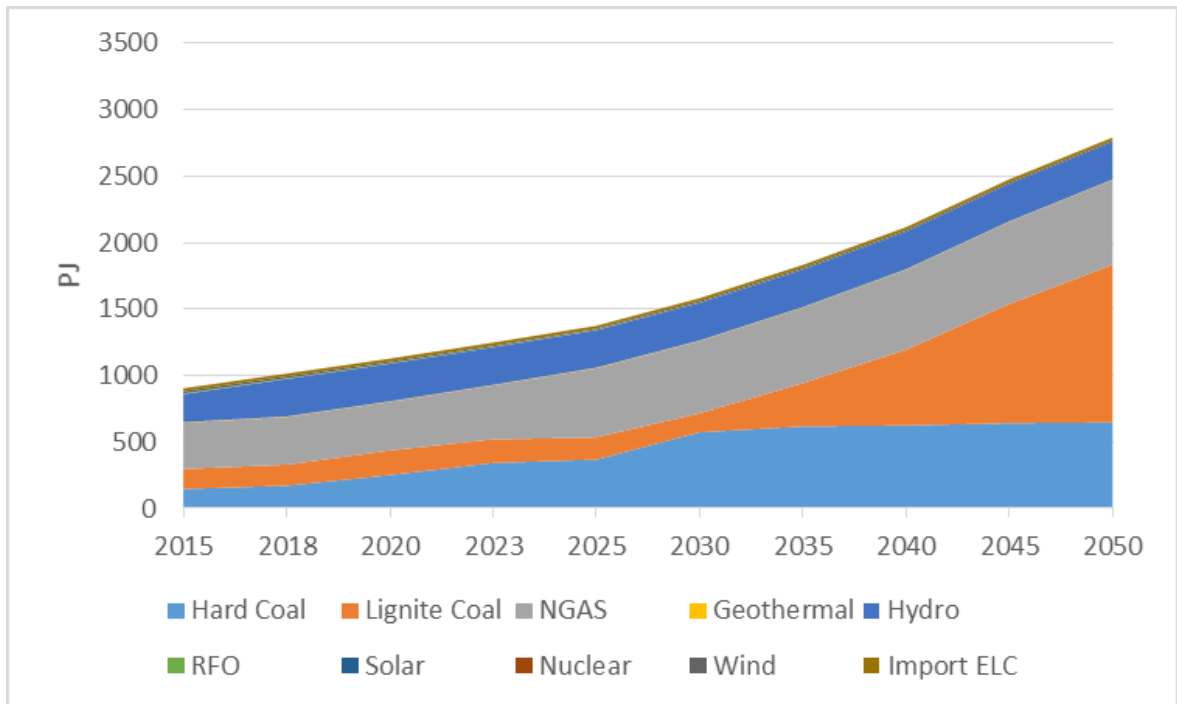


Figure 9.8. Electricity Generation w.r.t. type of resource under 20\$ Tax Scenario

Electricity generation levels under 50\$ tax is shown in Figure 9.9. Under 50\$ tax, electricity generation from hard coal decreases in 2018 (the year which tax is applied) by 9.71% but remains approximately on the same levels of the base scenario after 2018 until the end of the model horizon. Electricity generation from lignite coal also starts to decrease in 2018 by 31.34% compared to the base scenario. All other sources of electricity generation remain unchanged compared to the business as usual scenario.

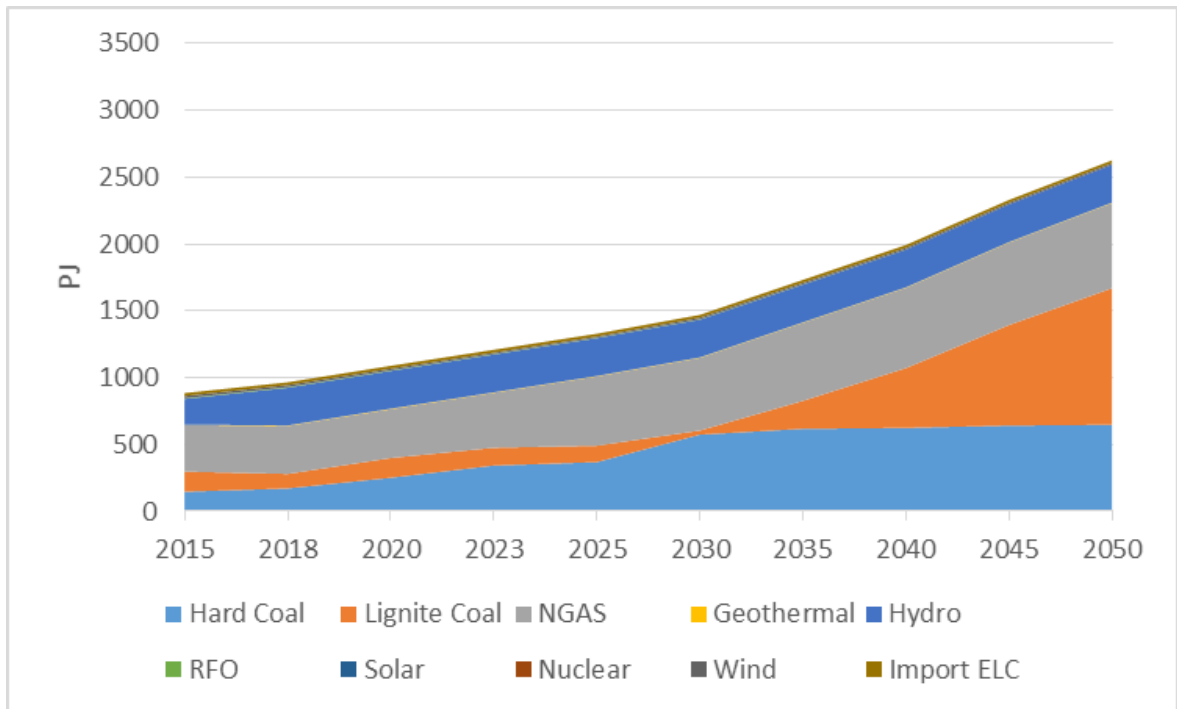


Figure 9.9. Electricity Generation w.r.t. type of resource under 50\$ Tax

9.5. Total Energy Consumption

In all of the four emission tax scenarios, total energy consumption is expected to decrease during the period 2015-2050. As can be seen in Figure 9.10, in the long run there are higher reductions in fuel consumption levels among the tax scenarios compared to the base scenario, due to investments on more efficient technologies and reductions in demand levels.

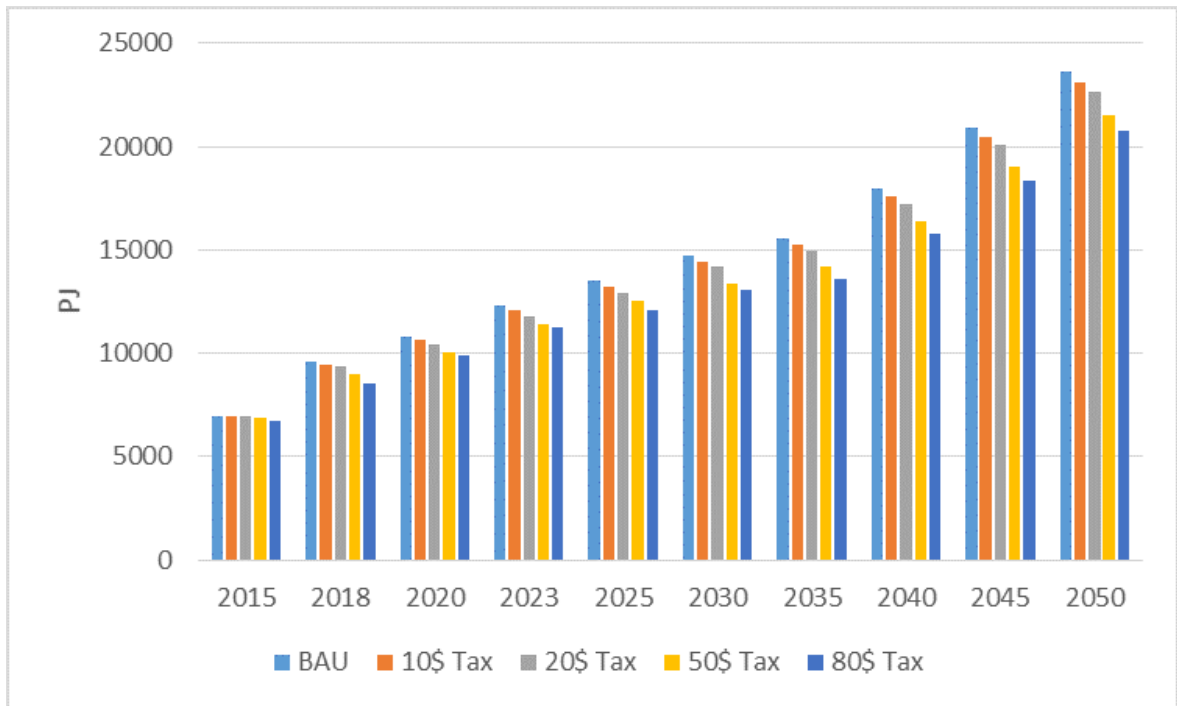


Figure 9.10. Consumption Levels in BAU and Tax Scenarios

9.6. Emissions

CO₂ emission results in the reference case and carbon tax scenarios are presented in this section. As can be seen from Figure 9.11, as the level of applied tax increases, the overall CO₂ emission decreases and the decline in CO₂ emission levels under these scenarios follows the similar pattern that emerges in the base scenario. The decreased levels of demand is the most important cause of emission reductions, along with improved efficiency and using more renewable sources.

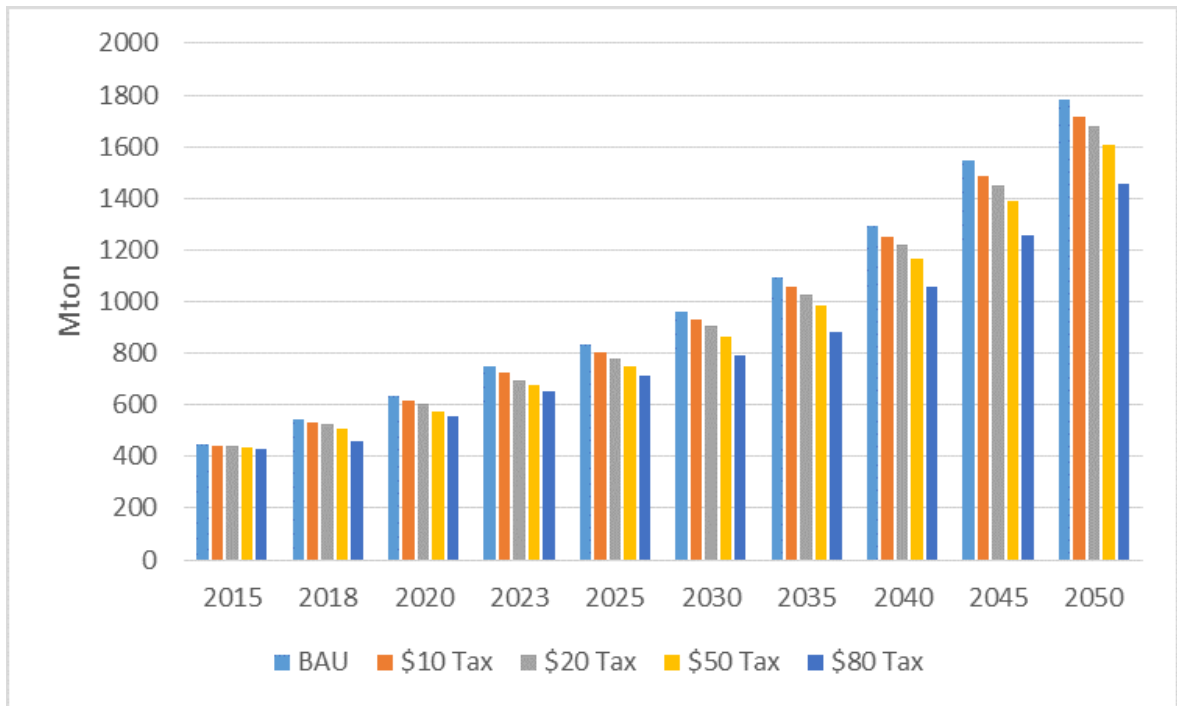


Figure 9.11. Emission Levels predicted in Tax Scenarios (Mton)

9.7. Economic Impacts of Tax Scenarios

Figure 9.12 illustrates the percentage of GDP loss with respect to the base scenario for tax scenarios. As mentioned, taxes are introduced in 2018 in all scenarios. GDP starts to decline from 2020 in each scenario. As can be seen in Figure 9.12, GDP loss rate increases as the tax level goes up. The rate of GDP loss relative to the base scenario starts increasing from 2020 and, hits the lowest rate in 2023 and reaches the highest in 2025 and then decreases. GDP losses are greater when higher constraints are applied across the planning trajectory. In 50\$ tax scenario, GDP losses are between 0.36% and 0.82% except for the periods that have high resource costs and constraints on capacity levels of technologies, where losses are 1.47% in 2025 and 0.91% in 2035.

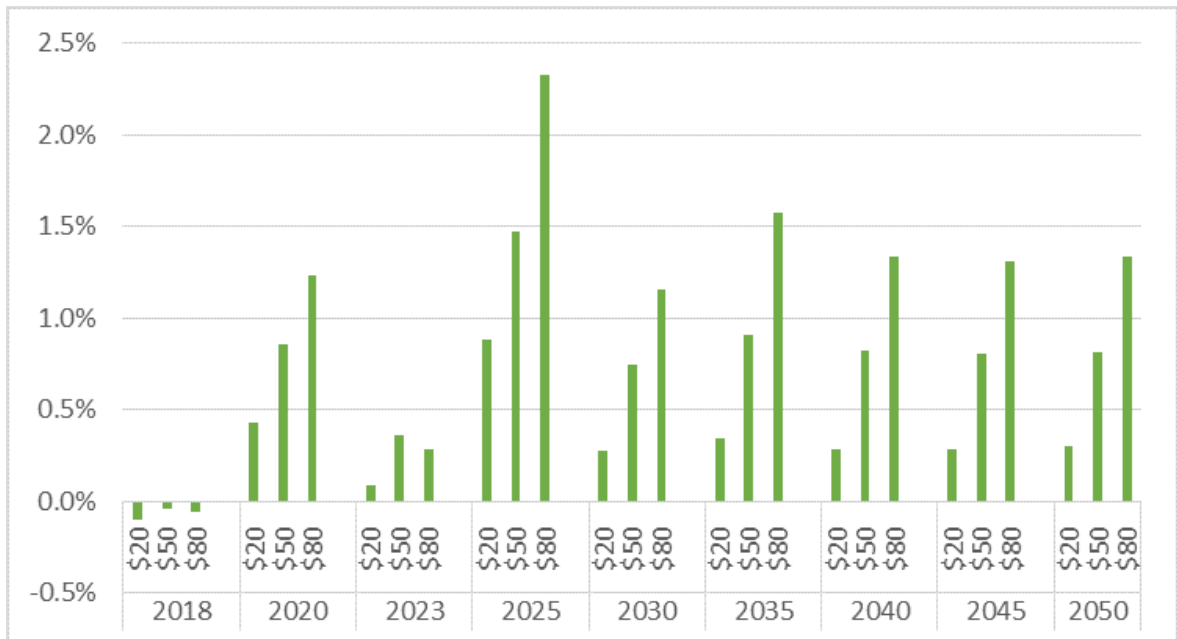


Figure 9.12. Percentage GDP Loss w.r.t BAU in Tax Scenarios

9.8. Emission Bound Scenarios and Emission Tax Scenarios

By comparing the results from emission bound scenarios and emission tax scenarios, we can observe that all scenarios decrease energy consumption levels and improve energy efficiency and also it can be seen that emission bound scenarios are more effective than tax scenarios, for instance, as can be seen in Figure 9.13, in 2030 the 21% bound scenario results in 9.56% reduction while the 20\$ tax results in 3.62% reduction and 50\$ tax, reduces total consumption by 8.93%. Share of renewable sources in 80\$ tax scenario reaches the highest share in 2035 (13%), while under 21% emission bound, renewable share is 21% in 2035, which can indicate that under tax scenarios, the optimization process prefers to shrink demand growth in order to pay less for taxes, instead of investing in renewable sources.

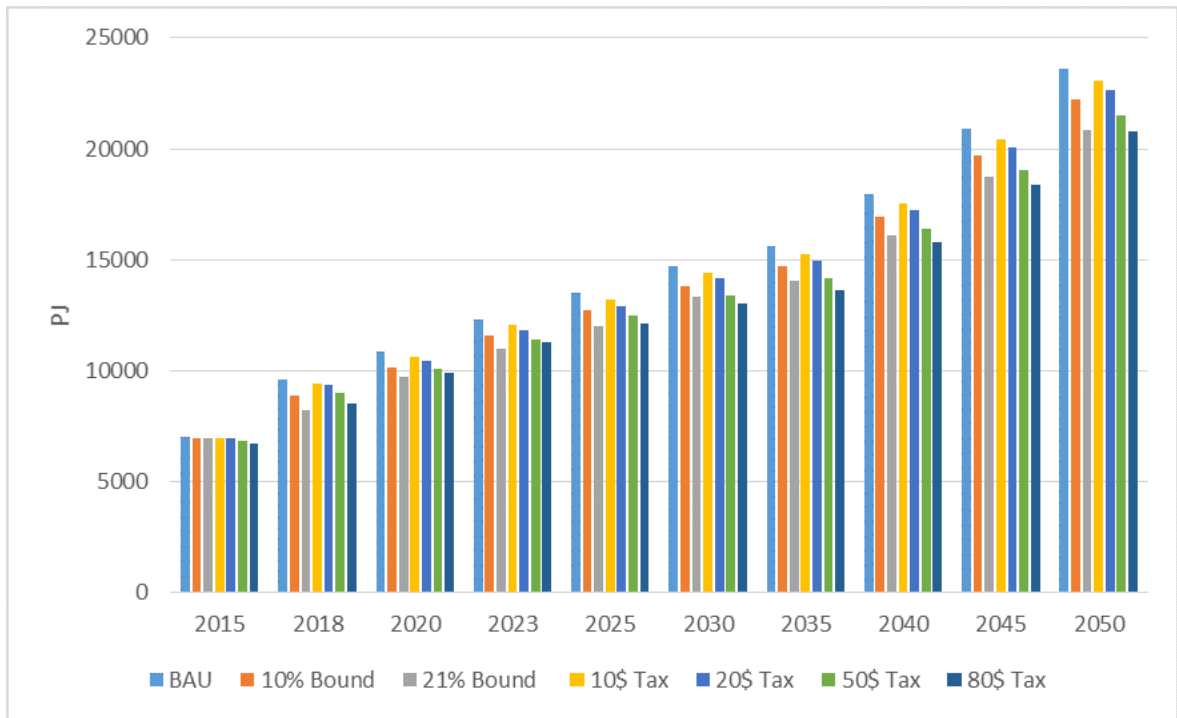


Figure 9.13. Consumption Levels in both Emission Bound and Emission Tax Scenarios

As depicted in Figure 9.14, electricity generation levels of emission restriction scenarios are lower than tax scenarios. Under tax scenarios, electricity generation from coal is reduced. However, the reduction amount is less than the emission restriction scenarios. For instance, 21% reduction has approximately the same electricity generation levels as 80\$ tax, although, 80\$ tax produces almost the same generation levels by using more coal, that is another indication that emission bound scenarios are more effective than tax scenarios.

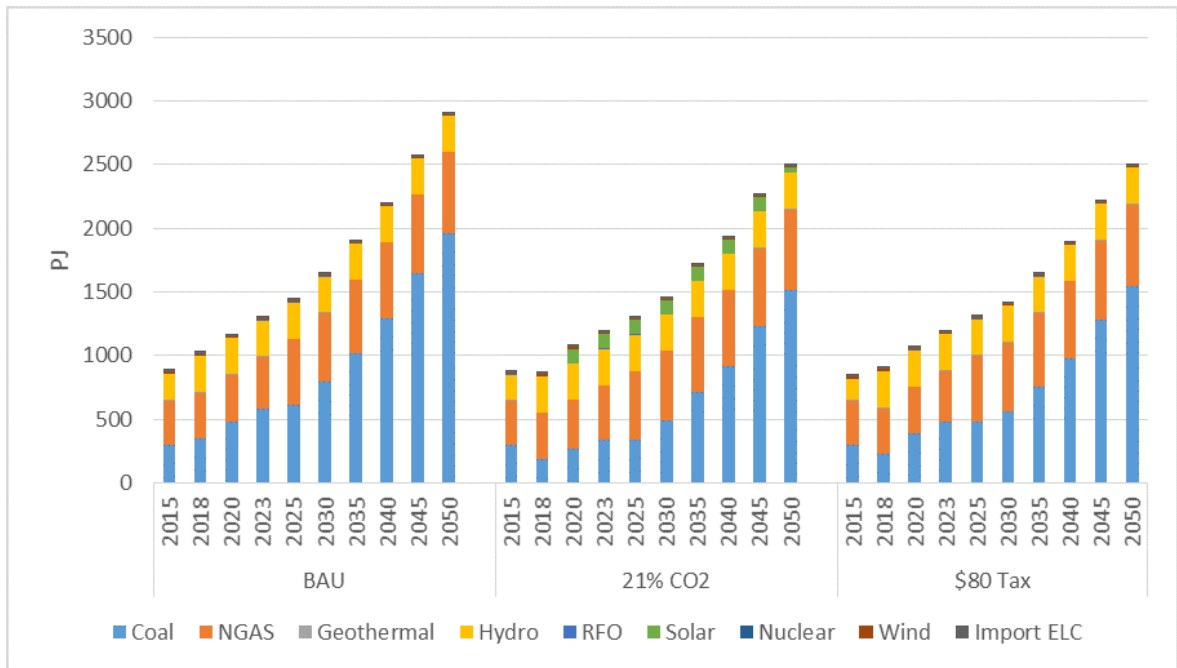


Figure 9.14. Electricity generation levels in Emission Bound Scenarios and tax Scenarios

9.9. Policy Scenarios

The Akkuyu nuclear power plant will be Turkey's first nuclear power plant that is under construction. It will be including four 1200 MW units, and the first unit is anticipated to become operating in 2023. The other units are predicted to be finalized in 2025. Thus, in Akkuyu scenario, in order to analyze the impacts of this nuclear power plant, it has been assumed a total installed capacity of 1200 MW for 2023, followed by 4800 MW for each year after 2025.

9.9.1. The Akkuyu Nuclear Power Plant and 21% Emission Bound

Another scenario is implemented by introducing the Akkuyu nuclear power plant as mentioned before in the previous section and limiting the carbon emissions at 21% lower than the BAU scenario at the same time. As can be seen in Figure 9.15, total energy consumption decreases compared to the base scenario. In 2018, there is a 14.16%

reduction in total fuel consumption compared to the base scenario. The reduction in total consumption continues until the end of model horizon but with a lower rate, for example in 2050, the reduction rate is 10.37% (compared to the base scenario).

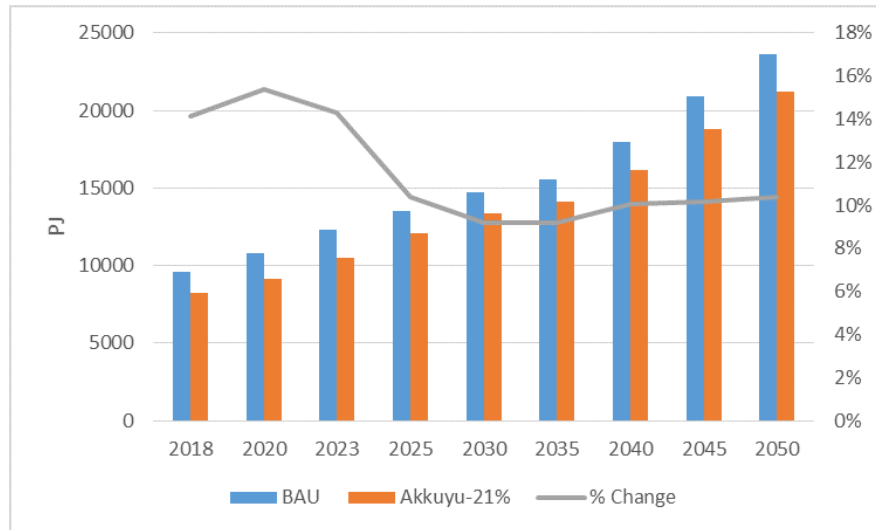


Figure 9.15. Consumption Levels and Percent Changes in BAU and Akkuyu-21% Scenario

As illustrated in Table 9.1, by limiting the emissions from 2018, the realized GDP starts decreasing from 2018 that indicates economy shrinkage. As a result, energy demand and thus energy consumption both decrease. Another reason for reductions in total consumption is using more efficient technologies.

Table 9.1. Actualized GDP in BAU and Akkuyu-21 Scenarios.

2012\$USb	2015	2018	2020	2023	2025	2030	2035	2040	2045	2050
BAU	934.5	1030	1122.5	1269	1381.5	1697	2074	2512	2997	3543
Ak21%	939.1	1024	1090.9	1260	1344.9	1677	2051	2486	2967	3505

As can be seen from Figure 9.16, the energy intensity in 21% emission bound scenario is the lowest one (except in the 2020-2023 period) and is almost the same

with intensity levels in the Akkuyu-21% scenario. In 2020, both total energy supply and realized GDP are lower in Akkuyu-21% scenario compared to the 21% bound scenario and since, the reduction rate in total supply level is greater than the rate at which GDP has decreased, energy intensity also decreases. In 2023, total supply level in Akkuyu-21% scenario is lower and GDP is higher than 21% bound scenario that directly indicates intensity decline and efficiency improvement in this year. After 2023 (the year in which nuclear power plant is introduced), energy intensity in 21% emission bound scenario starts to be lower than Akkuyu-21% scenario, which indicates this emission bound scenario without nuclear power plant is more efficient.

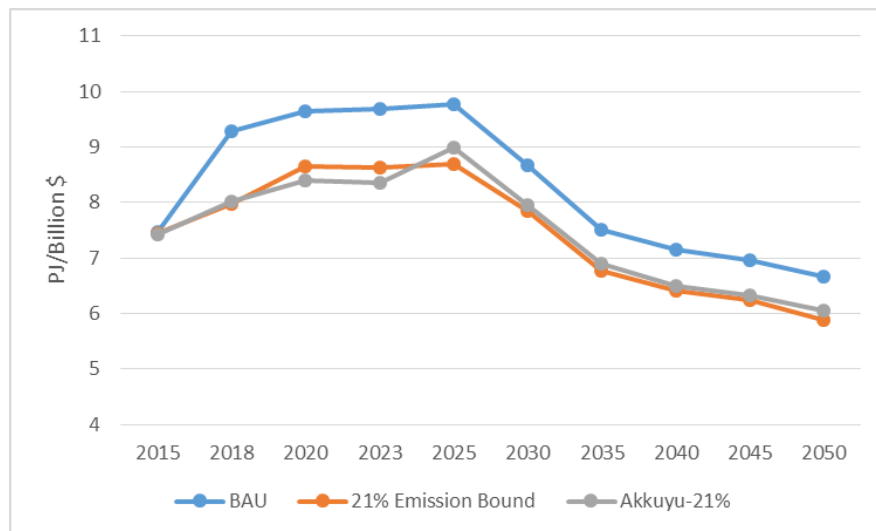


Figure 9.16. Predicted Energy Intensity for BAU, 21% Emission Bound, and Akkuyu 21% Scenarios.

9.9.2. Electricity Generation

Emission constraint rises the cost of fossil fuels in the end-use technologies and as a result of this price increase, fossil fuels are replaced by electricity, which results in a higher use of electricity to replace fossil fuels and thus higher production of electricity from non-fossil fuels in the Akkuyu-21% scenario (can be seen in Figure 9.17). As depicted in Figure 9.17 Electricity generation starts decreasing from 2018, due to using more efficient technologies and also the shrinkage in the economy. The 21% emission

bound scenario generates more electricity in the 2020-2023 period compared to the Akkuyu-21% scenario, since investments are being made on solar PVs in 2020. After 2025, electricity generation gets higher in Akkuyu-21%, because new nuclear capacity will be added in 2025. The electricity that is generated from coal is replaced by solar and nuclear in the emission bound and the policy scenario, respectively. The share of renewable sources jump to 34.4% and 34.46% in the 21% bound scenario and the Akkuyu-21% scenario, respectively, while renewable share was 24.5% in 2015. Then, although the renewable energy sources do not reach their maximum capacity, the share of renewable sources decrease throughout the model horizon, which can be an indicator that using renewable energy sources is forced by the model.

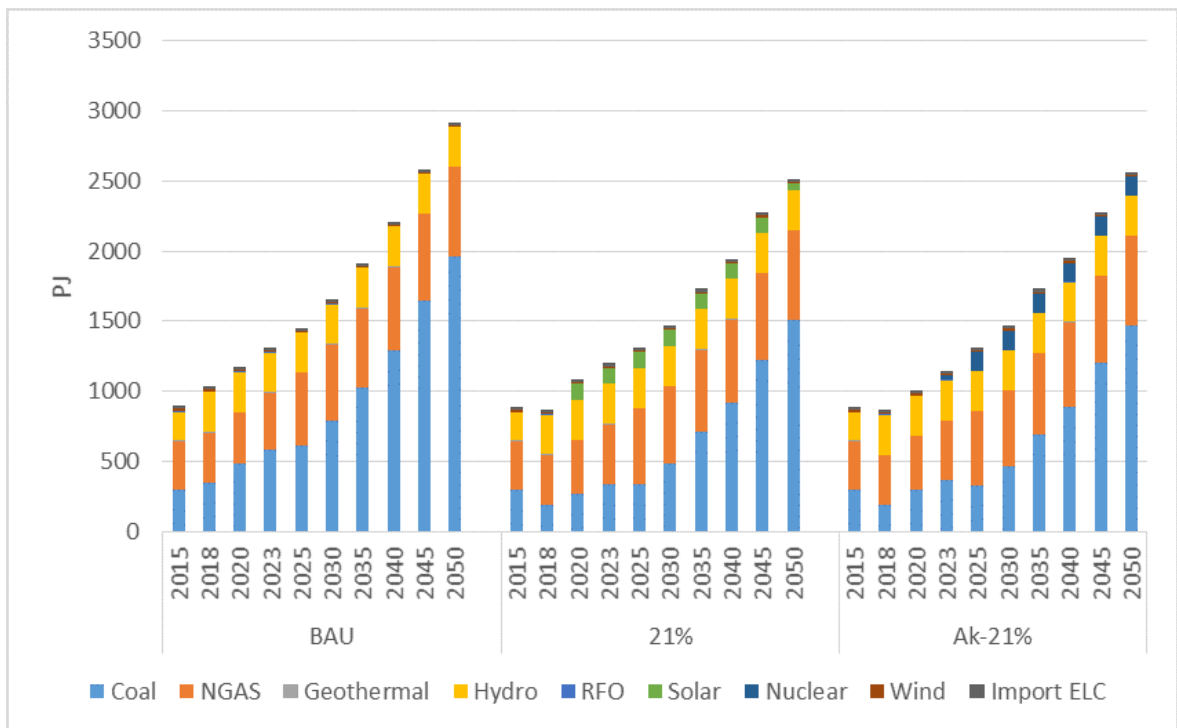


Figure 9.17. Electricity Generation Levels in BAU, 21% Bound, and Akkuyu-21% Scenarios

9.9.3. Abatement Cost

Abatement Costs in 21% Bound and Akkuyu-21% Scenarios are illustrated in Figure 9.18. Comparing 21% emission bound scenario with the scenario in which the same emission bound is applied while the nuclear power is available at the same time, it can be concluded that in both cases, the total energy system cost declines by limiting the CO₂ emissions. Between these two scenarios, total undiscounted system costs are higher in 21% emission bound scenario. The reason is that investing on technologies that use renewable energy sources is expensive and that higher levels of capacity of renewable technologies should be installed. The abatement costs are higher in the 21% emission bound scenario compared to the other scenario. The reason is that although investment cost of new capacity per GW is higher for nuclear power plants (in Akkuyu-21% scenario) compared to the solar PVs (in 21% emission bound scenario), the nuclear installed capacity level is lower than the forecasted installed capacity of solar power.

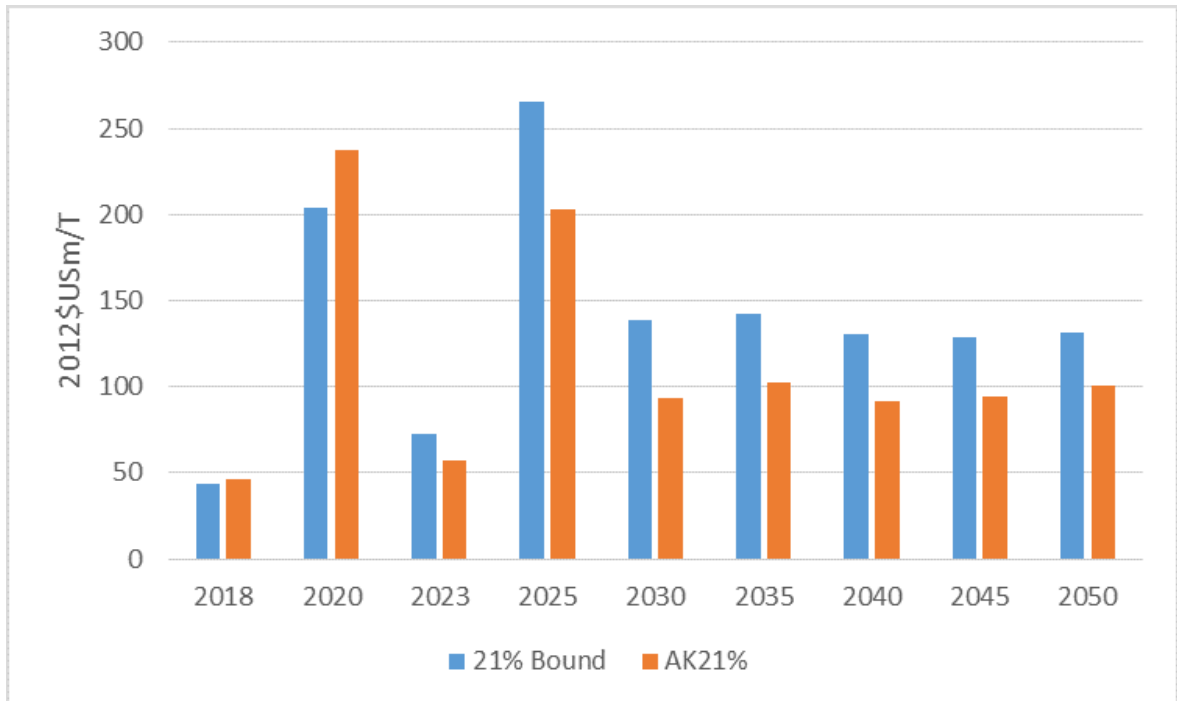


Figure 9.18. Abatement Costs in 21% Bound and Akkuyu-21% Scenarios

10. SENSITIVITY ANALYSIS

A sensitivity analysis is carried out as a result of the uncertainty coming from the MACRO model parameters. The same policy scenarios have been analyzed by changing the value of the elasticity of substitution (ESUB) from 0.25 (the main calibration has been done with this value) to ESUB=0.13 (the least possible value that the model was responsive to). By changing the value of ESUB, the calibration procedure has been carried out this time with the new ESUB=0.13 and then every policy scenario was run with the new calibrated model.

In addition, another sensitivity has been examined to analyze changes in main assumptions that is considering higher energy prices. This additional scenario has been implemented to evaluate the impacts of higher energy prices.

10.1. Sensitivity of Model Results to the Elasticity of Substitution

As has been mentioned before, the elasticity of substitution is defined as $\frac{\partial \ln\left(\frac{A_{KL}}{E}\right)}{\partial \ln\left(\frac{P_{KL}}{P_E}\right)}$, that is, if ESUB=0.25, a 1% change in the relative ratio between the capital-labor aggregate and the energy aggregate, will require a 4% change in the relative proportion of prices. Now that this value has dropped to ESUB=0.13, it means that a 1% change in the ratio between the capital-labor aggregate and the energy aggregate, needs a relative price change of approximately 7.69%, so by reducing the value of ESUB from 0.25 to 0.13, it has been made harder to substitute the energy aggregate by the capital-labor aggregate. ESUB can be interpreted differently in another way: the value of ESUB measures the extent of availability of technologies, in other words, it can be seen as a list of alternative options that are available. Thus, the higher the value of ESUB, the higher are the alternatives for producing the given amount of output with various combinations of production factors (capital, labor and energy).

As can be seen from Table 10.1, emission abatement cost (relative tax) is sensitive to ESUB, while energy consumption and GDP are less sensitive and has changed at

lower rates. By examining the results, it can be seen that the values of the realized GDP is lower when $ESUB=0.13$, in other words, the growth has been reduced. This is due to the fact that by reducing the value of $ESUB$, it will be more difficult to substitute energy by capital and labor.

Table 10.1. Sensitivity Analysis on $ESUB$.

Energy Consumption -PJ					
2023		2035		2050	
$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$
10958.4	11356.7	14059.7	14306.1	20851.3	21145.3
GDP(2012 US Billion \$)					
2023		2035		2050	
$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$
1259.4	1251.1	2044.7	2033.7	3499.5	3474.9
%GDP Loss (compared to the Baseline)					
2023		2035		2050	
$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$
0.8347	1.4846	1.4456	1.9766	1.2429	1.9338
Marginal Abatement Cost-Tax(2012\$Usm/T)					
2023		2030		2050	
$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$	$\sigma=0.25$	$\sigma=0.13$
193.1	255.1	79.8	90.5	100.6	135.6

The response of the model by reducing the elasticity of substitution is illustrated in Figure 10.1. As mentioned before TIMES-MACRO computes a general equilibrium, so in the base scenario, the model has reached an equilibrium with the associated

demand curve. By defining an emission constraint, the cost of supplying energy increases and the equilibrium shifts to a lower level of demand with a higher price. It is assumed that the amount of tax (marginal abatement cost) that corresponds to this shifted equilibrium is E_1 . By decreasing the value of ESUB to 0.13, the demand curve becomes steeper (high price changes hardly influence the quantity demanded) and the equilibrium moves to E_3 which corresponds to an increase in the amount of tax and also leads to an increase in energy consumption.

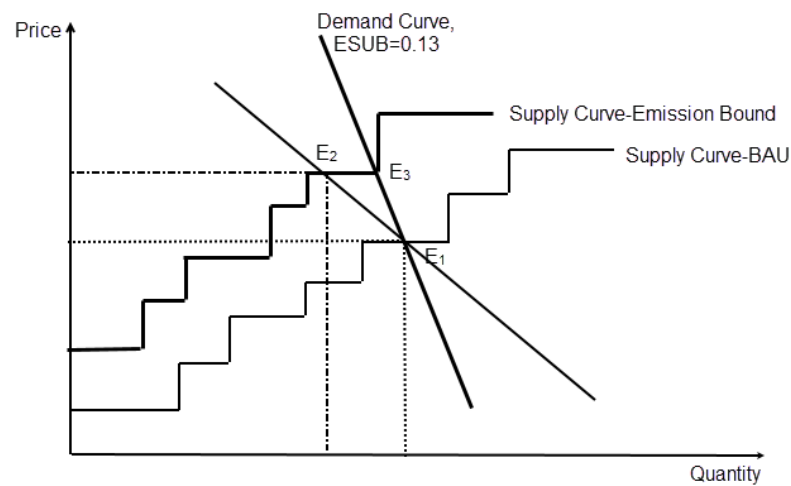


Figure 10.1. Model Response in ESUB Reduction

10.2. Sensitivity of Model Results to Resource Prices

The model runs that have been developed in this chapter, examine 21% emission reductions throughout the model horizon. This sensitivity has been examined to analyze changes in main assumptions that is considering higher energy prices. This additional scenario has been implemented to evaluate the impacts of higher energy prices.

The names and description of model runs are shown in 10.2.

Table 10.2. Model runs and descriptions.

Name	Description
21% Bound	21% emission bound by 2050
21% Bound-HP	As for 21% bound scenario, except higher resource prices have been assumed.

Figure 10.2 compares energy consumption levels in 21% bound scenario and 21% bound-HP scenario that has higher resource costs. In 21% bound-HP scenario, that energy resource costs are doubled in the base case in TIMES, consumption levels are less than 21% bound scenario, where energy demand is lower as a result of higher resource costs. The higher resource price scenario (21% Bound-HP) has lower consumption levels compared to the other case (21% Bound), as expected, since the higher resource prices triggers the response from end-use demands and lowers the level of consumption.

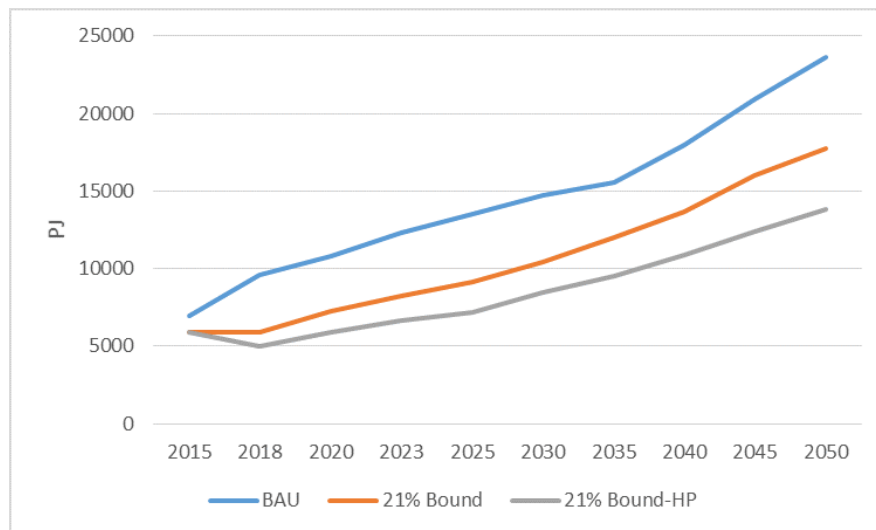


Figure 10.2. Energy Consumption Levels in BAU, 21% Bound and 21% Bound-HP Scenarios

Figure 10.3 illustrates the impact of higher resource costs on the electricity generation sector. High resource price scenario (21% Bound-HP), further cuts base case electricity generation by an overall shift to using more efficient technologies and also as a result of demand response, reflecting higher energy costs.

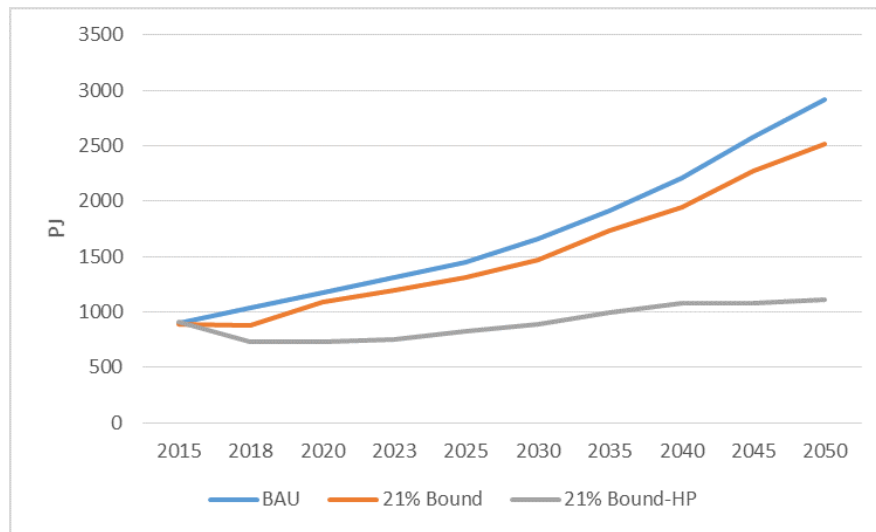


Figure 10.3. Electricity Generation Levels in BAU, 21% Bound and 21% Bound-HP Scenarios

Figure 10.4 illustrates marginal abatement costs in 21% emission bound scenarios and the scenario in which the same emission bound is applied along with assuming higher energy prices compared to the prior scenario. As can be seen in the figure, the 21% Bound-HP scenario in which higher resource prices are assumed, has higher abatement costs.

As can be seen in Figure 10.5, in the 21% emission bound scenario, GDP losses are between 0.44% (the minimum percentage loss) and 3.01%(the maximum percentage GDP loss) except for the high resource price scenario, where GDP losses increase and are between 1.2% and 6.74% respectively, which is expected.

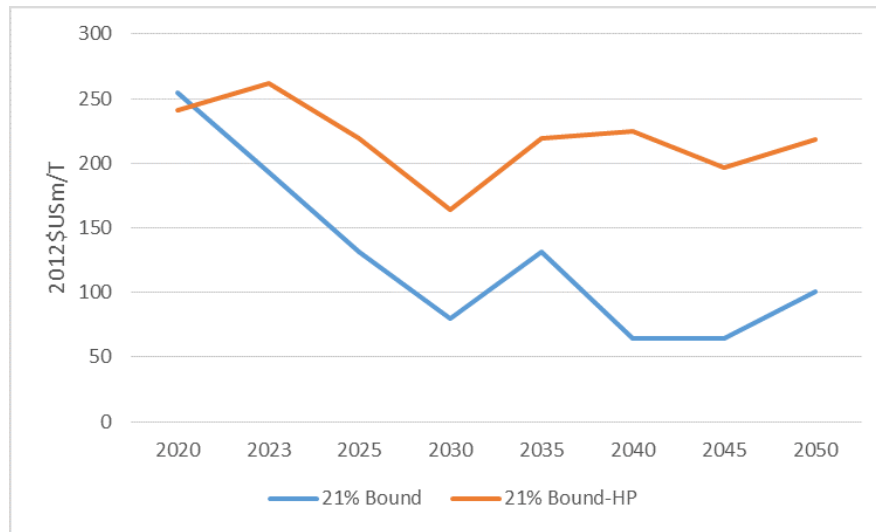


Figure 10.4. Marginal Abatement Costs in 21% Bound and 21% Bound-HP Scenario

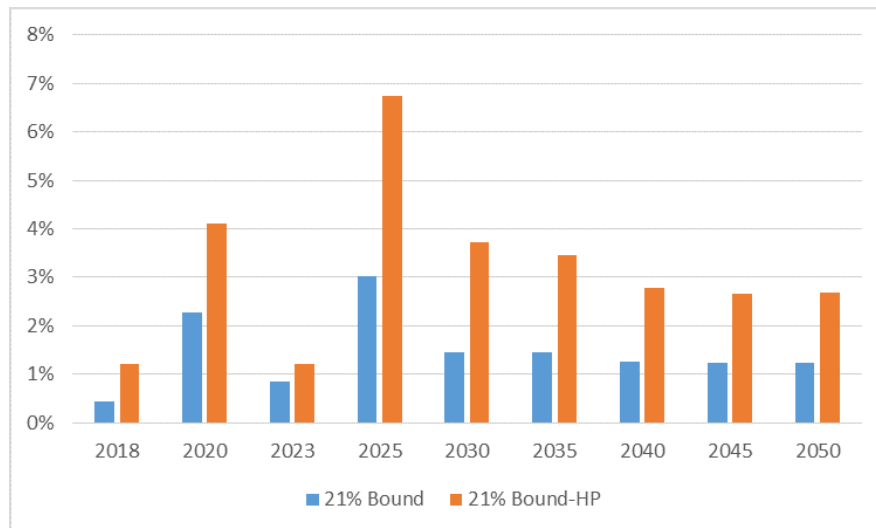


Figure 10.5. Percentage GDP Loss compared to Baseline in 21% Bound and 21% Bound-HP Scenarios

11. CONCLUSION

When significant emission reductions are needed, which is the case in Turkey, energy demand and energy price are essential factors in cutting down emissions and the abatement costs on the national levels are estimated to reach a considerable level such that could be measured as a ratio of GDP. Since there are no interactions between the energy system and the rest of the economy in TIMES, and useful energy demands are exogenous parameters and not responsive to price changes, and economic impacts are not estimated in this modeling framework, the TIMES-MACRO modeling framework, which overcomes all these shortcomings, has been considered in this thesis to study the economic impacts of emission abatements in Turkey in a more comprehensive way. By introducing the same emission reductions in both models, energy consumption levels are lower in TIMES-MACRO than in stand-alone TIMES. The reason is that by applying an emission constraint in TIMES-MACRO, the model responds by reducing GDP and also by reducing useful energy demands per unit GDP, which is caused by the substituting energy with capital and labor.

In this thesis, the macroeconomic impacts of restricting CO₂ emissions under different scenarios have been evaluated. In order to control emissions either by introducing emission constraints or applying emission taxes, there will be considerable costs, although it becomes obvious that these costs can be lowered in both the supply and demand sides of the energy sector. Based on the obtained results, the potential improvements are capable of reducing the costs of emission constraints. The TIMES-MACRO modelling framework that has been employed in this study, has been calibrated to represent the whole energy system of Turkey along with its interactions with the entire economy in an optimization framework which makes choices based on a system-wide infrastructure. More specifically, it measures the advantages of each option by considering the characteristics of technologies, fuel costs, supply and conversion costs, alternative technologies and demand sectors, and effects on the environment and the macroeconomy. In this modelling framework, different technologies are evaluated and sorted corresponding to their cost, efficiency and environmental advantages. As

a result, in the absence of environmental constraints, the model prefers to use coal as the dominant fuel which is the cheapest primary energy source in Turkey. Another reason for dominance of coal is that even by making renewable sources attractive through various scenario definitions, most of them reach their economic potentials and cannot compete with cheap coal. However, in electricity generation, despite the fact that hydropower has a low unit production cost, it cannot compete with coal-fueled power plants because of its limited technical potential. Another important issue is the availability level of different technologies. Based on the limited availability and also high investment costs of solar, wind and geothermal sources, these energy sources are not able to cut down the demand for coal to reasonable levels. Natural gas starts to compete with coal in the supply combination and maintains its share in the medium term, but because of its high price compared to coal, it tends to decrease in the long run. Scenarios that are run under the MACRO module, determine energy demands endogenously based on the energy prices. Therefore, in these scenarios, demand levels are reduced. By comparing emission cap scenarios with emission tax ones, it is found that an emission cap is more effective than emission taxation. Total energy supply levels are lower in the emission reduction scenarios which indicates investment into more efficient technologies. The abatement cost of emission reduction, in terms of GDP loss, is found to be in the range of 45-265 \$/ton CO₂ while high costs are observed to occur in early periods and stabilize in the long run at about 100 \$/ton for 10% reduction and 130 \$/ton for 21% reduction. In tax scenarios, the GDP loss remains below 2% with similar behavior as observed in emission bound scenarios. The abatement costs in terms of GDP loss of taxation is found to be less than 100 \$/ton CO₂ in the long run for tax rates up to 20 \$/ton CO₂. The 80\$ tax scenario, which produces emissions similar to the 21% reduction scenario, implies a cost of up to 275 \$/ton CO₂ being ranged 10-15 \$/ton more expensive than the bound scenarios. As such, the cap-and-trade policy option appears to be a more rational choice for emission reduction in Turkey when compared to taxation.

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