MIT JOINT PROGRAM
SCIENCE
POLICY
GLOBAL CHANGE

Report 332
July 2018

Turkish Energy Sector Development and the Paris Agreement Goals: A CGE Model Assessment

Bora Kat, Sergey Paltsev and Mei Yuan

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/

Turkish Energy Sector Development and the Paris Agreement Goals: A CGE Model Assessment

Bora Kat[1,2,3,4], Sergey Paltsev[1], Mei Yuan[1]

Abstract: In the 2015 Paris Agreement, Turkey pledged to reduce greenhouse gas (GHG) emissions by 21% by 2030 relative to business-as-usual (BAU). However, Turkey currently relies heavily on imported energy and fossil-intensive power generation. Despite significant wind and solar energy potential, only 5.1% of its total power is generated by wind and solar installations; additionally, although two nuclear power stations are planned, no nuclear capacity currently exists. We expect that fulfilling Turkey's Paris Agreement pledge will likely require a reduced reliance on fossil-based energy and additional investments in low-carbon energy sources, which may impact Turkey's GDP, energy use, and electricity generation profiles. To fully assess these impacts, we develop a computable general equilibrium (CGE) model of the Turkish economy that combines macroeconomic representation of non-electric sectors with a detailed representation of the electricity sector. We analyze several scenarios to assess the impact of an emission trading scheme in Turkey: one including the planned nuclear development and a renewable subsidy scheme (BAU), and in the other with no nuclear technology allowed (NoN). Our assessment shows that in 2030, without policy, primary energy will be mainly oil, natural gas and coal. Under an emission trading scheme, however, coal-fired power generation vanishes by 2030 in both BAU and NoN due to the high cost of carbon. With nuclear (BAU), GHG emissions are 3.1% lower than NoN due to the resulting energy mix, allowing for a lower carbon price ($50/tCO_2$ in BAU compared to $70/tCO_2$ in NoN). Our results suggest that fulfillment of Turkey's Paris Agreement pledge may be possible at a modest economic cost of about 0.8–1% by 2030.

1 Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, United States
2 The Scientific and Technological Research Council of Turkey (TÜBİTAK), Ankara, Turkey
3 Graduate School of Natural and Applied Sciences, Earth System Science, Middle East Technical University, Ankara, Turkey
4 Corresponding author. E-mail address: borakat@gmail.com (Bora Kat)

1. Introduction

For several decades, Turkey has acknowledged the importance of preventing dangerous anthropogenic interference with the climate system. In 1992, the country joined the United Nations Framework Convention on Climate Change (UNFCCC), but refrained from signing the UNFCCC for a long time due to obligations related to emission reductions and financial support to developing countries. Meanwhile, however, Turkey took several important actions to align with global climate policies. After 2012, a significant change has been observed in Turkey's attitude towards global efforts against climate change. Declaration of intention to become a party to the new agreement with a flexible target at COP19 in 2013 and at United Nations Climate Change Leaders' Summit in New York in 2014 were remarkable signs of this change. The history of climate change milestones in Turkey between the years 1992–2010 is summarized in **Figure 1**.

The Paris Agreement, a UN treaty adopted in 2015 and ratified by a majority of the world nations, aims at mitigating greenhouse gas (GHG) emissions to reduce risks and impacts of climate change. Each participating country determines its own contribution to GHG reductions over a certain period of time, with the first round of contributions currently covering the pledges for the period 2020–2030. Turkey prepared and submitted its Intended Nationally Determined Contribution (INDC) in 2016 (UNFCCC, 2016) after COP21 in Paris in 2015. Major measurable highlights in Turkey's INDC, which sets targets for the year 2030, are summarized below:

- Up to 21% reduction in GHG emissions compared to the business-as-usual (BAU) scenario of the government. This decrease corresponds to have a CO_2 equivalent (CO_2e) emission level of 929 million tonnes (Mt) in 2030.
- Installed capacity of 10 gigawatts (GW) solar power and 16 GW wind power.
- Full utilization of hydro plants which sums up to 36 GW.

It should be noted that these targets assume an optimistic view about future economic growth in Turkey and the resulting emissions in the BAU projections. Specifically, a 21% reduction in GHG emissions relative to the Turkish Ministry's BAU results in an emission level twice as the 2013 level. In fact, this target indicates a 40% increase in average emission growth rate in 2010–2030 compared to the 1990–2010 average (TUSIAD, 2016).

To assess the impacts of Turkey's contribution on its GDP, electricity generation profiles, and the resulting carbon prices, we developed a computable general equilibrium (CGE) model of Turkey with a detailed representation of power generation technologies.

Among many CGE models developed for assessing the impacts of various policy applications on Turkish economy, only a few of them focused on environmental policies. Kumbaroğlu (2003), Telli *et al.* (2008), Yeldan & Voyvoda (2015) and Akın Olçum & Yeldan (2013) employed an aggregated power sector representation, thus did not fully capture technological details or accurately represent abatement potential from the sector. Kat (2011) constructed a hybrid optimization model with detailed representation of the power sector and five non-electricity sectors of the Turkish economy; however, this model has numerous simplifications, such as exogenous setting of fuel prices and unspecified capital and labor costs.

We aim to fill this gap in the literature by developing a CGE model of the Turkish economy with a detailed representation of power generation technologies. Because Turkey's power sector has huge potential for emissions reduction, a CGE model that better characterizes the power sector and generation technologies will improve the ability to evaluate the impact of Turkey's INDC pledge and subsequent policy changes. Although our CGE framework simplifies representation of power generation and does not capture hourly dispatch or capacity expansion decisions, it allows us to capture important characteristics of separate generation technologies and considers the intermittent nature of renewable power.

This paper is organized in the following way. In Section 2 we provide an overview of the main characteristics of the Turkish economy and its energy sector development as well as details of GHG emissions in Turkey. Section 3 discusses the features of the newly created TR-EDGE (Electricity Detailed General Equilibrium Model for Turkish

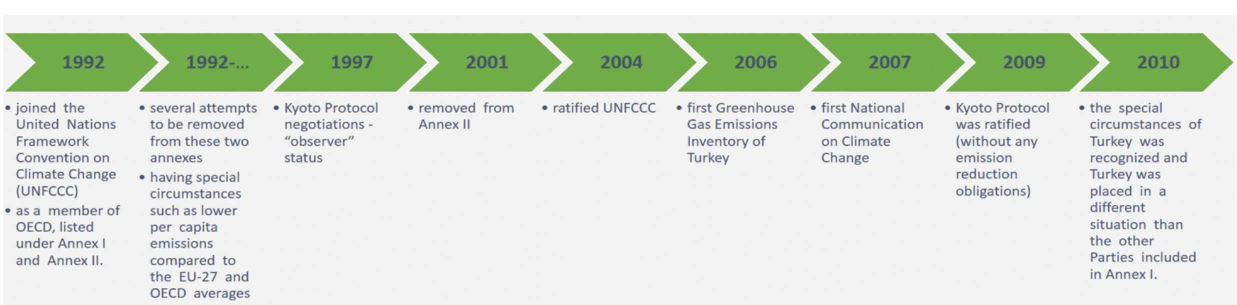


Figure 1. History of climate change policy in Turkey, 1992–2010.

Economy) model. In Section 4 we describe the scenarios for energy and climate policy, and Section 5 provides the model results in these scenarios. Section 6 concludes. Detailed descriptions and nesting structures of the TR-EDGE model are given in the Appendix.

2. An Overview of the Turkish Economy and Energy Sector

Between 1990 and 2015, Turkey has shown a high rate of economic growth despite several economic and political crises. As illustrated in **Table 1**, cumulative GDP growth in this era was 159% (average annual growth rate of 3.9%) in real terms. Primary energy demand increased by 144% (3.6% average annual rate) and electricity generation increased by 355% (6.3% average annual rate). At the same time, the domestic share of total energy supply declined from 50% in 1990 to 25% in 2015. Total GHG emissions increase at an average annual rate of 3.2%, which is almost on par with energy demand and faster than any Annex I country in the last decade.

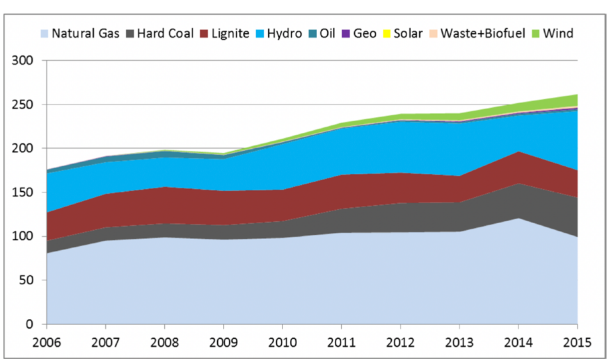
Figure 2 (a) and **(b)** show the power generation profile of Turkey between 2006 and 2015. Two thirds of the total electricity demand are based on fossil fuels. Hydroelectric power accounts for a quarter of total generation and there is a slow penetration of wind power in recent years. **Figure 3** shows the primary energy profile of Turkey for the same years. Aside from slight increases in renewables, there is no significant change in most resources.

Recent studies indicate that the wind and solar energy potential in Turkey is significant (i.e., 48GW for wind and 1.527 kWh/m^{2}year for solar energy (MENR, 2015)), yet only 5.1% of total power is generated by wind and solar installations by the end of year 2015. Currently, there are no nuclear power plants in Turkey; however, two plants (with installed capacities that correspond to more than 10% of the current total capacity) are on the government agenda (MENR, 2016). These plants, each having four units, are proposed to be commissioned gradually between years 2019 and 2028.

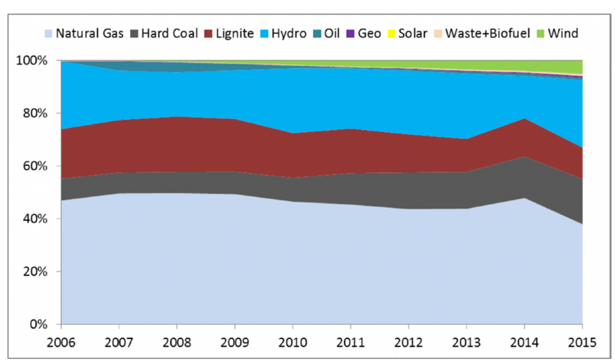
Table 1. Key indicators of Turkey (TUIK, 2017; MENR, 2015; MENR, 2016).

	1990	2000	2010	2011	2012	2013	2014	2015	Growth Avg. 1990–2010	Growth Avg. 2011–2015	Growth Total 1990–2015
Population *millions*	56.5	67.8	73.7	74.7	75.6	76.7	77.7	78.7	1.34%	1.32%	39.40%
GDP *constant 2010 Billion US$*	350.2	500.2	731.1	795.3	812.2	846.3	871.8	906.4	3.75%	3.32%	158.80%
Primary Energy Demand *Million TOE*	53.0	80.5	109.3	114.5	120.1	120.3	123.9	129.3	3.68%	3.08%	144.00%
Electricity Generation *TWh*	57.5	124.9	211.2	229.4	239.5	240.2	252.0	261.8	6.72%	3.36%	354.90%
Electricity Installed Capacity *GW*	16.32	27.26	49.52	52.91	57.06	64.01	69.52	73.15	5.71%	8.43%	348.30%
CO_2e emissions *Mt CO_2*	214.0	296.5	406.8	436.4	448.9	442.2	455.6	475.1	3.26%	2.15%	122.02%

Note: Because the model base year is 2011, we report the growth rates for periods 1990–2010 and 2011–2015 separately in Table 1.



(a) TWh



(b) Percentage

Figure 2. Electricity generation by technology, Turkey, 2006–2015 (TEIAS, 2017).

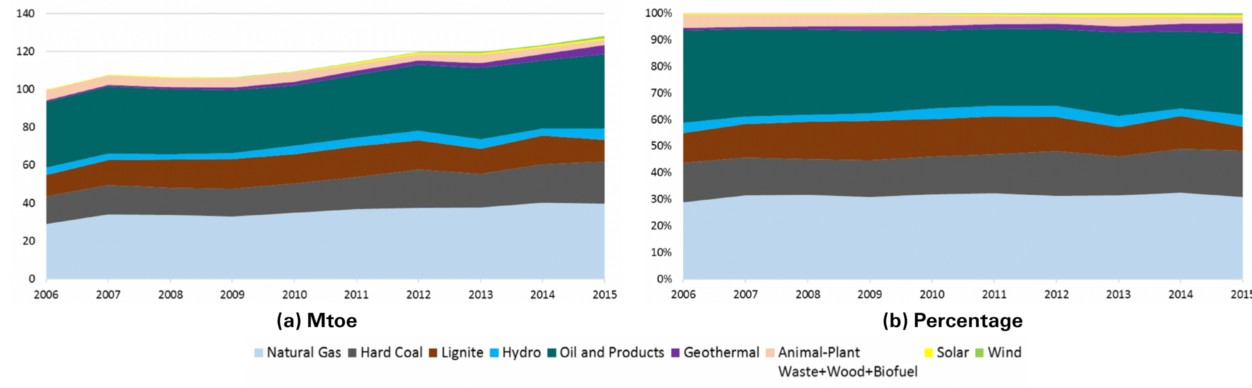


Figure 3. Primary energy supply by resource type, Turkey, 2016–2015, (MENR, 2016).

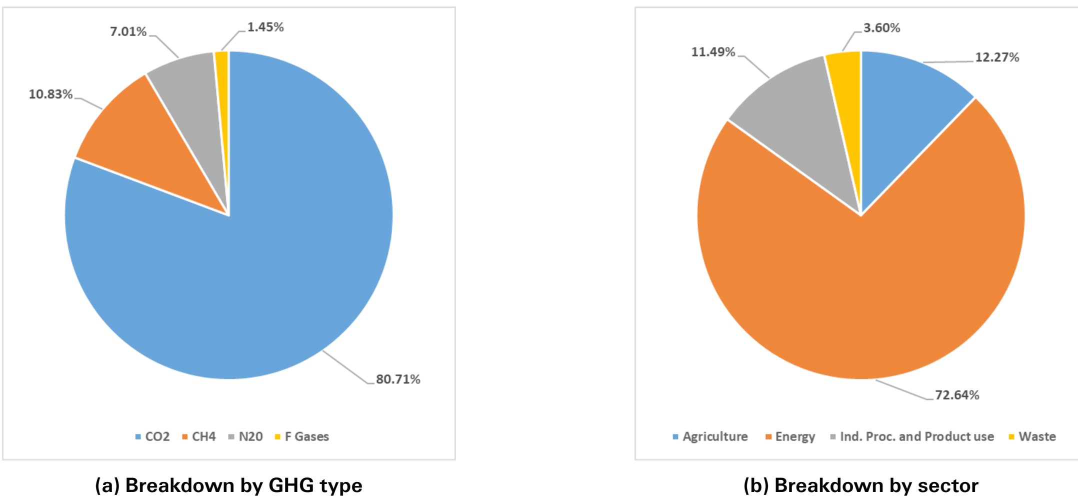


Figure 4. GHG emissions, Turkey, 2015 (TUIK, 2017)

Figure 4 illustrates the breakdown of 475.06 Mt of CO_2e emissions by type and by sector in 2015. As depicted from these figures, CO_2 is the main GHG with a share of 80.71% followed by the CH4, NO2 and F gases with corresponding shares of 10.83%, 7.01% and 1.45%, respectively. Sectoral decomposition, on the hand, shows that most emissions (72.64%) arise from energy sector activities, and 40% of those energy sector emissions (135.97 Mt of CO_2e) belong to the conversion and power generation sector.

3. TR-EDGE Model

3.1 Theoretical Framework

TR-EDGE is a recursive-dynamic model built on the GTAP-Power Data Base (Peters, 2016). Supplemental information from national accounts data published by Turkish Statistical Institute (TUIK) and energy statistics by Ministry of Energy and Natural Resources of Turkey are used to calibrate the model to recent economic and energy trends. Its benchmark year is 2011 and it is solved from 2015 to 2030 at 5-year intervals. The model is formulated as a mixed complementary problem (MCP), which includes both equations and inequalities (Mathiesen, 1985; Rutherford, 1995). The model is coded in GAMS using Mathematical Programming System for General Equilibrium (MPSGE) (Rutherford, 1999) and solved by PATH (Dirkse & Ferris, 1995).

In a CGE model, activities of different agents in the economy are described by three types of conditions (Paltsev, 2004):

- **zero-profit conditions:** these conditions require that the value of inputs must be equal to or greater than the value of outputs (i.e., any activity operated at a positive level must earn zero profit). The condition can be described as follows:

$$-\text{profit} \geq 0;\ \text{output} \geq 0;\ \text{output}^{T} \cdot (-\text{profit}) = 0 \quad (1)$$

- **market-clearing conditions:** these conditions imply that supply must be equal to demand for each commodity with a positive price. This condition can be described with the following expressions:

$$\text{supply}-\text{demand} \geq 0;\ p \geq 0;\ p^{T} \cdot (\text{supply}-\text{demand}) = 0 \quad (2)$$

- **income-balance conditions:** for each agent, including the government, expenditures must exhaust total income (value of factor endowments and tax revenue)

$$income = endowment + tax\ revenue \quad (3)$$

3.2 Dynamic Process

The recursive structure implies that production, consumption, savings and investment are determined by current period prices. The aggregate investment is equal to the level of savings determined by the household utility function. The dynamic process of capital evolution reduces the capital stock by depreciation and grows it by previous period investment, described as follows:

$$K_{r,t} = Inv_{r,t-1} + (1-\delta_r) \cdot K_{r,t-1} \quad (4)$$

where $K_{r,t}$ is the capital in region r in period t; $Inv_{r,t-1}$ is the investment in region r in period t-1 and δ_r is the depreciation rate of capital in region r from t-1 to t.

TR-EDGE relies on exogenous rates of population growth published by TUIK and OECD to specify projections of regional labor endowment over the model horizon. Similarly, government expenditures and current account balance are exogenously assumed based on historical data.

Besides the dynamic progress summarized above, we assume 2.5% productivity growth for both capital and labor through the planning horizon of the model, and a 1% annual increase for land use to account for improvements in land use productivity. These assumptions are consistent with those made in the EPPA model (Chen *et al.*, 2015).

Based on the recent rate of consumption and existing reserves, natural resources are assumed to be depleted at an annual rate of 2% in Turkey and 0.1% in the rest of the world. Our assumption of a much higher depletion rate relative to the rest of the world reflects the gradual decrease of domestic resource in the last decade.

3.3 Data

GTAP-Power (Peters, 2016), the main data base for TR-EDGE, is an electricity-detailed extension of the GTAP 9 Data Base (Augiar *et al.*, 2016). Like the GTAP 9 Data Base, GTAP-Power includes 140 regions (aggregated into Turkey and the Rest of the World (ROW)) with reference years 2004, 2007, and 2011. However, GTAP-Power disaggregates the GTAP 9 electricity sector into: transmission & distribution, nuclear, coal, gas, oil, hydroelectric, wind, solar, and other (including waste, biofuels, biomass, geothermal, tidal and oil). The data base distinguishes factor endowments into four main categories: capital, land, natural resources and labor. Labor is further disaggregated into five sub-categories (officials and managers, technicians, clerks, service/shop workers, agricultural and unskilled workers); however, in TR-EDGE a single aggregated labor endowment is used.

The sectoral data is aggregated to form a compact dataset while maintaining the requirements of the policy issues addressed by TR-EDGE. We have verified that the aggregated data is quite consistent with actual values reported by the Turkish Electricity Transmission Company (TEIAS, 2017). **Table 2** shows the 17 aggregated sectors, eight of which are related to electricity generation. Note that although GTAP-Power contains base-load and peak-load generation data for gas, oil, and hydroelectric technologies, as a first attempt, we assume no distinction between the two. In addition to electricity sectors, there are five non-energy sectors (agriculture, services, energy-intensive industries, other industries, and transport), and four non-electric energy sectors (crude oil, refined oil products, coal, and natural gas).

In addition to the GTAP 9 Data Base, National accounts data published by Turkish Statistical Institute (TUIK, 2017) are employed to approximate the government expenditure growth rate. Energy consumption and production data published by Republic of Turkey Ministry of Energy and Natural Resources and Turkish Electricity Transmission Company (MENR, 2016; TEIAS, 2017) are used to cali-

Table 2. List of sectors

Non-Energy Sectors	
agri	Agriculture
eint	Energy-intensive Industry
serv	Services
tran	Transportation
othr	Other Industries
Energy Sectors	
coal	Coal
gas	Natural gas
oil	Crude oil
roil	Refined oil products
Electricity Technologies	
ColE	Coal-fired power
GasE	Gas-fired power
HydE	Hydroelectric power
NucE	Nuclear power
WndE	Wind power
SolE	Solar power
OthE	Other power –waste, biofuels, biomass, geothermal, tidal, oil
TnD	Transmission and distribution

brate the model to replicate the economy in 2015. Finally, emission coefficients by sector and technology are calculated based on U.S. Energy Information Administration (EIA) estimates where calculated emissions are seen to be consistent with those reported in the GHG emissions inventory published by TUIK (2017).

Non-energy and non-CO_2 GHG emissions are represented in CO_2 equivalent terms. The nesting structures of the sectors in the model are provided in the Appendix.

3.4 Backstop Technologies

Two backstop technologies are defined for Turkey: nuclear power plants and solar power. As mentioned in Section 2, currently there are no nuclear power plants in Turkey and solar power generation is close to zero. These power generation options are not currently employed, but may make a substantial contribution should they gain policy support and become cost competitive. The input structures for these power plants are approximated using the corresponding values for ROW. To represent the backstop cost relative to the conventional technologies, e.g. coal-fired generation, we use a mark-up factor based on the joint report by World Wide Fund for Nature-Turkey and Bloomberg New Energy Finance (WWF-Turkey & BNEF, 2014). In accordance with this document, mark-up factors are estimated to be 1.5 for nuclear and 1.4 for solar relative to coal-fired power plants in Turkey.

4. Scenarios

We develop several scenarios to analyze the impact of an emission trading scheme with and without nuclear power generation in Turkey.

4.1 Business as Usual (BAU) Scenario

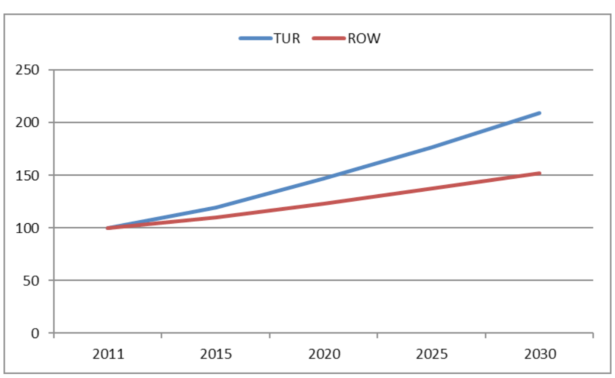
This scenario represents the current government plans to complete two nuclear plants before 2030: Akkuyu Nuclear Power Plant on the south coast of Turkey and Sinop Nuclear Power Plant on the north end of Turkey. According to official plans, Akkuyu consists of four identical units, each with a capacity of 1.2 GW (total capacity 4.8 GW). The first unit will be commissioned by 2019 and one additional unit will become operative every year until 2023. Sinop consists of four identical units, each with a capacity of 1.12 (total capacity 4.48 GW). The units will be commissioned in 2023, 2024, 2027 and 2028, respectively. Accounting for likely political and financial delays, we assume commissioning of Akkuyu by year 2025 and Sinop by year 2030.

Turkey has shown significant progress in its renewable energy industry since revising its feed-in tariff scheme in 2010. The share of wind generation has increased from 0 to 5% in the last decade. The revised feed-in tariff structure is incorporated into the BAU scenario and assumed constant through horizon.

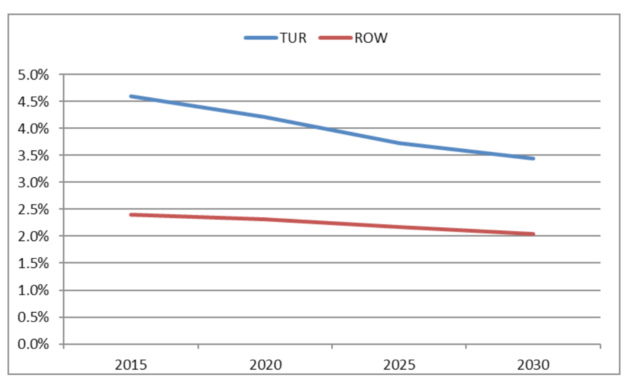
Official projections of energy use, electricity generation and GHG emissions are driven by the assumption of high GDP growth. However, recent political turbulence in the country as well as uncertainty in the neighborhood areas dampen the likelihood that Turkey will keep up with this high-growth assumption. Recent figures indicate that more modest growth paths would be needed to accurately represent medium-term progress in Turkey. For example, electricity demand in 2015 and 2016 is lower than the projections even for the low-growth scenarios produced by the government. Moreover, actual generation values for wind and solar fell far behind the targets specified in "National Renewable Energy Action Plan for Turkey" (MENR, 2014). In correspondence with GDP growth projections from the World Bank (2017), we assume in our BAU scenario that real GDP grows at an annual average rate of around 4% through 2030. This results in differing GHG emissions paths—the official BAU projects emissions at 1,175 $MtCO_2$-equivalent by 2030, 40% higher than our BAU projections of 836 $MtCO_2$-equivalent (see **Figure 5**).

4.2 No Nuclear (NoN) Scenario

Although recent movements suggest that the Turkish government is very decisive on building nuclear plants, many people, especially non-governmental environmental organi-



(a) GDP index (100 for base year)



(b) Annual growth rates

Figure 5. Development of real GDP: BAU

zations, are against nuclear power due to the accompanying risks. This creates uncertainties associated with the cost impact of emissions reduction goals. For these reasons, the NoN scenario is proposed to characterize another baseline where nuclear power plants are not allowed in Turkey.

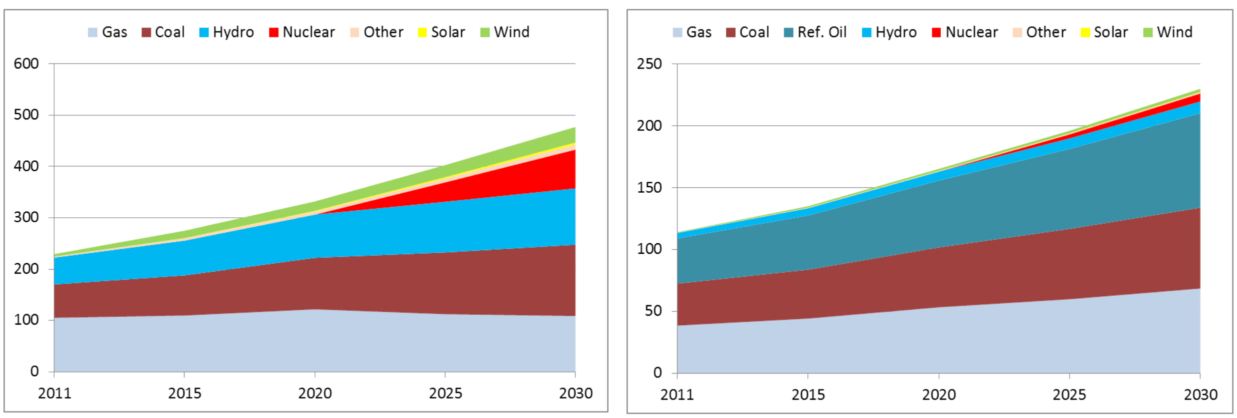
4.3 National Emission Trading Scheme (TrEm) Scenarios: BAU+TrEm and NoN+TrEm

These scenarios assume that Turkey designs a national emission trading market to be implemented from 2020 to 2030. No policies are imposed in the rest of the world. A national emission cap is derived to achieve a gradual reduction path with 5% reduction by 2020, 10% by 2025, and 21% by 2030 relative to BAU levels. Emissions from all fuels and sectors are covered from 2020 to 2030. The permit trading scheme equalizes carbon prices across fuels and sectors. Applying the same emission caps to BAU and NoN, we evaluate the role of nuclear and analyze the impacts of emissions reduction on electricity, the non-electric energy market, and GDP.

Our scenarios assume a policy that covers all fuels and sectors. It has been shown that partial coverage can substantially increase policy costs while achieving the same emission targets (Rausch and Karplus, 2014). We argue that to reduce the overall cost of the policy, an efficient policy design in Turkey should be economy-wide with emission allowance trading - allowing sectors with high abatement costs to purchase allowances from sectors with lower abatement cost.

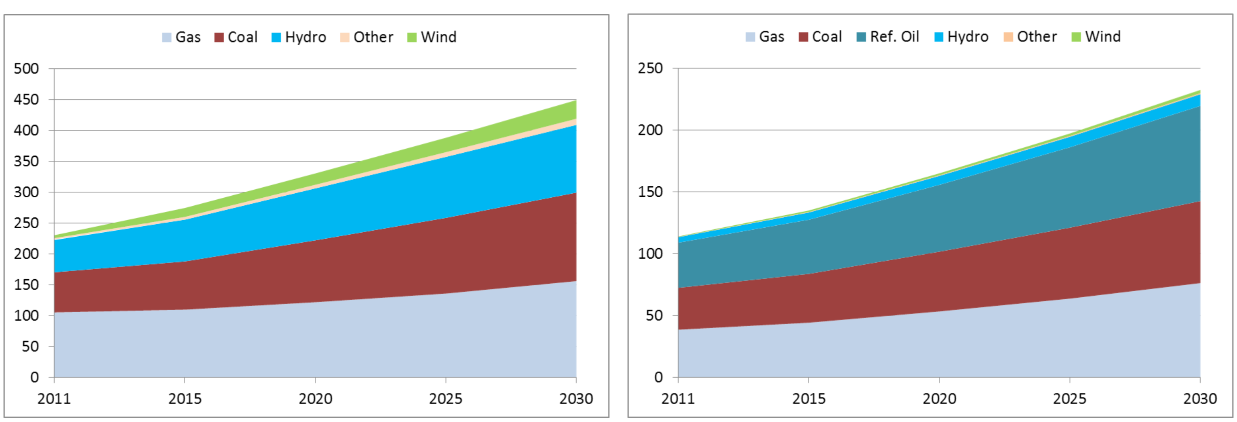
5. Results

We start our discussion with an assessment of electricity and total energy in the BAU and NoN scenarios under the no climate policy setting. Profiles of power generation and primary energy supply in the BAU scenario are represented in **Figure 6 (a)** and **(b)**, respectively. In BAU, total generation reaches about 480 TWh in 2030 (from 229 TWh in 2011) and total primary energy grows to about 230 Mtoe by 2030 (from 114 Mtoe in 2011). The natural gas share decreases from 46% in 2011 to 23% in 2030, but the amount of natural gas-based generation stays almost flat during these years. The reduced natural gas share reflects an increase in total electricity generation.



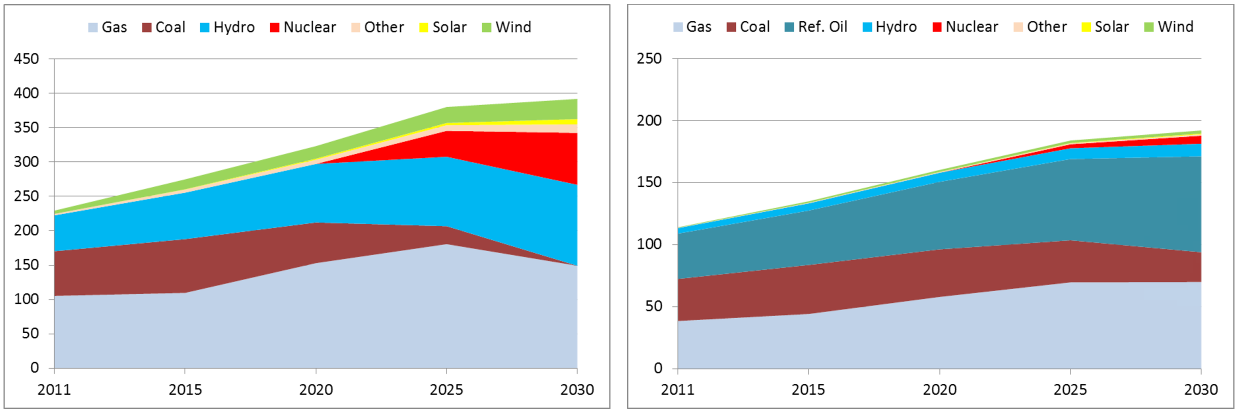
(a) Electricity generation by technology, TWh **(b) Primary energy supply by source, Mtoe**

Figure 6. Electricity generation and primary energy supply: BAU, Turkey



(a) Electricity generation by technology, TWh **(b) Primary energy supply by source, Mtoe**

Figure 7. Electricity generation and primary energy supply: NoN, Turkey



(a) Electricity generation by technology, TWh **(b) Primary energy supply by source, Mtoe**

Figure 8. Electricity generation and primary energy supply: BAU+TrEm, Turkey

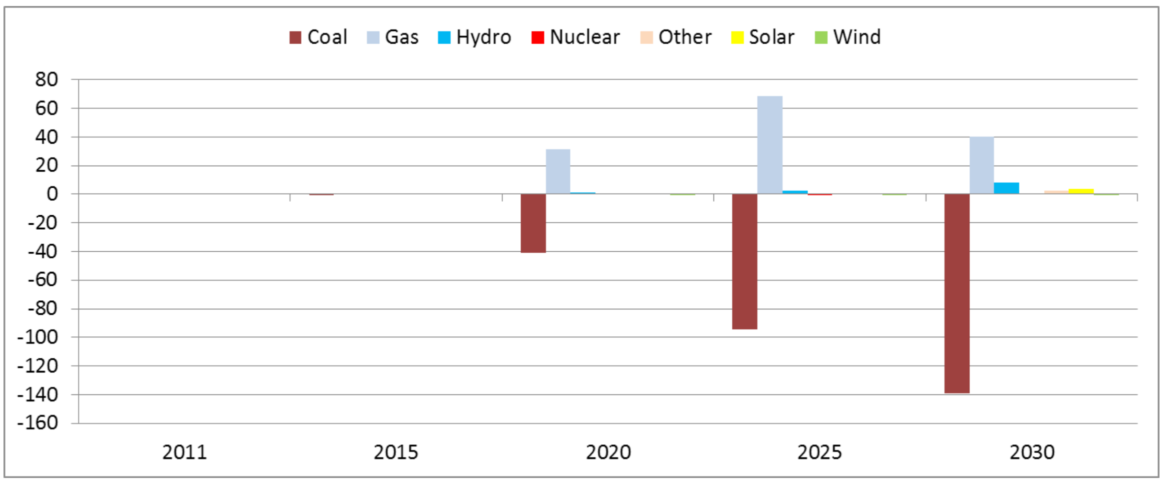


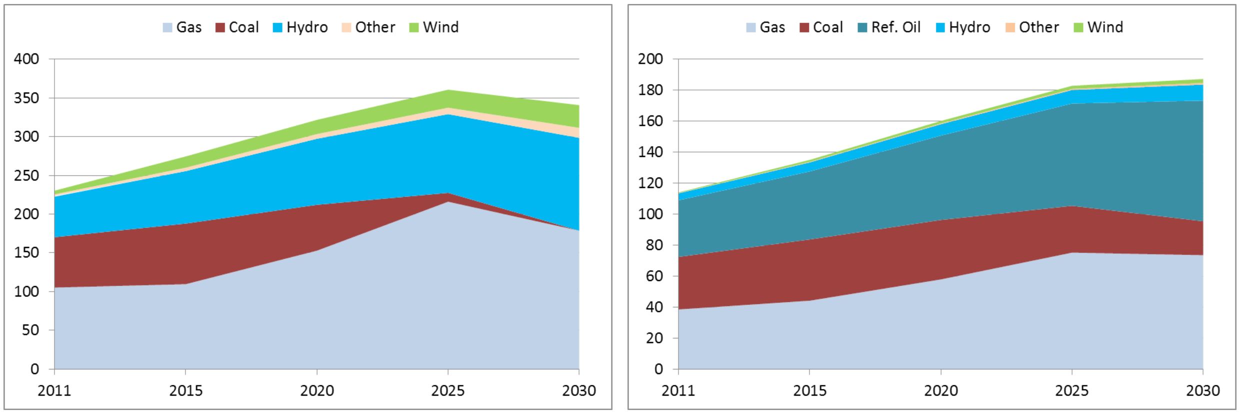
Figure 9. Difference between BAU and BAU+TrEm: Electricity generation by technology, TWh

Nuclear power penetrates in 2025 and the share of nuclear power reaches 16% of total generation by 2030. Renewable generation (mostly wind and solar) increases its share from 2.06% in 2011 to 7.2% in 2030 - far behind the official target of 14% in 2023. As of November 2017, actual wind and solar generation was at 6%, which is 35% behind the targets addressed in "National Renewable Energy Action Plan for Turkey" (MENR, 2014). In 2030, primary energy continues to rely on oil (33.2%), natural gas (29.7%) and coal (28.4%).

Figure 7 (a) and **(b)** show the electricity generation and primary energy supply in the NoN scenario. Natural gas replaces nuclear generation and gains a larger share in the primary energy supply (32.7%, a 3% increase from BAU). Other fuels do not substantially change their profiles between BAU and NoN. Removing the development of nuclear power means also removing the effective subsidy that would have accompanied nuclear development. This results in an overall decrease in electricity generation for the NoN scenario (by 24 TWh in 2030).

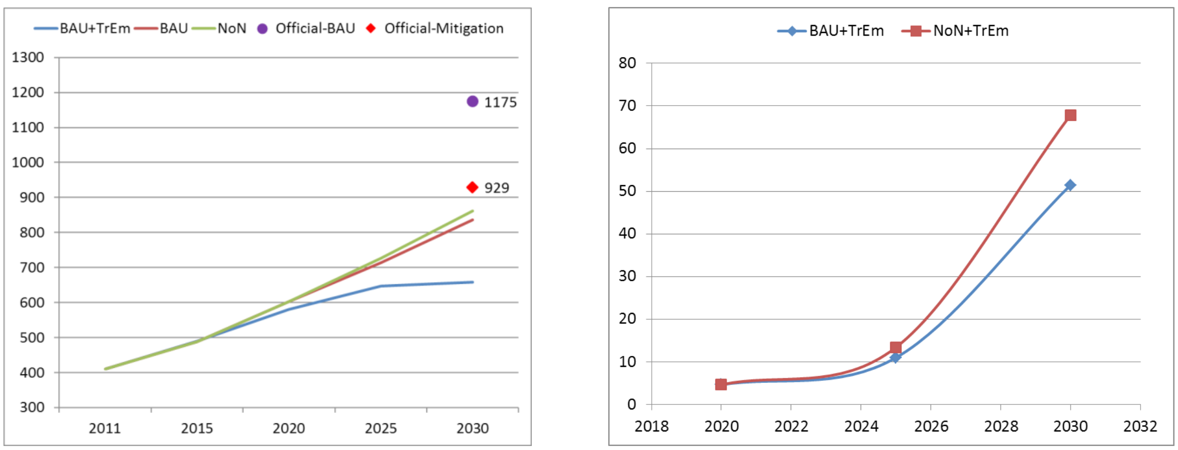
Next we turn to an analysis of emission reduction scenarios. **Figure 8** shows power generation and primary energy profiles under the BAU+TrEm scenario, where an emission cap leads to reductions in both power generation (17.8%) and primary energy supply (16.4%) by 2030 relative to BAU. The carbon constraint leads to a removal of all coal-fired generation by 2030 due to coal's high emission intensity (when combusted, the CO_2 content of coal is almost twice that of natural gas (EIA, 2016)). Wind and solar generation increases to 9.5% of total generation (37.2 TWh) by 2030, compared to 7.2% (34.1 TWh) in BAU. Going along with the increase in renewable generation, there is a 2.2% decrease in the domestic share of the primary energy supply due to increasing use of imported natural gas.

Figure 9 provides a visualization of the impact of the emissions trading scheme on electricity generation by technology type relative to the BAU scenario. Coal-fired generation is reduced by 140 TWh by 2030. It is displaced by natural gas-fired (40 TWh in 2030) and renewable (10 TWh in 2030) generation, but the total amount of electricity gen-



(a) Electricity generation by technology, TWh **(b) Primary energy supply by source, Mtoe**

Figure 10. Electricity generation and primary energy supply: NoN+TrEm, Turkey



(a) CO_2 equivalent GHG emissions, Mtonne **(b) CO_2 equivalent GHG price: BAU+TrEm vs NoN+TrEm, \$/tonne**

Figure 11. Total emissions and emission price

eration is lower due to higher electricity prices that reflect carbon charges.

Figure 10 illustrates the power generation and primary energy profiles under NoN+TrEm scenario. Note that the difference between NoN+TrEm and BAU+TrEm in terms of power generation (10.8%) and primary energy (2.2%) in 2030 is more significant than the difference between BAU and NoN. This result implies that the potential benefits of nuclear power might be higher under emission restrictions. Consistent in both scenarios, coal-fired power generation vanishes regardless of the assumption about the availability of nuclear power.

Figure 11 (a) compares total GHG emissions from the BAU, BAU+TrEm and NoN scenarios. It also shows the official GHG projections and official targets published in Turkey's INDC (UNFCCC, 2016). Because of our differing growth rate assumptions, the level of GHG emissions in our BAU scenario in 2030 is lower than the level submitted by Turkey in its INDC as a policy target (929 $MtCO_2$-equivalent). In our estimate, this level will be achieved by Turkey without any emission trading (or other climate policy) required. Therefore, we have chosen to target a 21% reduction relative to our BAU rather than relative to government BAU projections. The resulting target is 658 $MtCO_2$-equivalent emissions. We provide a discussion of alternative settings for the BAU projection and the emission reduction profiles at the end of this section.

Figure 11 **(a)** also indicates that even without any further abatement action, GHG emissions are lower with the nuclear program (by 3.1% in BAU, relative to NoN). Since the NoN+TrEm scenario is constructed in such a way that the same target of 658 $MtCO_2$-equivalent emissions in Turkey in 2030 is achieved, the emission profiles in BAU+TrEm and NoN+TrEm are the same. Figure 11 **(b)** compares the emission prices with and without a nuclear program. The carbon price in 2030 is around \$50/tCO_2e with the nuclear program and almost \$70/tCO_2e without it. This difference is driven by the fact that the nuclear program results in lower emissions, so less abatement is needed to reach the same emission targets.

Sectoral contributions to GHG mitigation under BAU+-TrEm are shown in **Figure 12**. Over three quarters of GHG emissions reduction comes from energy sectors. Energy-intensive industry contributes 13%. All other sectors combined achieve about 10% reduction.

The TrEm scenario results in significant changes in coal and electricity prices, as shown in **Figure 13**. The decrease in producer coal prices is driven by a lower demand for coal under the emission constraint. Consumer prices for coal (those that include a carbon charge) are substantially higher under the emission trading scheme as they reflect the carbon content of coal. The increase in electricity prices is the result of a carbon penalty. In this scenario, no significant changes have been observed in the producer prices of oil and natural gas, as these are determined by international markets.

A policy to reduce GHG emissions leads to slightly slower economic growth, mostly due to the need to invest in more expensive technologies relative to BAU and the corresponding impacts on prices. Compared to BAU, real GDP decreases in the BAU+TrEm scenario 0.82% by 2030. GDP still grows substantially from 2015 to 2030, but at a somewhat lower rate - the average 2015–2030 GDP growth is 3.8% for BAU and 3.74% for BAU+TrEm.

When emission reduction is imposed on the NoN scenario, larger reductions are required to meet the same GHG emission target. Compared to NoN, real GDP decreases in the NoN+TrEm scenario by 1.1% by 2030. The TR-EDGE model also estimates a change in welfare that is measured as "equivalent variation" - this can be interpreted as the amount of extra income consumers would need to compensate for losses caused by the policy change. The percentage changes in welfare are of a similar magnitude as the percentage changes in GDP. Impacts on the outputs of non-energy sectors in the BAU+TrEm scenario can be seen in **Figure 14**. This figure suggests that under a GHG mitigation scenario, the energy-intensive industry is affected the most among all non-energy sectors - showing nearly a 6% decrease in output. The agriculture and transportation sectors also show significant decreases - around 1.5%.

Turkey's INDC provides a figure indicating the trajectory of the emissions reduction path through different periods (UNFCCC, 2016). In the text of the INDC these reductions are not mentioned and the target is specified for 2030 only. Calculated relative to BAU in the corresponding years, the emissions reduction path appears to be 6% in 2015, 11% in 2020, 15% in 2025 and 21% in 2030. We consider this path to be rather aggressive, especially considering that policies were not implemented to achieve the proposed 2015 reductions. In our analysis we used a trajectory of 5% in 2020, 10% in 2025, and 21% in 2030. Our BAU emissions in 2030 are about 30% lower than the BAU provided in the INDC, likely due to our assumption of a lower GDP growth rate than that assumed in the INDC.

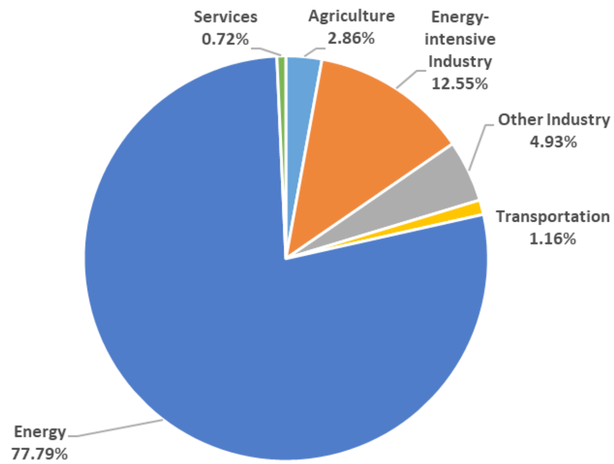
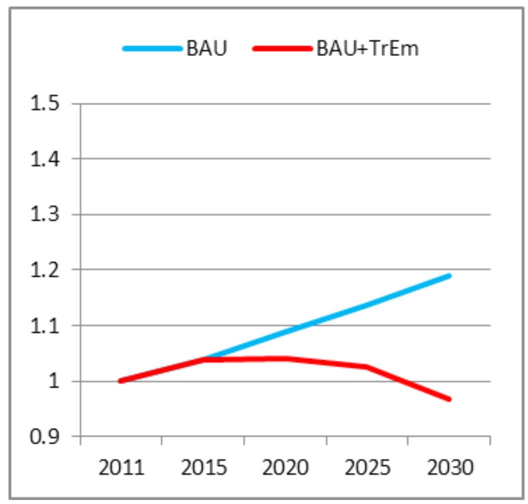
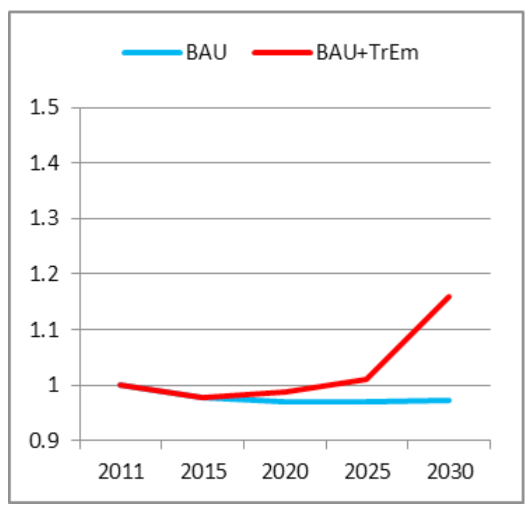


Figure 12. Sectoral shares of contributions to GHG mitigation in year 2030 in the BAU+TrEm scenario



(a) coal



(b) electricity

Figure 13. Producer price index of coal (net of carbon charge) and electricity price index (inclusive of carbon charge): BAU vs TrEm

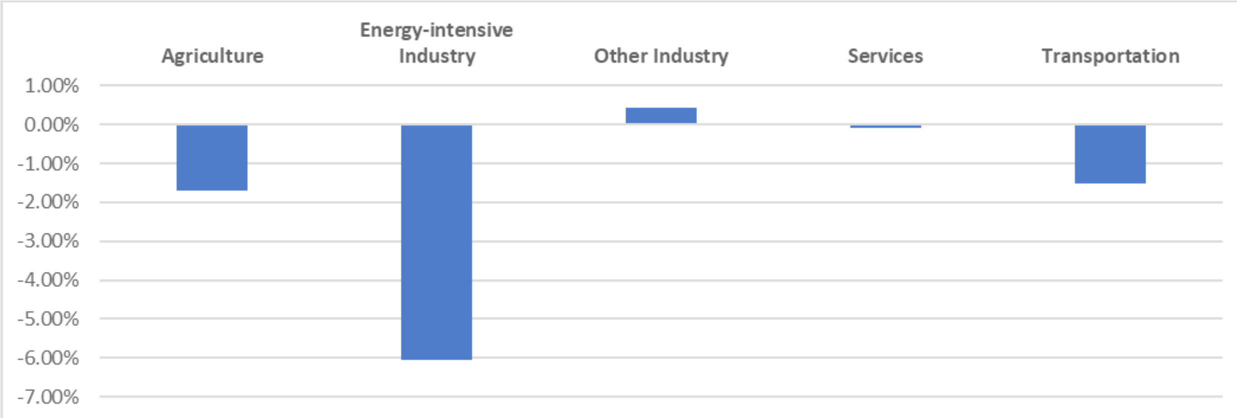


Figure 14. Impacts of BAU+TrEm on sectoral outputs (% change relative to BAU) for year 2030

We have performed a sensitivity analysis with respect to: 1) a BAU profile with higher emissions, similar to the BAU provided in the INDC figure; and 2) a more aggressive target path for 2020–2025, similar to that illustrated in the INDC figure. Higher emissions with no change in the target path leads to larger GDP impacts in absolute levels, but similar impacts in percentage terms – a decrease of about 1% of GDP in 2030 relative to the respective BAU. The resulting carbon prices are also similar – in the range of $50/tCO_2e$ in 2030. A more aggressive target path ultimately leads to GDP impacts and carbon prices in 2030 that are similar (in percentage terms) to those presented in the main scenarios. However, during the intermediate years we observe larger GDP impacts and higher carbon prices. Both the GDP reduction and carbon prices are about four times higher in 2020 (0.29% vs 0.05% GDP reduction and $22/tCO_2e$ vs $5/tCO_2e$ carbon prices) and almost twice as high in 2025 (0.39% vs 0.17% GDP reduction and $22/tCO_2e$ vs $11/tCO_2e$ carbon prices).

6. Conclusion

Turkey supports the Paris Agreement and climate stabilization policies, and Turkey's INDC - a proposed 21% reduction in its GHG emissions in 2030 relative to BAU levels - is a first step on the low-carbon development pathway. Developing models to assess the impacts of various policy scenarios is crucial for strategic planning. We have developed and applied the TR-EDGE model for this purpose. TR-EDGE differs from other models by its representation of disaggregated electricity generating technologies in a general equilibrium framework - i.e., the model combines macroeconomic representation of the non-electric sectors with detailed representation of the electric sector.

Using TR-EDGE, we analyzed four different scenarios for Turkey: a business as usual scenario (BAU), which represents the current plans of the government including a nuclear program and revised feed-in tariff scheme for renewables; a no-nuclear scenario (NoN), in which nuclear power is omitted; and each of the previous scenarios coupled with a national emission trading scheme (BAU+TrEm and Non+TrEm). Our results indicate that a national emission trading market would mitigate negative impacts on the real growth rates while still encouraging reductions in GHG emissions. Our BAU emissions in 2030 are about 30% lower than those provided in Turkey's INDC, and while the INDC does not provide details or references to the underlying calculations, a likely cause of the overestimation is over-optimistic assumptions of GDP growth rates in the INDC.

Another important insight obtained from the TR-EDGE model is a projection of the resulting carbon price needed for Turkey to meet its emission reduction targets under a BAU scenario. We found the carbon price in 2030 is around $50 per ton of CO_2e emissions. The relative cost-competitiveness of energy technologies, as represented in the TR-EDGE model, leads to lower renewable (wind and solar) deployment than the official projections. This result is mainly due to the intermittent nature of these technologies - since they are treated as imperfect substitutes for other generation technologies, their cost is greater, making them less competitive.

Additionally, we assess the potential benefits of the nuclear program in Turkey. Without nuclear power, the required carbon prices are higher ($70/tCO_2e$ vs $50/tCO_2e$ with nuclear) and the GDP reductions accompanying the carbon policy are larger (1.1% vs 0.82% with nuclear, relative to the respective no policy scenarios) to achieve the same reduction of GHG emissions. Welfare impacts are similar to GDP impacts in percentage terms.

Our analysis discusses options for achieving a low-carbon energy system that maximizes welfare of Turkish citizens. Because Turkey's population and economy are growing rapidly, it is extremely important to provide a discussion for the best way to decarbonize the Turkish economy while keeping fast economic growth. The results will provide industry representatives and policymakers with information about the overall policy costs associated with different options. An important caveat to our study is that it provides only a cost-effectiveness analysis; we have not quantified the benefits of emission reductions, the damages related to continuing GHG emissions, or the risks associated with nuclear power plants. The current literature on the benefits of emissions reductions shows a wide range of estimates. Future research may focus on reducing uncertainty in these estimates to improve cost-benefit analysis. Our results show that the targets that Turkey envisioned for the Paris Agreements are reachable at a modest economic cost of about 1% of GDP in 2030.

Acknowledgments

The authors thank Jamie Bartholomay for their help with the paper. Bora Kat's research activities at MIT Joint Program on the Science and Policy of Global Change were funded by the Turkish Fulbright Commission under Visiting Scholar Program. The MIT Joint Program is supported by an international consortium of government, industry and foundation sponsors (see the list at: https://globalchange.mit.edu/sponsors).

7. References

Akın Olçum, G. & E. Yeldan (2013): Economic impact assessment of Turkey's post-Kyoto vision on emission trading. *Energy Policy* **60**: 764–774.

Augiar, A., B. Narayanan & R. McDougall (2016): An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis* **1**(1): 181–208. Available at: https://jgea.org/resources/jgea/ojs/index.php/jgea/article/view/23/7 [Accessed Apr 9, 2017].

Chen, Y.-H.H. *et al.* (2015): *The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption*. MIT Joint Program **Report 278**, Cambridge, MA (https://globalchange.mit.edu/publication/16262).

Dirkse, S.P. & M.C. Ferris (1995): The path solver: a nommonotone stabilization scheme for mixed complementarity problems. *Optimization Methods and Software* **5**(2): 123–156. (doi: 10.1080/10556789508805606) [Accessed Dec 24, 2016].

EIA (2016): U.S. Energy Information Administration (EIA): Carbon Dioxide Emissions Coefficients. Available at: https://www.eia.gov/environment/emissions/co2_vol_mass.php [Accessed Dec 30, 2018].

Kat, B. (2011): *Mathematical Modeling for Energy Policy Analysis*. Ankara, Turkey: Middle East Technical University. Available at: http://etd.lib.metu.edu.tr/upload/12613762/index.pdf [Accessed Jan 9, 2017].

Kumbaroğlu, G.S. (2003): Environmental taxation and economic effects: a computable general equilibrium analysis for Turkey. *Journal of Policy Modeling* **25**(8): 795–810.

Lanz, B. & S. Rausch (2011): General Equilibrium, Electricity Generation Technologies and the Cost of Carbon Abatement. *Energy Economics* **33**(5): 1035–1047.

Mathiesen, L. (1985): Computational experience in solving equilibrium models by a sequence of linear complementarity problems. *Operations Research* **33**(6): 1225–1250. (doi: 10.1287/opre.33.6.1225) [Accessed Apr 9, 2017].

MENR (2015): *Blue Book-2015*. Ankara. Available at: http://www.enerji.gov.tr/File/?path=ROOT%2F1%2FDocuments%2FMavi Kitap%2FMavi_kitap_2015.pdf.

MENR (2016): *Blue Book-2016*. Available at: http://www.enerji.gov.tr/File/?path=ROOT%2F1%2FDocuments%2FMavi Kitap%2FMavi_kitap_2016.pdf.

Paltsev, S. (2004): *Moving from static to dynamic general equilibrium economic models*. MIT Joint Program **Technical Note 4**, Cambridge, MA (https://globalchange.mit.edu/publication/14238).

Paltsev, S. *et al.* (2005): *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. MIT Joint Program **Report 125**, Cambridge, MA (https://globalchange.mit.edu/publication/14578).

Peters, J.C. (2016): The GTAP-Power Data Base: Disaggregating the Electricity Sector in the GTAP Data Base. *Journal of Global Economic Analysis* **1**(1): 209–250.

Rausch, S. *et al.* (2009): *Distributional Impacts of a U.S. Greenhouse Gas Policy: A General Equilibrium Analysis of Carbon Pricing*. MIT Joint Program **Report 182**, Cambridge, MA (https://globalchange.mit.edu/publication/13874).

Rausch, S. and V.J. Karplus (2014): Markets versus Regulation: The Efficiency and Distributional Impacts of U.S. Climate Policy Proposals. *Energy Journal* **35**(S1): 199–227

Rutherford, T.F. (1999): Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. *Computational Economics* **14**(1): 1–46.

Rutherford, T.F. (1995): Extension of GAMS for complementarity problems arising in applied economic analysis. *Journal of Economic Dynamics and Control* **19**(8): 1299–1324.

TEIAS (2017): Turkish Electricity Generation-Transmission Statistics. Available at: https://www.teias.gov.tr/tr/turkiye-elektrik-uretim-iletim-istatistikleri.

Telli, Ç., E. Voyvoda & E. Yeldan (2008): Economics of environmental policy in Turkey: A general equilibrium investigation of the economic evaluation of sectoral emission reduction policies for climate change. *Journal of Policy Modeling* **30**(2): 321–340.

TUIK (2017): Main Statistics. Available at: http://www.turkstat.gov.tr/UstMenu.do?metod=temelist.

TUSIAD (2016): *Addressing Climate Change from an Economic Policy Perspective*. Istanbul. Available at: http://tusiad.org/tr/yayinlar/raporlar/item/9388-ekonomi-politikalari-perspektifinden-iklim-degisikligi-ile-mucadele [Accessed Jan 7, 2017].

UNFCCC (2016): Republic of Turkey Intended Nationally Determined Contribution. Available at: http://www4.unfccc.int/Submissions/INDC/Published Documents/Turkey/1/The_INDC_of_TURKEY_v.15.19.30.pdf [Accessed Jan 7, 2017].

World Bank (2017): *The World Bank in Turkey: Country Snapshot*. Available at: http://pubdocs.worldbank.org/en/254861507539327826/Turkey-Snapshot-Fall2017.pdf [Accessed Jan 30, 2018].

WWF-Turkey & BNEF (2014): *TURKEY'S RENEWABLE POWER: Alternative Power Supply Scenarios for Turkey*. Available at: http://awsassets.wwftr.panda.org/downloads/wwf_turkey___bnef___turkey_s_renewable_power___alternative_power_supply_scenarios_until_.pdf [Accessed Apr 9, 2017].

Yeldan, E. & E. Voyvoda (2015): *Low carbon development pathways and priorities for Turkey*. İstanbul. Available at: http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Low_Carbon_Development_Pathways_for_Turkey_October_2015_FullStudy.pdf [Accessed Jan 9, 2017].

Appendix. Production and Consumption Structures

Nesting structures of production and consumption activities are constructed with reference to several versions of the MIT EPPA model (Paltsev *et al.*, 2005; Chen *et al.*, 2015) and the MIT USREP model (Rausch *et al.*, 2009; Lanz & Rausch, 2011). **Table A1** summarizes the types of substitution elasticities and their notation; elasticity values are specified in the nesting diagrams from Figure A1 through Figure A10.

Figure A1 shows the preference structure of households. Savings enters directly into the utility function of households, which endogenizes the consumption-investment decision within the model. Note that emissions are fixed in proportion to fuel use while all other substitution possibilities are represented via CES functions.

Since TR-EDGE mainly focuses on the power sector, we pay more attention in defining the nesting structure of this sector. **Figure A2** shows the nesting structure of alternative power technologies. Electricity generated by fossil-fired, nuclear, hydro and "other" (see OthE in Table 2) power plants are treated as perfect substitutes while the renewable electricity generation from solar and wind are treated as imperfect substitutes for the non-renewable technologies, consistent with the treatment in EPPA models (Paltsev *et al.*, 2005; Chen *et al.*, 2015). This formulation captures the intermittent nature of renewable technologies, which tends to increase system cost with a large share of electricity production.

Figure A3 (a) and **(b)** show the nesting structures of hydroelectric and nuclear power technologies, respectively. Note that a fixed factor is built into these technologies to allow for gradual penetration (Paltsev *et al.*, 2005). Both technologies have similar structures in which the KL composite is combined with the relevant resource of the fixed

Table A1. Types of substitution elasticities and their notation in TR-EDGE

Type of substitution elasticity	Notation
between domestic & imported goods	sdm
among non-electricity energy	noe
between non-electric energy & electricity	noe_{el}
between capital/labor bundle & energy bundle	kl_{e}
between material & energy bundles	e_{m}
between land & energy/material bundle	ln_{em}
between land/energy/material bundle & capital/labor aggregate	$lnem_{kl}$
between capital & labor	kl
between capital/labor bundle & material	kl_{m}
between fixed resource & capital/labor/material bundle	klm_{f}
between fixed resource & capital/labor bundle	kl_{f}
among capital, labor & material	klm
between land & capital/labor/material/fixed resource bundle	$klmf_{ln}$
between fixed resource & capital/labor/energy bundle	kle_{f}
between technology specific factor & capital/labor/energy bundle	kl_{tsf}
between technology specific factor & capital/labor/energy/material bundle	klm_{tsf}
between land & capital/labor/material/technology specific factor bundle	$klmtsf_{ln}$
domestic-export transformation	sde
among energy inputs	e
among material inputs	m
Intra-import elasticity of substitution	imp

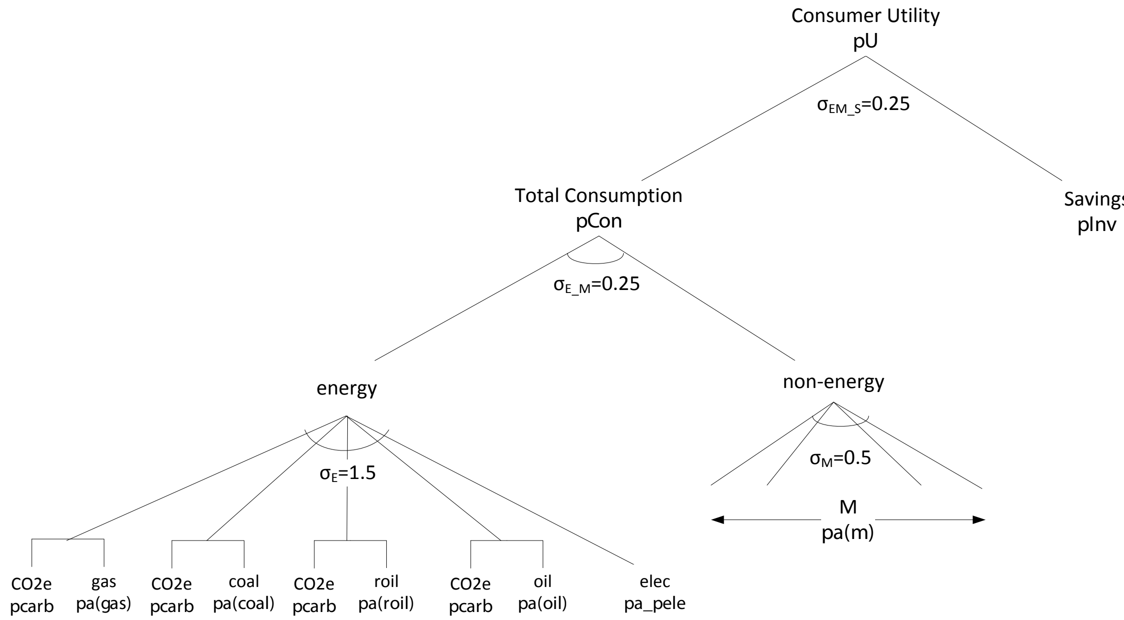


Figure A1. Nesting structure of the household sector.

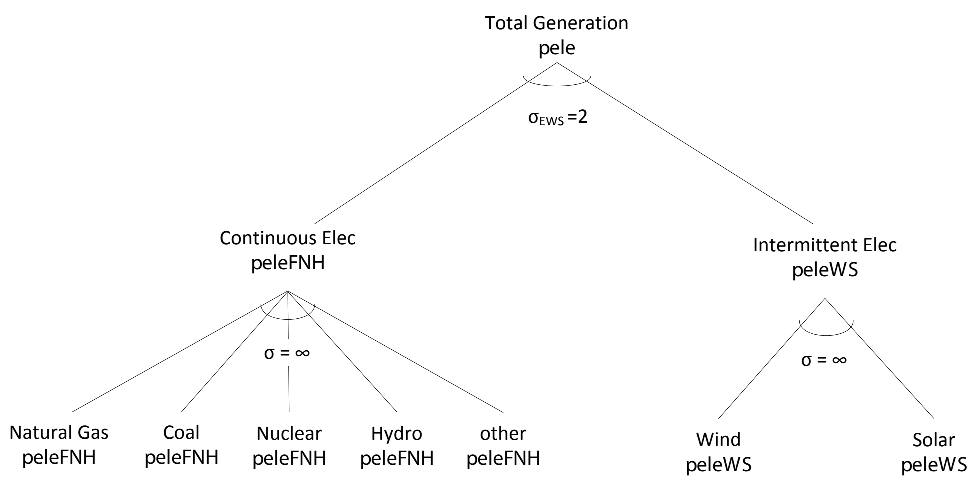
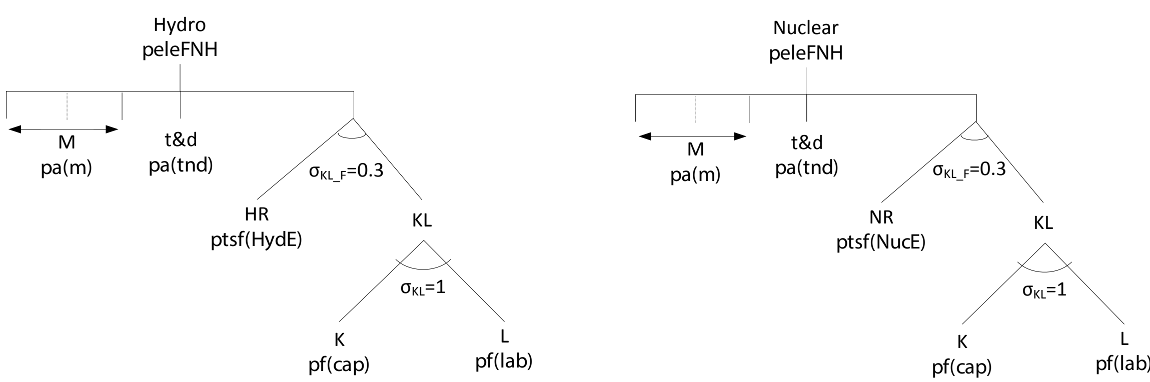


Figure A2. Nesting structure of electricity generation.



(a) Hydro **(b) Nuclear**

Figure A3. Nesting structure of hydro and nuclear generation factor endowments. We assume a Leontief technology that combines the material inputs, transmission and distribution services with a composite of capital, labor and fixed factor.

Wind and solar technologies are represented by the nesting structure illustrated in **Figure A4** (**a**) and (**b**), respectively. Capital, labor and other material inputs enter at the lower nest and the composite of these inputs substitutes against technology-specific factors in the upper nest. Next, these inputs are combined with land. Finally, transmission and distribution services are aggregated with the composite of remaining inputs with a Leontief function.

Fossil-fired power technologies (**Figure A5**) and "other" power technologies (**Figure A6**) have similar nesting structures. Capital-labor composite and energy inputs are combined with a CES function in the lower nests while other material inputs and transmission and distribution services enter at the top nest in fixed proportions. Due to the data structure, TR-EDGE differs from EPPA and US-REP in that non-electric energy inputs and electricity are assumed in fixed proportions. Because the GTAP-Power Data Base provides disaggregated data for the power sector, representing substitution among technologies at the fuel level is unnecessary. Different from fossil-fired power technologies, "other" power technologies also include a technology-specific factor in its nesting structure to represent the nature of technologies aggregated under this option, i.e., geothermal, waste, biofuels, biomass and tidal.

Figure A7 illustrates the non-electric energy sectors. In the refined oil sector, Figure A7 (a), Crude oil is used as "feedstock" to produce refined petroleum products and enters as a Leontief intermediate input in the top nest. Primary energy sectors (coal, natural gas and crude oil), in Figure A7 **(b),** combine a fuel-specific resource and non-resource input bundle at the top nest while the capital-labor composite is combined with other inputs in the lower nest via Leontief function.

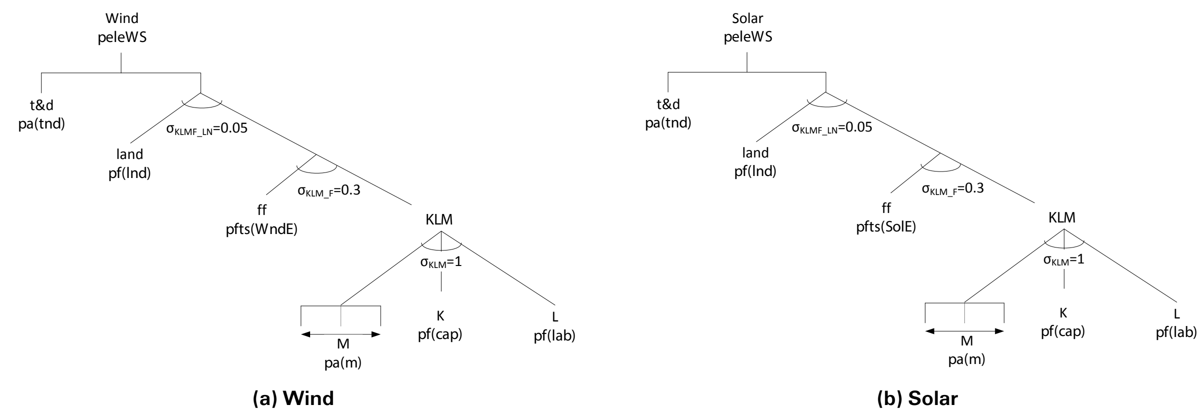


Figure A4. Nesting structure of wind and solar generation

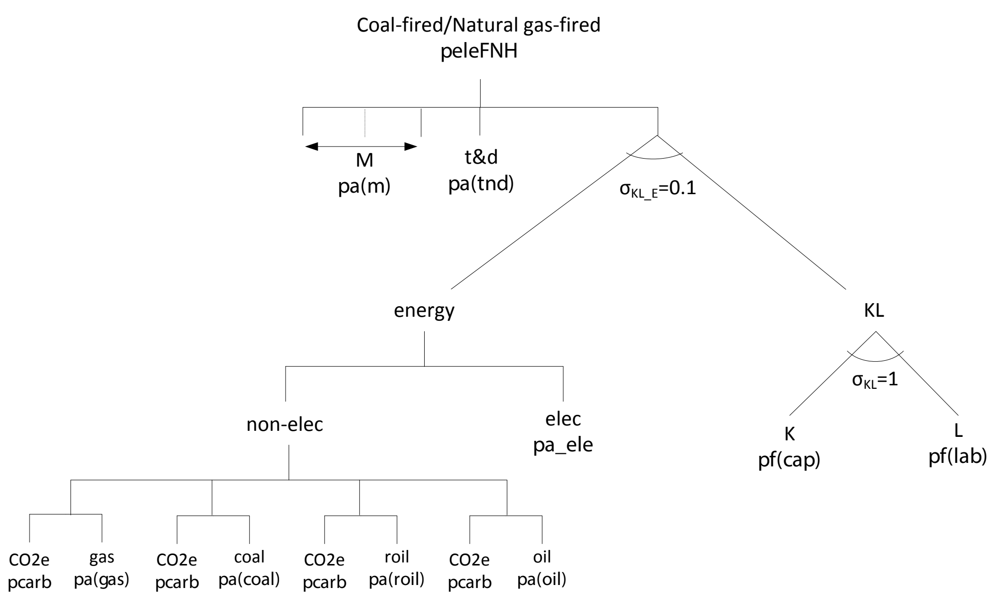


Figure A5. Nesting structure of fossil-based generation (coal and natural gas are modeled as separate generation technologies)

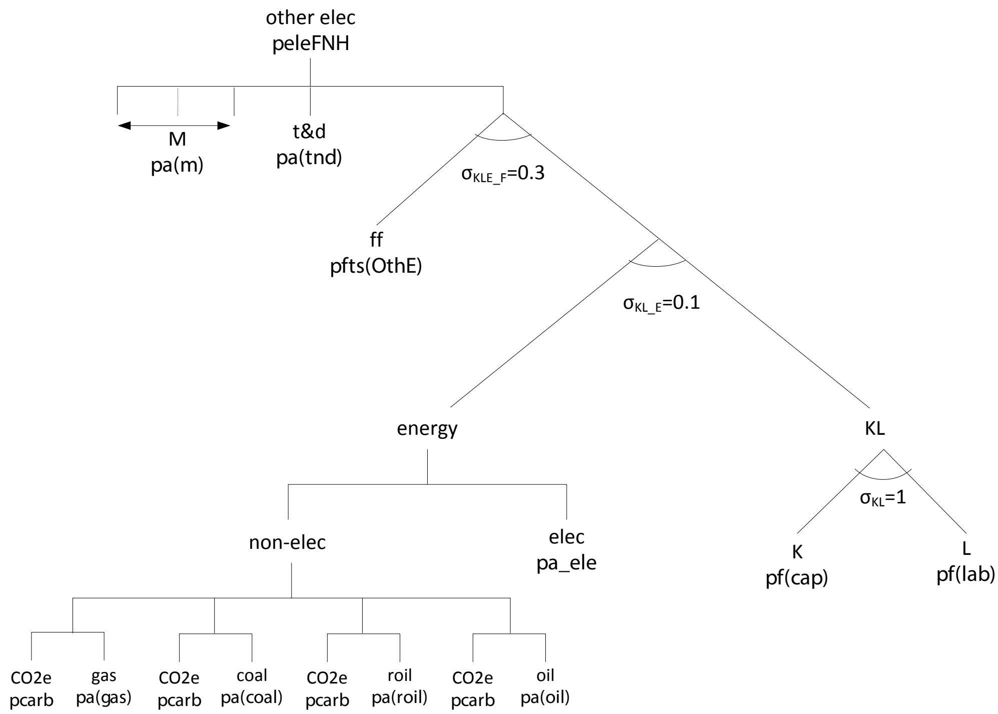
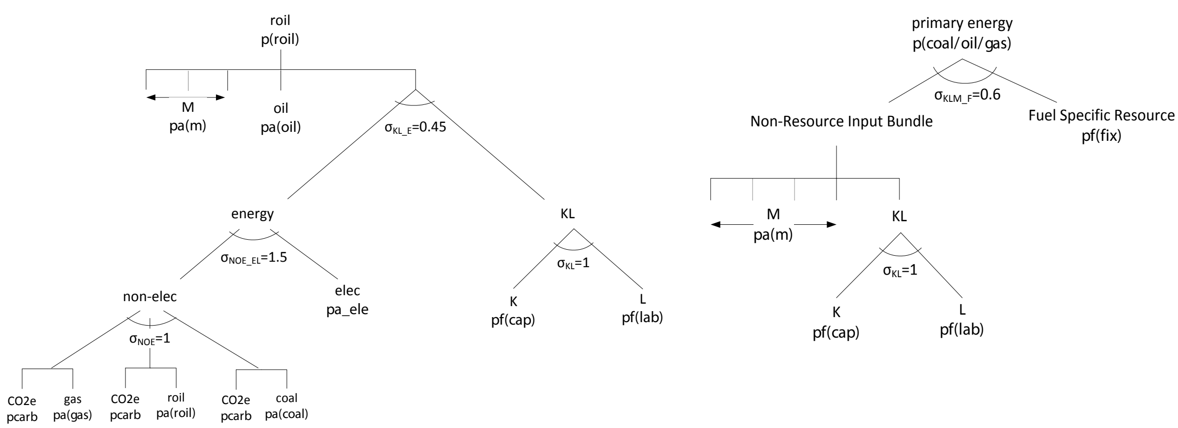


Figure A6. Nesting structure of generation from "other" sources (biomass, waste)



(a) Refined oil sector **(b) Primary energy sectors**

Figure A7. Nesting structure of energy sectors

Non-energy sectors are represented in two categories: agriculture and the rest of the production sectors. Since the land input is unique to agricultural production, the nesting structure for agriculture (**Figure A8**) includes substitution between land and other inputs. Natural resources and GHG emissions are included as fixed proportions in the top nest.

Figure A9 illustrates the nesting structure for non-energy sectors other than agriculture. The materials inputs are in fixed proportion to the energy-value-added composite, which combines energy and value-added with a CES function. The energy bundle assumes CES substitution between electricity and the non-electric energy. Non-electric energy inputs are combined with a CES function.

TR-EDGE aggregates imported and domestic goods to create an Armington composite (Armington, 1969) that captures the substitutability between domestic and imported goods. **Figure A10** (a) and (b) show the Armington formulation for the non-electric goods and electricity, respectively. Elasticity of substitution between imported and domestic goods is assumed to be 1 for electricity, 1.5 for non-electric energy goods and 3 for non-energy goods. The aggregate domestic output is allocated between domestic sales and exports subject to a constant elasticity of transformation (CET) with an elasticity of 2.

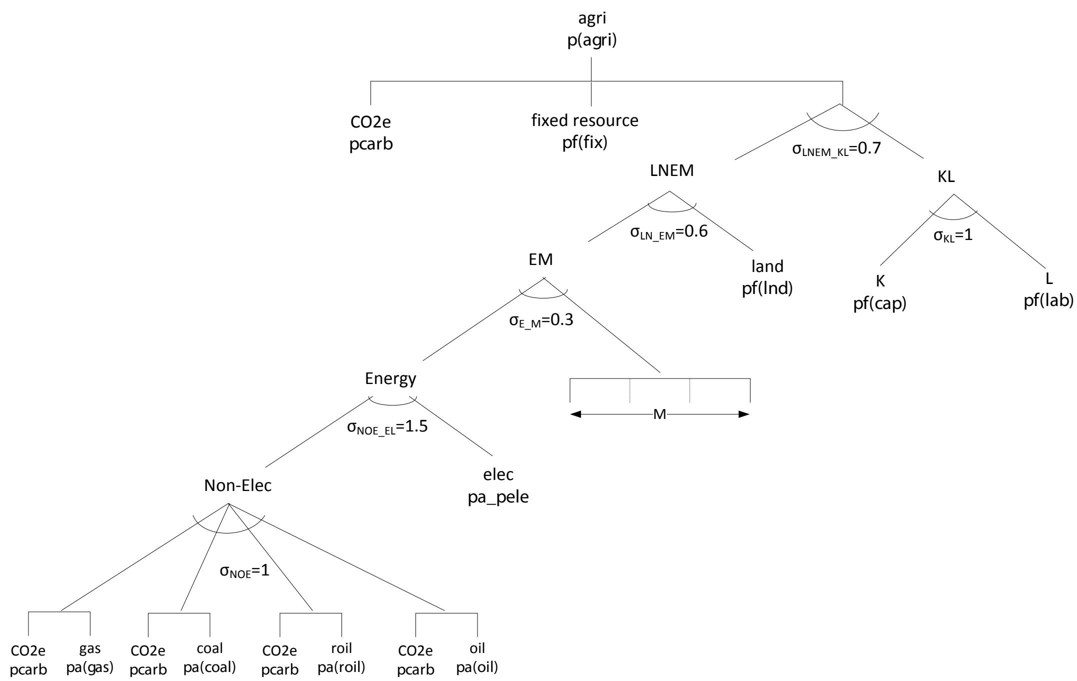


Figure A8. Nesting structure of agriculture sector

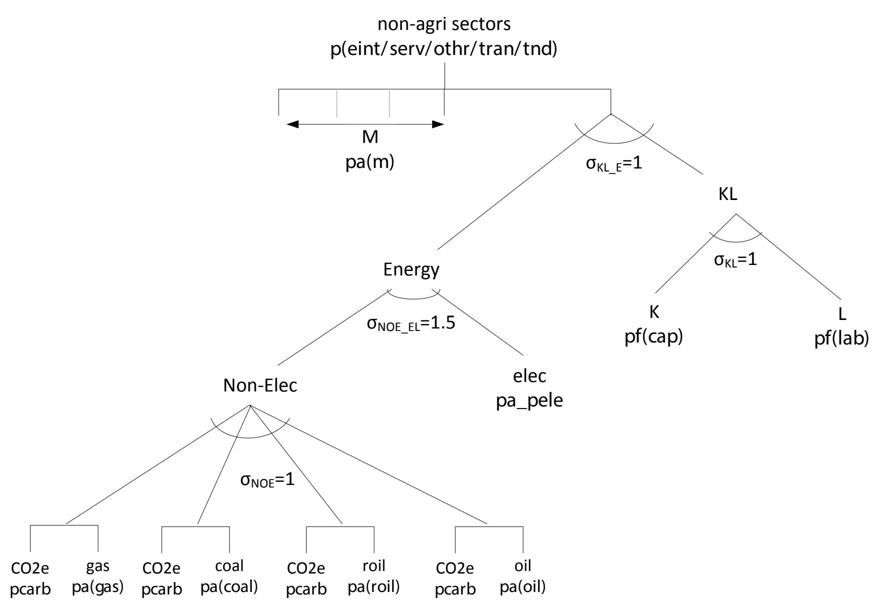
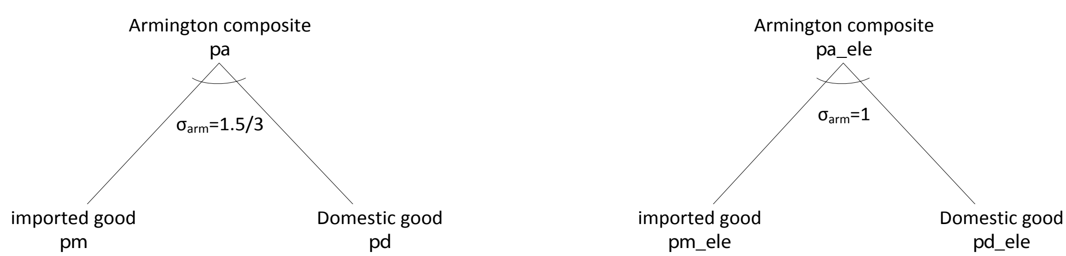


Figure A9. Nesting structure of Services, Transportation, Energy Intensive Industry, Other Industries, Transmission and Distribution



(a) Non-electric sectors **(b) Electricity sector**

Figure A10. Armington structure of non-electric sector and electricity sector.

Joint Program Report Series - Recent Articles

For limited quantities, Joint Program Reports are available free of charge. Contact the Joint Program Office to order.
Complete list: http://globalchange.mit.edu/publications

332. Turkish Energy Sector Development and the Paris Agreement Goals: A CGE Model Assessment. *Kat et al., Jul 2018*

331. The economic and emissions benefits of engineered wood products in a low-carbon future. *Winchester & Reilly, Jun 2018*

330. Meeting the Goals of the Paris Agreement: Temperature Implications of the Shell Sky Scenario. *Paltsev et al., Mar 2018*

329. Next Steps in Tax Reform. *Jacoby et al., Mar 2018*

328. The Economic, Energy, and Emissions Impacts of Climate Policy in South Korea. *Winchester & Reilly, Mar 2018*

327. Evaluating India's climate targets: the implications of economy-wide and sector specific policies. *Singh et al., Mar 2018*

326. MIT Climate Resilience Planning: Flood Vulnerability Study. *Strzepek et al., Mar 2018*

325. Description and Evaluation of the MIT Earth System Model (MESM). *Sokolov et al., Feb 2018*

324. Finding Itself in the Post-Paris World: Russia in the New Global Energy Landscape. *Makarov et al., Dec 2017*

323. The Economic Projection and Policy Analysis Model for Taiwan: A Global Computable General Equilibrium Analysis. *Chai et al., Nov 2017*

322. Mid-Western U.S. Heavy Summer-Precipitation in Regional and Global Climate Models: The Impact on Model Skill and Consensus Through an Analogue Lens. *Gao & Schlosser, Oct 2017*

321. New data for representing irrigated agriculture in economy-wide models. *Ledvina et al., Oct 2017*

320. Probabilistic projections of the future climate for the world and the continental USA. *Sokolov et al., Sep 2017*

319. Estimating the potential of U.S. urban infrastructure albedo enhancement as climate mitigation in the face of climate variability. *Xu et al., Sep 2017*

318. A Win-Win Solution to Abate Aviation CO_2 emissions. *Winchester, Aug 2017*

317. Application of the Analogue Method to Modeling Heat Waves: A Case Study With Power Transformers. *Gao et al., Aug 2017*

316. The Revenue Implications of a Carbon Tax. *Yuan et al., Jul 2017*

315. The Future Water Risks Under Global Change in Southern and Eastern Asia: Implications of Mitigation. *Gao et al., Jul 2017*

314. Modeling the Income Dependence of Household Energy Consumption and its Implications for Climate Policy in China. *Caron et al., Jul 2017*

313. Global economic growth and agricultural land conversion under uncertain productivity improvements in agriculture. *Lanz et al., Jun 2017*

312. Can Tariffs be Used to Enforce Paris Climate Commitments? *Winchester, Jun 2017*

311. A Review of and Perspectives on Global Change Modeling for Northern Eurasia. *Monier et al., May 2017*

310. The Future of Coal in China. *Zhang et al., Apr 2017*

309. Climate Stabilization at 2°C and Net Zero Carbon Emissions. *Sokolov et al., Mar 2017*

308. Transparency in the Paris Agreement. *Jacoby et al., Feb 2017*

307. Economic Projection with Non-homothetic Preferences: The Performance and Application of a CDE Demand System. *Chen, Dec 2016*

306. A Drought Indicator based on Ecosystem Responses to Water Availability: The Normalized Ecosystem Drought Index. *Chang et al., Nov 2016*

305. Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields. *Blanc et al., Nov 2016*

304. The Impact of Oil Prices on Bioenergy, Emissions and Land Use. *Winchester & Ledvina, Oct 2016*

303. Scaling Compliance with Coverage? Firm-level Performance in China's Industrial Energy Conservation Program. *Karplus et al., Oct 2016*

302. 21st Century Changes in U.S. Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. *Gao et al., Oct 2016*

301. Combining Price and Quantity Controls under Partitioned Environmental Regulation. *Abrell & Rausch, Jul 2016*

300. The Impact of Water Scarcity on Food, Bioenergy and Deforestation. *Winchester et al., Jul 2016*

299. The Impact of Coordinated Policies on Air Pollution Emissions from Road Transportation in China. *Kishimoto et al., Jun 2016*

298. Modeling Regional Carbon Dioxide Flux over California using the WRF-ACASA Coupled Model. *Xu et al., Jun 2016*

297. Electricity Investments under Technology Cost Uncertainty and Stochastic Technological Learning. *Morris et al., May 2016*

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/