TRANSPORT SECTOR ENERGY USE, ELECTRIC VEHICLE DEPLOYMENT AND CO_2 EMISSIONS IN TURKEY: AN EVALUATION USING THE BOGAZICI UNIVERSITY ENERGY MODELING SYSTEM

by

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ABSTRACT

TRANSPORT SECTOR ENERGY USE, ELECTRIC VEHICLE DEPLOYMENT AND CO2 EMISSIONS IN TURKEY: AN EVALUATION USING THE BOGAZICI UNIVERSITY ENERGY MODELING SYSTEM

Considering the data of CO_2 emissions of Turkey in 2017 by sectors, the main contributor is the energy sector with 41%, followed by the transport sector with 23% according to Turkey's latest National Inventory Submission. CO2 emissions from fuel combustion are driven by road transportation and power generation while emissions from oil products, mainly used in the transport sector, account for 27%. Road transportation that contains 90% of all passenger transport and 89% of all freight dominates Turkey's transport system and is responsible for 93% of CO_2 emissions from the transport sector. Based upon this interdependent relationship of power generation, transportation and CO2 emissions, this study evaluates the impact of electric vehicle deployment on power generation and CO2 emissions in Turkey using Boğaziçi University Energy Modeling System (BUEMS) which is designed as a linear optimization model to reflect Turkish energy system. In this study, BUEMS which estimates CO_2 emissions, energy technologies and primary energy supply levels for each 5-year time period between 2012 and 2052 has been calibrated according to the latest Turkish energy and transport data. All the complex relationships between producing, transforming, transmitting and/or supplying energy sources according to the useful demand characteristics are represented with great technological detail. The objective is the minimization of the total energy system cost. The levels and prices of the various energy sources are in equilibrium in each period, which guarantees that the net total cost of supplying all levels of energy services are minimized, while satisfying a number of constraints, such as, system constraints regarding energy sources, demands, capacities, activities, electricity generations, emissions and other optional constraints such as user imposed policy constraints, including emissions restrictions, bounds on activities, capacities, and energy source supply levels. For the base scenario definition, the current energy system of Turkey is represented with its business-as-usual assumptions, together with a modest prediction for electric vehicles. Based on the base scenario, various electric vehicle diffusion and policy scenarios have been carried out and the results of these alternative scenarios are compared with the base scenario.

ÖZET

TÜRKİYE’DE ULAŞTIRMA SEKTÖRÜ ENERJİ KULLANIMI, ELEKTRİKLİ ARAÇ YAYILIMI VE CO$_2$ EMİSYONLARI: BOĞAZİÇİ ÜNİVERSİTESİ ENERJİ MODELLEMESİ SİSTEMİ İLE BİR DEĞERLENDİRME

Türkiye’nin en son Ulusal Envanter Beyanına göre 2017 yılı Türkiye sektörel CO2 emisyon verileri dikkate alınırsa ana katkı payının %41 ile enerji sektöründe, ardından % 23 ile ulaştırma sektöründe olduğu görülür. Yakıtın yanmasından kaynaklanan CO2 emisyonlarına karayolu taşımacılığı ve enerji üretimi sektörü neden olurken, ağırlıklı olarak taşımacılık sektöründe kullanılan petrol ürünlerinden kaynaklanan emisyonlar %27 oranındadır. Tüm yolcu taşımacılığının %90'ını ve tüm yük taşımacılığın %89'unu oluşturan karayolu taşımacılığı, Türkiye'nin ulaştırma sistemine hakimdir ve ulaştırma sektöründen kaynaklanan CO$_2$ emisyonlarının %93'ünden sorumludur. Elektrik üretimi, ulaştırma sektörü ve CO$_2$ emisyonlarının birbirine bağımlı ilişkisine dayanarak, bu çalışma, Türk enerji sistemini yansıtacak şekilde doğrusal bir optimizasyon modeli olarak tasarlanan Boğaziçi Üniversitesi Enerji Modellemesi Sistemi (BUEMS) ile elektrikli araç kullanımının Türkiye'de elektrik üretimi ve CO$_2$ emisyonları üzerindeki etkisini değerlendirmektedir. Bu çalışmada, CO$_2$ emisyonlarını, enerji taleplerini ve birincil enerji arz seviyelerini tahmin eden BUEMS, Türkiye'nin en son enerji ve ulaştırma verilerine göre kalibre edildi. Faydalı talep karakteristiklerine göre enerji kaynaklarının üretilmesi, dönüştürülmesi, iletilmesi ve/veya tedarik edilmesinin tüm karmaşık ilişkileri büyük teknolojik detaylarla sunulmuştur. Amaç toplam enerji sistemi maliyetinin en aza indirilmesidir. Enerji kaynaklarının seviyeleri ve fiyatları her periyotta dengededir. Bu şekilde, enerji kaynakları, talepler, kapasiteler, faaliyetler, elektrik üretimi ve emisyonlarla ilgili sistem kısıtları ile emisyon, faaliyetler, kapasiteler, enerji kaynağı tedarik seviyeleri üzerinde kullanıcının uyguladığı politika kısıtlarına dair denklemler sağlanırken; tüm enerji seviyelerini tedarik etmenin net toplam maliyetinin en aza indirilmesi sağlanır. Baz senaryo, Türkiye'nin mevcut enerji sistemini, mevcut durum varsayımlarıyla birlikte elektrikli araçlar için mütevazı bir talep tahmini yaparak temsil etmektedir. Baz senaryoya dayanarak, çeşitli elektrikli araç kullanımı ve politika senaryoları gerçekleştirilmiş ve bu alternatif senaryoların sonuçları baz senaryo ile karşılaştırılmıştır.

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af	Annual availability factor
agr	Agriculture sector demand technology
c	Energy conversion technology
capunit	Unit conversion factor between capacity and activity of the technology
ce	Electricity generation technology
cf	Capacity utilization factor
ch	LTH generation technology
cm	Cumulative supply
cokeprod	Level of coke production of the technology
costinv	Discounted annual investment cost
crf	Capital recovery factor
cum	Supply cumulative capacity
cumem	Cumulative emission level
d	Demand technology
decayr	Decay rate
demand	Sectoral demand level of technology
discount	Discount rate
dm	Demand of energy utilization sectors
e	Energy carriers
edistinv	Unit investment cost for electricity distribution system
edistom	Unit operation and maintenance cost for electricity distribution system
eff	Efficiency rate
envact	Emission factor for energy conversion technologies
envcost	Emission cost per unit emission
envsep	Emission factor for supply technologies
etraninv	Unit investment cost for electricity transmission system

etranom	Unit operation and maintenance cost for electricity transmission system
fixom	Fixed operation and maintenance cost per unit capacity
growthr	Growth rate
ind	Industry sector demand technology
inpelc	Electricity demand level per unit activity
inpent	Level of input requirement
inplth	LTH demand level per unit activity of technology
invcost	Investment cost
k	Process technology
l	Lifetime of technology
life	Lifetime
limit	Activity limitation on a multiple output technology
m	All technologies
nyrsper	Number of years
outelc	Electricity generation level
outent	Level of output generation per unit of technology activity
outlth	LTH generation level per unit activity of technology
pdf	Period discount factor
pridisc	Periodic discount factor other than investment
priinv	Periodic discount factor for the investment
qhr_d	Fraction of the year "day share"
qhr_n	Fraction of the year "night share"
qhr_s	Fraction of the year "summer share"
qhr_w	Fraction of the year "winter share"
res	Residential sector demand technology
resid	Residual capacity that was invested prior to the start of the planning horizon
s	Supply technology
salvinv	Salvage component of the investment
scost	Supply cost
ser	Service sector demand technology
sex	Export technology

sim	Import technology
smn	Mining (extraction) technology
srn	Renewable technology
t	Time period
teent	Transmission efficiency
totcost	Total system cost
totemis	Total system emissions
tra	Transport sector demand technology
v	Emission type
varom	Variable operation and maintenance cost per unit activity of the technology
y	Year

LIST OF ACRONYMS/ABBREVIATIONS

BEV	Battery Electric Vehicle
BUEMS	Boğaziçi University Energy Modeling System
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CV	Conventional Vehicle
DTGM	General Directorate of Maritime Affairs
EFOM	Energy Flow Optimization Model
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCV	Fuel Cell Vehicle
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	Green House Gas
GPS	Global Positioning System
$GtCO_2$	Giga Tone Carbon Dioxide
GW	Giga Watt
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IETT	Istanbul Electric Tramway and Tunnel Establishments
kb/d	Kilo barrels per day
KGM	General Directorate of Highways
ktoe	Thousand tons of oil equivalent
kton	Kiloton
kW	Kilo Watt

kWh	Kilo Watt Hours
LEAP	Long-range Energy Alternatives Planning
LDV	Light-Duty Vehicle
LPG	Liquefied Petroleum Gas
LR	Learning Rate
LTH	Low Temperature Heat
MARKAL	Market Allocation Model
MENR	Ministry of Energy and Natural Resources
MoTI	Ministry of Transport and Infrastructure
$MtCO_2$	Million Tone Carbon Dioxide
Mtoe	Millions of tons of oil equivalent
Mton	Million ton
OECD	Organization for Economic Co-operation and Development
O&M	Operation and Maintenance
PEV	Plug-in Electric Vehicle
PJ	Peta Joule
R&D	Research & Development
TCDD	Turkish State Railways
TCO	Total Cost of Ownership
tCO_2	Tone Carbon Dioxide
TEIAS	Turkey Electricity Transmission Company
TIMES	The Integrated MARKAL-EFOM System
TK	Turkish Airlines
TUIK	Statistical Institute of Turkey
TWh	Tera Watt Hours
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US / USA	United States of America
USD	United States Dollars
VAT	Value Added Tax

1. INTRODUCTION

The International Energy Agency (IEA, CO_2 Emission from Fuel Combustion Report, 2018) indicates that global CO_2 emissions from fuel combustion in 2016 were 32.31 $GtCO_2$ similar to previous year (32.28 $GtCO_2$ in 2015). In consequence of increased economic output, emissions increased by around 40% since 2000. Global CO_2 emissions from fuel combustion were stable between the years of 2013 and 2016, they exceeded 32 $GtCO_2$ in 2013. On the other hand, initial IEA analysis (March 2018 - Global Energy & CO_2 Status Report) reported that 2017 emissions showed around 1.5% increase, particularly because of China, India and the European Union.

Considering that CO_2 emission sources for 2016, emissions from oil for transport and gas for electricity and heat generation grew by 120 $MtCO_2$ and 170 $MtCO_2$ respectively. In 2016 transport emissions showed 2% increase statistically similar to previous years. While emissions from oil and gas had smoother growth trends before 2013, they continued to rise about 4-5% depending on growing demand of oil for transport and gas for electricity production, especially in Asia and America for the last three years.

In 2016, 25% of total emissions (around 8 $GtCO_2$) was caused by transport sector with an increase rate of 71% according to 1990. Road had the highest absolute increase with +2.5 $GtCO_2$. Based on overall shares of 1990, while road transport emissions had 2% increase (from 72% to 74%), there was no increase in air and water transport. Considering the global transport CO_2 emissions by regions in 2016, The Americas had the highest transport emission levels all over the world and United States caused 69% of CO_2 emissions of the Americas, while China had 0.8 $GtCO_2$ (half of the US) emissions with a rate of 35% of transport emissions in Asia.

According to the IEA Electricity Information Report (2018), OECD (Organization for Economic Co-operation and Development) total electricity consumption was 9512 TWh in 2016 with 1.4% increase rate to previous year. Transport sector (mainly rail) is a smaller consumer of electricity. However, road transport has double-digit growth rates each year since 2012 in electricity consumption due to increasing electrification of the transport sector.

However, electricity used in road transport is only 0.07% of total electricity consumption despite the fact that market share of electric vehicles is growing across OECD countries, particularly in Europe.

Global sales of electric vehicles (EVs) – including passenger vehicles, commercial vehicles, buses, two- and three-wheelers – are estimated to have reached around 27 million in 2017. Most of these vehicles are two- and three-wheelers (around 26 million) and they are sold in China. Electric passenger vehicles (including passenger cars and passenger light trucks) is the next largest market. In 2017 their annual sales growth rose to 54% (to 1.1 million for the first time). With sales of around 100,000 totally, the electric bus market is stable in 2017 and electric cars are sold mostly in China (IEA World Energy Investment Report, 2018).

Since, excluding two- and three-wheelers, the share of EVs is still low (less than 0.4%), their impact on oil and electricity demand remains modest. Yet, electric cars, buses and commercial vehicles that were sold in 2017 (half of them are buses in China) will reduce global oil demand by around 30 thousand barrels per day (kb/d). Besides, the annual electricity needs of EVs sold in 2017 is around 10 TWh if two- and three-wheelers are included.

To actualize IEA’s Sustainable Development Scenario projections about EV expansion, the average annual electric car sales should grow 33% until 2030. Certainly, this EV deployment will hinge on a decrease in car prices and O&M (operation and maintenance) costs to meet customers’ expectations without unsustainable increases in government budgets for purchase incentives. Total purchase cost of electric cars sold globally in 2017 is USD 43 billion. Most of these purchases benefited from national or local government incentives (amounting to USD 10 billion). For electric car incentives (such as grants, tax exemptions and tax credits), public budgets have increased 55% around the world in recent years.

There is not yet a clear decline in average electric car prices. However, with increasing subsidies and a rising share in worldwide sales of China, sales-weighted average electric car prices are falling. As a result of cost reductions and smart EV policies, the need for development of charging infrastructure arises. In 2017, around 117,000 publicly accessible charging stations, at a total cost of around USD 3 billion, were installed globally. Currently, the total number of publicly accessible charging stations is 430,000. 25% of them are fast chargers and 50% of these charging points are in China.

IEA (Oil Information Report, 2018) indicates that the most used fuel in the world energy mix in 2016 is still oil. Its share increased from 31.8% in 2015 to 31.9% in 2016. In addition to that, the dominant oil consuming sector is road transport with 1927 Mtoe (82 Mtoe of biofuels, 42 Mtoe of natural gas and 4 Mtoe of electricity). Global consumption of oil in road transport has increased by 11.1% since 2011. Although the gap between motor gasoline and road diesel has been reduced in recent years, motor gasoline still dominates the sector.

According to the IEA World Energy Balances Report (2018), the reason for increase in energy consumption of OECD in 2016 is mainly due to growth in transport sector (+19 Mtoe). Considering the longer-term trends, the largest and fastest growing sector is transport with 1.6% growth rate in 2016. This increase in transport was particularly significant in road energy consumption in Mexico, Poland, Turkey, and the United States.

Considering the data of CO_2 emissions of Turkey in 2017 by sectors, the main contributor is the energy sector with 41%, followed by the transport sector with 23% according to Turkey’s latest National Inventory Submission (UNFCCC, 2019). CO_2 emissions from fuel combustion are driven by road transportation and power generation while emissions from oil products, mainly used in the transport sector, account for 27%.

Road transportation contains 90% of all passenger transport and 89% of all freight; dominates Turkey’s transport system and is responsible for 93% of CO_2 emissions from the transport sector. While rail transportation accounts for 4.4% of freight and 1% of passenger transport, maritime supplies 6% of freight transport. Considering newly registered vehicles in 2017, the share of diesel cars has strongly increased by 63% over the past decade.

Based upon this interdependent relationship of power generation, transportation and CO_2 emissions, this study evaluates the impact of electric vehicle deployment on power generation and CO_2 emissions in Turkey using BUEMS which is designed as a linear optimization model to reflect the Turkish energy system (Işık, 2016).

In this study, BUEMS, a bottom-up model, which presents the energy sector in a technologically detailed way and estimates CO_2 emissions, energy technologies and primary energy supply levels for each 5-year time period between 2012 and 2052, has been calibrated according to the latest Turkish energy and transport data. All the complex relationships of producing, transforming, transmitting and/or supplying energy sources according to the useful demand characteristics are represented with great technological detail. The objective is the minimization of the total energy system cost. The levels and prices of the various energy sources are in equilibrium in each period, which guarantees that the net total cost of supplying all levels of energy services are minimized, while satisfying a number of constraints, such as, system constraints (which are standard for any model application) regarding energy sources, demands, capacities, activities, electricity generations, emissions and other optional constraints such as user imposed policy constraints, including emissions restrictions, bounds on activities, capacities, and energy source supply levels.

For the base scenario definition, the current energy system of Turkey is represented with its business-as-usual assumptions, together with a modest prediction for electric vehicles. Based on the base scenario, various electric vehicle diffusion and policy scenarios have been carried out and the results of these alternative scenarios are compared with the base scenario.

Other chapters are structured as follows. Chapter 2 presents the literature review on modeling, deployment and learning/growth rates of electric vehicles. Modeling framework of BUEMS with its technologies, variables, equations and constraints is described in Chapter 3. Chapter 4 explains transport sector structure and data which are used when building scenarios in this thesis study. Chapter 5 briefly explains the base and alternative scenarios and compares the results of each scenario in terms of emissions, demand of electric vehicles and energy supply levels of transport sector particularly. Sensitivity analysis is addressed in Chapter 6. In the last chapter, results and suggestions are indicated.

2. LITERATURE REVIEW

2.1. Electric Vehicles and Transport Sector Modeling Literature

Zhang *et al.* (2016) compare transport sector in China and USA from a decarbonization perspective by using TIMES (The Integrated MARKAL-EFOM System) model. Transport sector affects the decarbonization of the entire energy system to a considerable extent. The study aims to further understand the transport service demands, energy consumption, and CO_2 emissions from a comparison perspective through the carbon tax scenario analyses, in which TIMES model applied for China and USA. According to model results, liquid fuels will keep dominating the transport energy consumption meanwhile biofuels and electrification will assist the decarbonization of the transport sector both in China and USA. Drawing attention worldwide, transport sector has a significant effect on energy system, oil demand, energy security and CO_2 emissions. The USA is the largest economy currently and responsible for 17.5% of the world's total CO_2 emissions in 2012. Transport sector of the USA accounts for 27.9% of the total final energy consumption and constitutes 31.7% of the total CO_2 emissions in 2011. Like China, road sector of the USA also causes a large part of the transport energy consumption, 87% of the total in 2010. The primary exogenous factor of transport-related energy consumption and carbon emissions in TIMES model is the transportation service demand, measured in passenger kilometer or ton kilometer. The factors that specify demand for transportation are income, population, and the weighted average service cost of transportation models and technologies. Examining the various levels along the energy and service flows eases the analysis of the decarbonization of transport sector. The final energy which vehicles with various technical levels and different fuel types consume, is determined by the energy service demands and supplied by the conversion of different fundamental energy sources. It can be worked to advance energy efficiency or reduce carbon emissions in each level. In the study, decarbonization characteristics and alternatives of transport in China and USA for future years are modeled by carrying out carbon tax scenarios and analyses. Based on the scenarios and their results, biofuel will reduce the carbon emissions in the near-term, and substitute at least 20% of oil products in China and USA by 2050. On the other hand, it is expected that electrification will help the decarbonization of transport sector in the long-term, as long as less carbon-intensive power generation technologies become more economical.

Wu and Aliprantis (2013) develop a model of light-duty plug-in electric vehicles for national energy and transportation planning in the USA. They analyze that in the model when it is switched from CVs (conventional gasoline vehicles) to HEVs (hybrid electric vehicles) and, then again switched to PEVs (plug-in electric vehicles), an increase in the capital cost and a decrease in the fuel cost happens. The ideal composition of LDVs (light-duty vehicles) change among groups due to dependence of reduction in fuel cost on the travel pattern. Extra electricity consumption caused by PEV charging raises capital and O&M costs, in addition to cost of extraction and transportation of primary energy sources like coal and natural gas. Caused by the variation of electric energy cost among regions, the optimal composition of LDVs varies a little across regions, among vehicles with the same travel pattern. Situations that display other GHG (greenhouse gas) limits are examined too, in which emissions go down linearly to 50%, 20%, and 10% of year-1 levels by year 40. It is starting to be increasingly expensive to cut down on GHG emissions, shown by the system cost incrementing as a super linear function of GHG emissions reduction. To quantify this, GHG reduction price is defined as the cost increase over total emissions decrease from one level to the next. With a stepped but aggressive introduction of PEVs combined with investments in renewable energy, cost from energy and transportation systems can be reduced by 5%, emissions from electricity generation and LDV tailpipes can be reduced by 10%, in a 40-year interval. By the time this planning horizon ends, gasoline consumption from LDVs per annum can be decreased by 66%, but an extra 800 TWh of yearly electricity demand will be faced, which constitutes for one-fifth of today's total yearly electricity consumption in the USA. When renewable sources are used for electricity generation instead of fossil fuels, cumulative GHG emissions can be decreased with a marginal cost increase. For instance, yearly GHG emissions can reach 50% of year-1 levels in year 40, cumulative GHG emissions can be decreased by 18.3% with only increasing the total system cost by 0.03%, checked against to the case where the LDV fleet is provided electricity without caring about emissions. GHG emissions can be reduced even more, but comes with an increasing cost.

Rezvani *et al.* (2015) study on advances in consumer electric vehicle adoption research. Despite positive environmental consequences of electrifying the light-duty vehicle fleet, total number of electric vehicles (EVs) in use is still small. EV is the key point for reducing dependency on fossil fuels that cause CO_2 emissions and other environmental problems. Almost 20% of EU's total CO_2 emissions is derived from road transport. Between the years of 1990 and 2010, CO_2 emissions from road transport showed 23% increase and are still growing. Most of light-duty vehicles – cars and vans (often called passenger cars) – which are producing around 15% of the EU's CO_2 emissions currently in traffic are owned by private individuals. Regarding climate change, many governments have incentives to reduce CO_2 emissions by encouraging production, introducing and adopting EVs.

Contreras *et al.* (2009) model energy consumptions by vehicle and fuel types in the road transport sector of Madrid by using the MARKAL (Market Allocation) model for the period 2010-2050. Total energy consumption, sources, yearly amounts, vehicle fleets, population, passenger and cargo transport per kilometer, evolution ratio of the demand for energy and emissions data are collected in order to define the energy model. Also, technology and types of automotive fuels and vehicles are defined. Buses, cars, vans, two and three wheeled vehicles, light, medium and heavy trucks are included as vehicle types. For the model, three scenarios are built based on the average annual growth rate for transport sector: a base scenario with 2.5% and two alternative scenarios with 1.2% and 3.7%. According to the minimum growth scenario, almost 50% of the consumption is conventional fuels, while the rest is alternative fuels and hydrogen. In the base scenario, 23.3% of total consumption is conventional fuels, 18.6% alternative fuels, 3.6% electricity and 54.5% hydrogen. In the maximum growth scenario, two-thirds of total consumption is hydrogen and other alternative fuels.

Tsita and Pilavachi (2017) evaluate decarbonizing of the Greek road transport sector using alternative technologies and fuels. In order to decarbonize the Greek road transport sector, a number of scenarios of alternative technologies and fuels are built using the Long-range Energy Alternatives Planning (LEAP) software. For the scenarios, light and heavy duty vehicles are considered and time period is taken from 2010 (baseline year) to 2050. In the base scenario targets for the development of renewable energies and the reduction of GHG emissions are also included. Currently, internal combustion engines dominate transportation market. For alternative scenarios, hybrid vehicles, electric vehicles, fuel cell vehicles, biofuels and gas engine vehicles are defined regarding the vehicle technologies and fuels. The result shows that Greek road transport sector can be decarbonized using combinations of these vehicle technologies and fuels. In the best alternative scenario, CO_2 emissions are reduced by 38% (from 16,995 ktons CO_2 down to 10,531 ktons) and energy consumption is decreased by 26% (from 5784 ktoe down to 4299 ktoe) compared to the base scenario. As a result of the base scenario, in 2050 LDV energy consumption shares will be like 52% internal combustion engine (ICE) vehicles, 24% hybrid vehicles, 3% EVs, 1% fuel cell vehicles (FCV), 9% biofuels and 11% gas engine vehicles. HDV (heavy duty vehicle) energy consumption shares of year 2050 are expected as 91% ICE vehicles, 7% biofuels and 2% gas engine vehicles. Year 2050 results of the first alternative scenario are gasoline and diesel share (ICE and hybrids) decreases from 76% to 62% for LDV energy consumption and reduces from 91% to 68% for HDV energy consumption compared to the base scenario. In the second alternative scenario, gasoline and diesel share decreases from 76% to 59% for LDV and reduces from 91% to 66% for HDV in year 2050.

Wangsness (2018) examines what characterizes second-best road prices of driving EV and ICE vehicles and how this pricing fits with government goals related to reducing CO_2 emissions. An analytical framework is developed to determine road prices on vehicle kilometers. The results show that optimal road prices strongly depend on external cost. In large cities during peak hours, road prices for ICE vehicles are the highest because of high external costs. On the other hand, in rural areas, the road price for ICE vehicles is lower than that for EVs because of large fiscal interaction effects. Road prices are calculated by considering vehicle types, area (large cities, small cities, rural), car life span, vehicle kilometer, EV electricity intensity, electricity consumer price, fossil fuel price, Purchase tax + VAT, external congestion and non-congestion costs per kilometer and other tax rates. According to the model, driving an ICE vehicle in a large city during peak hours has the highest price due to external congestion costs. However, driving an ICE vehicle in rural areas has the lowest price. It is even lower than for EVs in these areas.

Robinson *et al.* (2013) analyze electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips. EV driver recharging demand profiles are determined by studying EV driver recharging habits in the north east of

England. 31765 EV trips, 7704 EV recharging events and 23805 recharging hours are analyzed for a six month period. The study shows that different user types and locations affect recharging profiles. Peak demand of private users is in the evening and at home recharging points. Organization pool users generally recharge in working hours at public points. Organization induvial users recharge when they arrive at work. There are three Plugged-in-Places schemes for national recharging infrastructure in UK. The scheme in the north east of England has 91 pieces of 3 kV home recharging points, 268 pieces of 3 kV public/work recharging posts and 8 pieces of 50 kV public/work fast chargers. $150 is paid as an annual membership fee by drivers. After that payment, additional electricity costs or parking charges are not taken. Parameters such as time of day, GPS coordinates, battery current, battery voltage and state of charge, temperature are recorded continuously. As a result, organization pool users have the highest average number of trips in the period with 520 trips. However, private users come in first in terms of average total distance traveled by traveling 4955 km and have the highest average trip length with 11.6 km.

Weiss *et al.* (2012) investigate learning rates and price forecasts for hybrid-electric and battery-electric vehicles. HEVs and BEVs (battery-electric vehicles) are more expensive than conventional passenger cars in the current situation. By technological learning they may become cheaper in the future. Since 1997, HEV prices have decreased 5-9% and price differential at learning rates has reduced 18-28%. It is expected that HEVs will be the dominant vehicle technology within 20 years while BEVs need time. Learning-by-doing, economies of scale, technological innovation and factor substitution mechanisms are referred to as technological learning which can be explained by experience curves. Production costs of HEVs and BEVs are estimated using the experience curve approach. Declining battery costs and improvements in battery performance are the main reasons of price decline. According to their forecast, BEVs may need learning investments of around 100 billion euro to reach price breakeven with HEVs and 150 billion euro for conventional ICE vehicles.

2.2. Electric Vehicles Deployment and Learning Rates Literature

Morrison *et al.* (2018) estimate the costs of battery electric (BEV) and hydrogen fuel cell electric vehicles (FCEV) from today up to 2040 to investigate the potential market size of both vehicle types. Initially, the total cost of ownership (TCO) – including vehicle purchase, fuel, maintenance, resale, and refueling inconvenience – is approximated for 77 light-duty vehicle (LDV) parts classified by driving range and size class. Secondarily, the portion of vehicle owners contained within each of the 77 parts is estimated using the information gathered on individual travel behavior. The estimations for 2020 are as follows: Up to 79–97 % of the LDV fleet, BEVs will be the cheaper vehicle option and have a weighted average cost advantage of $0.41 per mile below FCEVs among all vehicle categories and drivers. On the other hand, costs of the two powertrains change fast between 2025 and 2030. By the time 2040 arrives, FCEVs are approximated to be cheaper than BEVs per mile, constituting around 71-88 % of the LDV fleet and provide significant cost advantages in larger vehicle categories and for drivers with longer daily driving time. In the study, a competitive market for FCEVs and BEVs is shown in order to supply for the various needs of LDV consumers. According to the analysis, primarily, the TCO difference between BEVs and FCEVs declines over time, as it was predicted. Secondarily, the comparative change in costs over time is softly in favor of FCEVs, as an example majority of the high-mileage vehicle parts are cheaper for FCEVs by 2040. Thirdly, higher range BEVs compete less with FCEVs. It is found that both FCEVs and BEVs have market shares with essential cost advantages over one another from time to time, especially in early years. For instance, there is a more than $1.00 per mile cost advantage of a BEV-50 pickup truck in 2020 over an equivalent FCEV. As the relative TCOs turn to be more favorable for FCEVs, it is found that the number of FCEV-competitive parts increase over time and the effect of detour trips declines. Within all vehicle categories, not including pickup trucks, all except the 50- and 100-mile range segments of the 77 range-size class segments will be less expensive for FCEVs than BEVs by 2040.

Ratner and Zaretskaya (2018) intend to advance a method of forecasting the environmental effects of diffusion of EV technologies and put it to test on the example of the Krasnodar region of Russia, where is subject to the highest motorization ratios in the country. The recommended paradigm to anticipate the environmental outcomes of diffusion of EV technologies lets us predict the decline in emissions due to road transport in anywhere without causing a distortion in direction and speed of the following main trends: the growth of energy efficiency and environmental performance of traditional cars with combustion engines, the growth of the level of motorization of the population in Russia, and reduction of EVs costs. Learning curves methodology is used to foresee economic (the cost-competitiveness of individual elements in addition to finished products) and ecologic (CO_2 emissions) outcomes of all worked technologies such as traditional and improved internal combustion engines, variant car technologies (electric), in addition to electricity generation technologies which is in conjunction with electric cars. A homologous model is also declared for predicting the cost-competitiveness of electric cars. In this respect, a model that contains independent variables which show the core cost factor of electric cars and global electric cars stock is used. In this study, the core cost factor, which seen as the initial cost factor of the whole electric car in majority of modern research, is the cost of batteries for an electric vehicle ($/kWh). According to the forecasts declared in the Paris Declaration on Road Transport and Climate Change (UNFCCC 2015), the forecast of the International Energy Agency (IEA 2016), the forecast of the Ministry of Economy, Trade and Industry of Japan (METI 2016) and forecast of OECD (OECD 2015), the total global manufacture of electric vehicles' growth rate is predicted. The yearly anticipated growth rates have an average value of 10-12% regarding the data gathered from previously mentioned sources. Progress rates of EV technologies model estimate the learning rate in EV production and R&D as 10%. This expresses the 10% reduction of the unit cost of the battery in $/kW*h relating to doubling volume of the total production. It also provides us the prediction of progress rate as 15%, gained from learning-by-doing and learning-by researching. Now, a 15% increase in battery capacity, measured in kilowatt-hour/liter, can be expected, resulting from doubling of the total EV production volume. It is obtained that for the time up to 2025, in comparison to the levels of the year 2016 the total global production will be twice the size, at least 3 times- in 2018, 2021 and 2024. This makes us conclude that the cost of electric vehicles can fall down by 30% in 2025, compared to 2016. Assuming that the tempo of deployment of EV in Krasnodar Region is the same as the tempo of cost reduction besides EV penetration level is currently zero. The diffusion level of electric vehicles rises linearly up to 30% by the time 2025.

Safari (2018) states the significance of accurate price forecasts of battery electric vehicles (BEVs) for fitted policies. To determine deployment prospects of BEVs, an ex-post analysis of their learning rate and an ex-ante forecast of their price until 2040 are made and ICE vehicles which are in the same league with BEVs are used. Driving range, maximum speed of a vehicle, electrification components (battery pack, electric motor, power electronics etc.) and electrification cost parameters are considered in the price calculations of a BEV. According to price forecasts, government support for BEVs is needed to achieve breakeven price in terms of initial capital cost with ICE vehicles before 2040 with the estimated learning rates of 9±2% for the price and 15±1% for electrification costs. This learning rate which is lower than the 18±9% average rate of cost decline in energy demanding technologies, is insufficient for the deployment of electrified road transport.

According to the study of Berckmans *et al.* (2017), ICE vehicles are still the dominant product of the market in the current situation. But the market share of ICE vehicles is expected to drop from 99% in 2015 to 68% in 2030 while HEVs and BEVs start to rise in the market by the help of significance decrease in cost of battery. Price for silicon based batteries will catch 100 Dollar/kWh limit between 2020-2025 while lithium Nickel Manganese Cobalt Oxide batteries is estimated to reach 100 Dollar/kWh sales barrier between 2025 and 2030. According to this decrease in the battery prices will contribute to deployment of electric vehicles since batteries are the biggest cost item of electric vehicles.

Ruffini and Wei (2018) study a life cycle cost analysis of FCEVs comparing them to other vehicle technologies, assuming the implementation of international adoption tasks by a learning rate method. According to the results, the main element in making FCEV life cycle costs analogous to ICE vehicles costs is the fuel cell system. If the learning rate happens to be 18%, FCEVs are predicted to be comparable in cost with ICE vehicles by 2025, but if the rate is 8%, this situation is postponed nearly 25 years. Fueling infrastructure requires a big restoration and huge investment in both BEV and FCEV cases, but there seems to be more obstacles for FCEVs. High primal cost and customers' sense of insufficient performance and use of alternative vehicles are the core obstacles in customer adoption. Main technical problems with BEVs are: battery costs, driving range, and battery charging time. FCEVs are similar to ICE vehicles in the sense of driving scale and refueling period. On the contrary, fuel cell system costs and fueling infrastructure are initial hardships for FCEV. Below table gives a brief list of the learning rates used in this study. A floor cost is determined for individual vehicles' components, representing the lowest threshold value that can be obtained.

Table 2.1. Vehicle's learning rates and floor costs assumptions (Ruffini and Wei, 2018).

Component	**Learning rate**		**Floor cost**	
	FCEV	**BEV76**	**FCEV**	**BEV76**
FC system	18%	-	\$30/kW	-
H_2 tank	15%	-	\$266/kgH2	-
Battery	8%	8%	\$125/kWh	\$125/kWh
Electric motor	10%	10%	\$5.30/kW	\$5.30/kW

Suppose that between 2020 and 2025, Fuel Cell (FC) learning rate (LR), also this rate is break-even point with ICE vehicles, is 18%. At the same time BEV76s (driving range of 76 miles) are more or less \$2000 lower in life-cycle cost. The competition with gas-fueled cars is postponed about 25 years and the difference between costs compared to BEV76s is around \$10,000 in 2030 with a FC system LR of 8%. In this lower learning rate case, implementing long term actions and subsidies for FCEVs would be necessary, so they can compete with ICE vehicles and BEV76s in price.

Creti *et al.* (2018)'s goal is to replace 7.5 M gas-fueled vehicles by hydrogen vehicles over a period of 35 years (2015-2050). Initially, the production cost of a hydrogen vehicle is much higher at 60k euros than the cost of a gas-fueled vehicle at 22k euros. The manufacturing cost will decrease to 22.8k euros, making sum of the ownership costs of both technologies nearly come together in 2050. This is indicated by the learning-by-doing and the total manufacture of 13.4 M hydrogen vehicles. Supposing a 4% discount rate, the discounted transition cost of this process is predicted at 21.6 bn euros, implying 2882 euros per vehicle in the 7.5 M car park. An entire deployment schedule is taken into account. This method takes us to the lasting replacement of a given car park of 7.5 M units of gas-fueled cars by hydrogen cars over 35 years, 2015-2050. The first observation is the production cost of hydrogen cars falling from 60k euros in 2015 to 22.8k euros in 2050 by learning-by-doing. In addition, the infrastructure cost will decrease. The TCOs of hydrogen and gas-fueled cars will meet at 5.8k euros, in 2050. This is reached through a deployment cost of 21.6 bn euros. In time, the emissions that are kept away from increases to and balances at 2.18 t/year.

Table 2.2. Evolution of the discounted dynamic abatement cost with respect to the main parameters (Creti *et al.*, 2018).

Discounted DAC		**Market share**	**Gasoline price**	**Learning rate**
Scenario	**€ per tCO_2**	**% of total market**	**% annual growth rate**	**% decrease in cost for every doubling of cumulative production**
High	80	12	0.7	6.9
Base	52	15	1.4	6.8
Low	30	18	0.7	6.9

3. THE BUEMS MODELING FRAMEWORK

Boğaziçi University Energy Modeling System (BUEMS) is designed as a linear optimization model to reflect the Turkish energy system (Işık, 2016). BUEMS is built in a bottom-up structure, representing the energy sector in a technologically detailed way and featuring to evaluate various diffusion and policy scenarios and their long-term effects. It tries to find the minimum cost combination of energy technologies to meet final energy demands under model constraints over the pre-specified time horizon.

BUEMS estimates CO_2 emissions, energy technologies and primary energy supply levels throughout a pre-defined planning horizon using the General Algebraic Modeling System (GAMS) as programming language.

The objective is the minimization of the total energy system cost. The levels and prices of the various energy sources are in equilibrium in each period, which guarantees that the net total cost of supplying all levels of energy services are minimized, while meeting final demands and satisfying a number of constraints, such as, system constraints (which are standard for any model application) regarding energy sources, demands, capacities, activities, electricity generations, emissions and other optional constraints such as user imposed policy constraints, including emissions restrictions, bounds on activities, capacities, and primary energy resource levels (Kumbaroğlu, 2019).

3.1. The General Description of BUEMS

The BUEMS structure is similar to MARKAL and TIMES with regard to energy sources, energy services, technologies and their relations in the modeling system. BUEMS working mechanism is created to minimize data needs. The BUEMS framework starts from extraction and importation of primary energy sources, goes on with processing of conversion technologies and ends up with consumption of energy by end-use energy sectors.

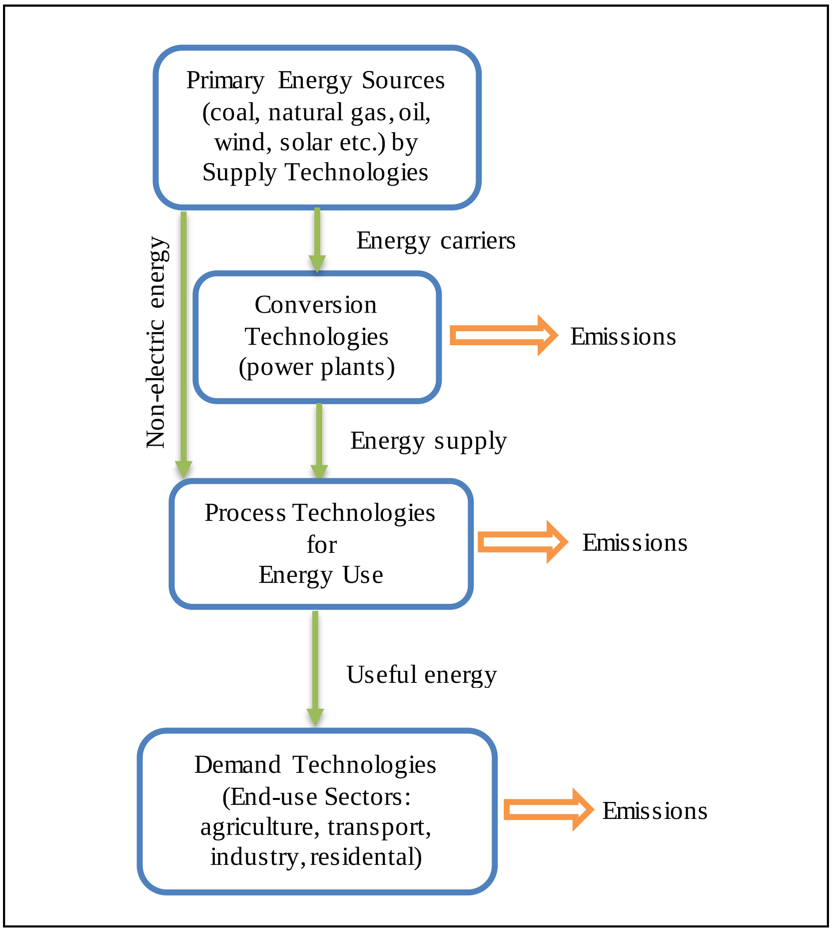


Figure 3.1. General framework of BUEMS.

Solution method of BUEMS is linear programming. In the end, BUEMS comes up with an optimal solution at minimum cost that meets energy demands by energy technologies considering the model constraints.

BUEMS working mechanism can be defined as follows. There are commodities that are introduced to the system by extraction, import and/or renewable resources. These commodities can be used directly as non-electric energy by process technologies. As a different way, they can be also used as energy carriers for power generation part of conversion technologies before they become energy supplies. After these processes, they are defined as useful energy for each energy sector such as agriculture, transport, industry and residential sectors. Within this flow, conversion technologies processes and demand devices emit CO_2 emissions.

In the next sections, terms of commodity, technology and demand devices are explained in detail and then, the model structure includes variables, the objective function, equations and constraints are described in depth. Therefore, sets and related abbreviations mentioned in the following sections are described below.

Table 3.1. Descriptions of set abbreviations.

Abbreviation	**Description**
c(m)	Energy Conversion Technology
ce(m)	Electricity Generation Technology
k(m)	Process Technology
d(m)	Demand Technology
agr(m)	Agriculture Sector Demand Technology
ind(m)	Industry Sector Demand Technology
ser(m)	Service Sector Demand Technology
res(m)	Residential Sector Demand Technology
tra(m)	Transport Sector Demand Technology
e	Energy carriers
m	All Technologies
l	Time segment
s(m)	Supply (Resource) Technology
sex(m)	Export Technology
sim(m)	Import Technology
smn(m)	Mining (Extraction) Technology
srn(m)	Renewable Technology
t	Time period
v	Emission type
y	Year

3.2. Commodities and Technologies

There are two main components, commodities and technologies in the BUEMS. The set of commodities which is generated or introduced by technologies forms the energy carriers. Coal, geothermal, hydrogen, hydropower, natural gas, nuclear, petroleum, solar and wind energy sources are all defined as energy carriers of which BUEMS has 209 in its structure. A commodity includes anything related to energy carriers that is generated or processed by a technology.

A technology is described as a tool that transforms one commodity into another type by processing, converting or transmitting. For instance, importing natural gas to introduce a primary energy resource to the system or an aircraft with jet-fueled used for transport sector. Each technology has some parameters such as operating and maintenance cost, investment cost, efficiency rate etc. in the modeling system.

In BUEMS, three main types exist for technologies: supply, energy conversion and demand. Description of these technologies and their connection via energy sources are explained in the following sub-sections.

3.2.1. Supply Technologies

Supply technologies do not require a commodity as input different than other technologies, besides they introduce primary energy sources into the system for the first time. Their mission is to provide energy carriers for the system because the model only be able to perform with energy sources.

Ways of introducing energy sources into the system are domestic supply (mining and renewable resources), importation and exportation. Import sources are included by import technologies and export sources are excluded by export technologies. On the side of domestic supply, mining (extraction) technologies and renewable technologies provide energy carriers.

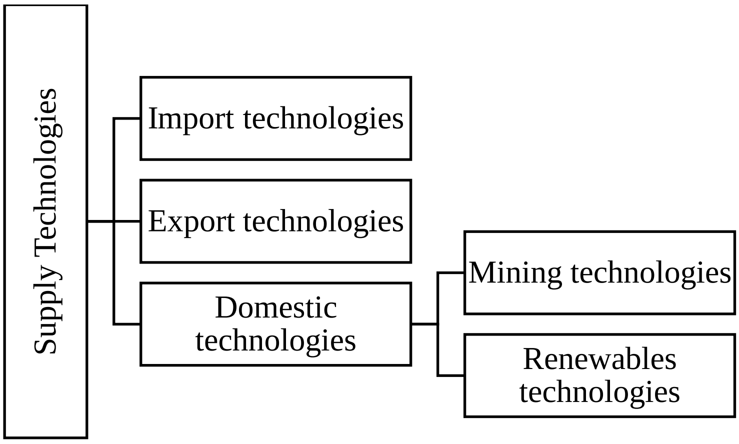


Figure 3.2. Supply technologies.

BUEMS has 108 energy resources totally such as fossil fuels (coal, natural gas, oil, jet fuel and kerosene etc.), renewables (solar, wind, geothermal, and hydroelectric), hydrogen and uranium for nuclear power generation.

The parameters for supply technologies in the model are supply cost, maximum available capacity, lower and upper bounds and decay/growth rates for each time periods throughout the planning horizon. Upper and lower bounds limit supply levels while cumulative capacity limits total supply for supply technologies during the whole periods. Decay and growth bounds indicate decay and growth rates for supply technologies.

Supply technologies also have a supply cost. Supply cost which is a unit cost for energy carriers to be introduced into the system is substantial point of objective function. While renewable sources do not cause a supply cost, fossil fuels have a considerable supply cost.

All these mentioned parameters are summarized below:

- bound_s_upper(s,t) : upper bound on the capacity at period t
- bound_s_lower(s,t) : lower bound on the capacity at period t
- bound_s_fix(s,t) : fix bound on the capacity at period t
- cum(m,cm) : supply cumulative capacity at period t
- decayr(m,t) : decay rate at period t
- growthr(m,t) : growth rate at period t
- scost(m,t) : supply cost at period t
- envsep(m,t) : emission factor at period t

3.2.2. Energy Conversion Technologies

Mission of energy conversion technologies is to transform an energy carrier to another one. They convert an energy carrier through their one of the three sub-category in order to be able to use by another demand device.

Electricity generation facilities are called as electricity generation technologies, while low temperature heat (LTH) production facilities are named as LTH generation technologies.

Other facilities that produce ethanol, methanol, coke and hydrogen etc. belong to process technologies.

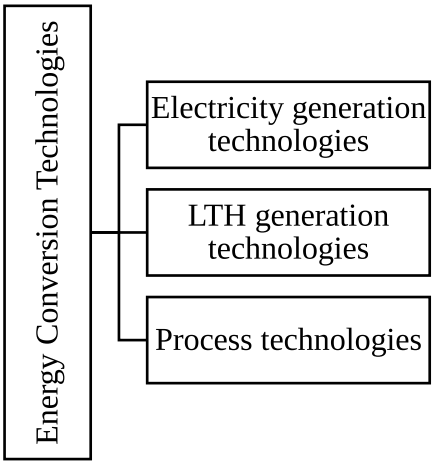


Figure 3.3. Energy conversion technologies.

Parameters of conversion technologies are mainly related to their investment level, capacity level, and activity level that indicate investment costs, maximum capacities, availability rates respectively. Operation and maintenance costs, emission factors and costs are other parameters of energy conversion technologies. These parameters are explained in Table 3.2 and Table 3.3.

Table 3.2. Descriptions of parameters.

Parameters
af (m,t) : annual availability factor of the technology m at period t
baseload(e,t) : the highest percentage of the baseload power plants in total electricity generation at period t
bound_c_lower(m,t), bound_c_fix(m,t), bound_c_upper(m,t) : annual lower, fix and upper bounds on the activity of a conversion technology at period t
bound_k_lower(m,t), bound_k_fix(m,t), bound_k_upper(m,t) : annual lower, fix and upper bounds on the activity of a process technology at period t
bound_p_fix(m,t), bound_p_upper(m,t) : annual fix and upper bounds on the capacity of a technology at period t
bounds(b,t) : annual bounds on scenario constraints at period t
capunit(m,t) : unit conversion factor between capacity and activity of the technology m at period t
cokeprod(e,t) : level of coke production of the technology e at period t
cumem(v,cme) : cumulative emission level of emission type v
decay(m,t) : maximum capacity decay rate of the technology m between consecutive periods
dtraninv(m,t) : unit investment cost for LTH transmission system of LTH generation technology at period t
dtranom(m,t) : unit operation and maintenance cost for LTH transmission system of LTH generation technology at period t
edistinv(m,t) : unit investment cost for electricity distribution system of electricity generation technology at period t
edistom(m,t) : unit operation and maintenance cost for electricity distribution system of electricity generation technology at period t
envact(m,t) : emission factor for process technologies at period t
envcost(v,t) : emission cost per unit emission at period t
ereserv(e,t) : peak reserve factor for electricity generation at period t
etraninv(m,t) : unit investment cost for electricity transmission system of electricity generation technology at period t
etranom(m,t) : unit operation and maintenance cost for electricity transmission system of electricity generation technology at period t
fixom(m,t) : fixed operation and maintenance cost per unit capacity of the technology m at period t
growth(m,t) : maximum capacity growth rate of the technology m between consecutive periods
hreserv(e,t) : peak reserve factor for LTH generation at period t

Table 3.3. Descriptions of parameters.

Parameters
ibond(m,t), ibondfx(m,t), ibondlo(m,t) : annual lower, fix and upper bounds on the investment of the technology m at period t
inpent : level of input requirement per unit of technology activity
invcost(m,t) : investment cost per unit of new capacity addition of the technology m at period t
life(m,l) : useful lifetime of the technology m
limit(m,t) : activity limitation on a multiple output technology
outent : level of output generation per unit of technology activity
peakcon(m,t) : the fraction of the technology m's capacity that should be credited towards the peaking requirement at period t
qhr_d(m,t) : fraction of the year "day share"
qhr_n(m,t) : fraction of the year "night share"
qhr_s(m,t) : fraction of the year "summer share"
qhr_w(m,t) : fraction of the year "winter share"
refinhlm(e,t) : "refinery parameter 1" for activity limitation on a multiple output technology at period t
refinstd(e,t) : "refinery parameter 2" for activity limitation on a multiple output technology at period t
resid(m,t) : residual capacity that was invested prior to the start of the planning horizon
teent(e,t) : transmission efficiency of electricity at period t
varom(m,t) : variable operation and maintenance cost per unit activity of the technology m at period t

3.2.3. Demand Technologies

Demand technologies, in other words demand devices, provide useful energy to meet the final demand needed in the energy utilization sectors by end-use technologies. They are separated into five main groups which are agriculture, residential, industry, transport and service demand sectors, and have a total ninety nine sub-sector demands in BUEMS.

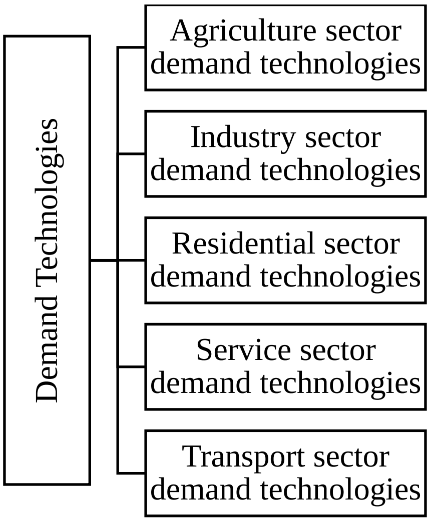


Figure 3.4. Demand technologies.

In the model, each demand device can be defined in its own consumption unit such as billion vehicle kilometers traveled for transport sector. In this case, each demand technology has a conversion factor which converts the unit of energy carrier into the unit of needed demand of the energy utilization sector.

Demand technologies have capacity and investment variables but do not have activity level variables different than energy conversion technologies. Because their activity level is proportional to their capacity and this rate is identified by capacity utilization factor. The capacity utilization factor is not same with annual availability factor. While capacity utilization factor represents active capacity ratio throughout the periods, annual availability factor gives at most available capacity share for each period. Thereafter, capacity and activity levels are made same units by using unit conversion factor for demand devices.

Moreover, input/output ratio of energy conversion technologies gives their efficiency rates, while “eff(m,t)” parameter directly indicates the efficiency rate of each demand technology. Additional parameters for demand devices which are different than energy conversion technologies are described below.

- cf(m,t) : capacity utilization factor at period t
- eff(m,t) : efficiency rate of demand technologies at period t
- demand(dm,t) : sectoral demand level of technology dm at period t

Data input for demands of energy utilization sectors is made exogenously into the modeling system for the base year 2012 and year 2017, then future demand projections for the next periods are predicted based on GDP projections. Demand data required by energy sectors except transport sector are taken from Isik (2016). Demand data of transport sector for years 2012 and 2017 are updated as a part of this study and explained in detail through the following chapter.

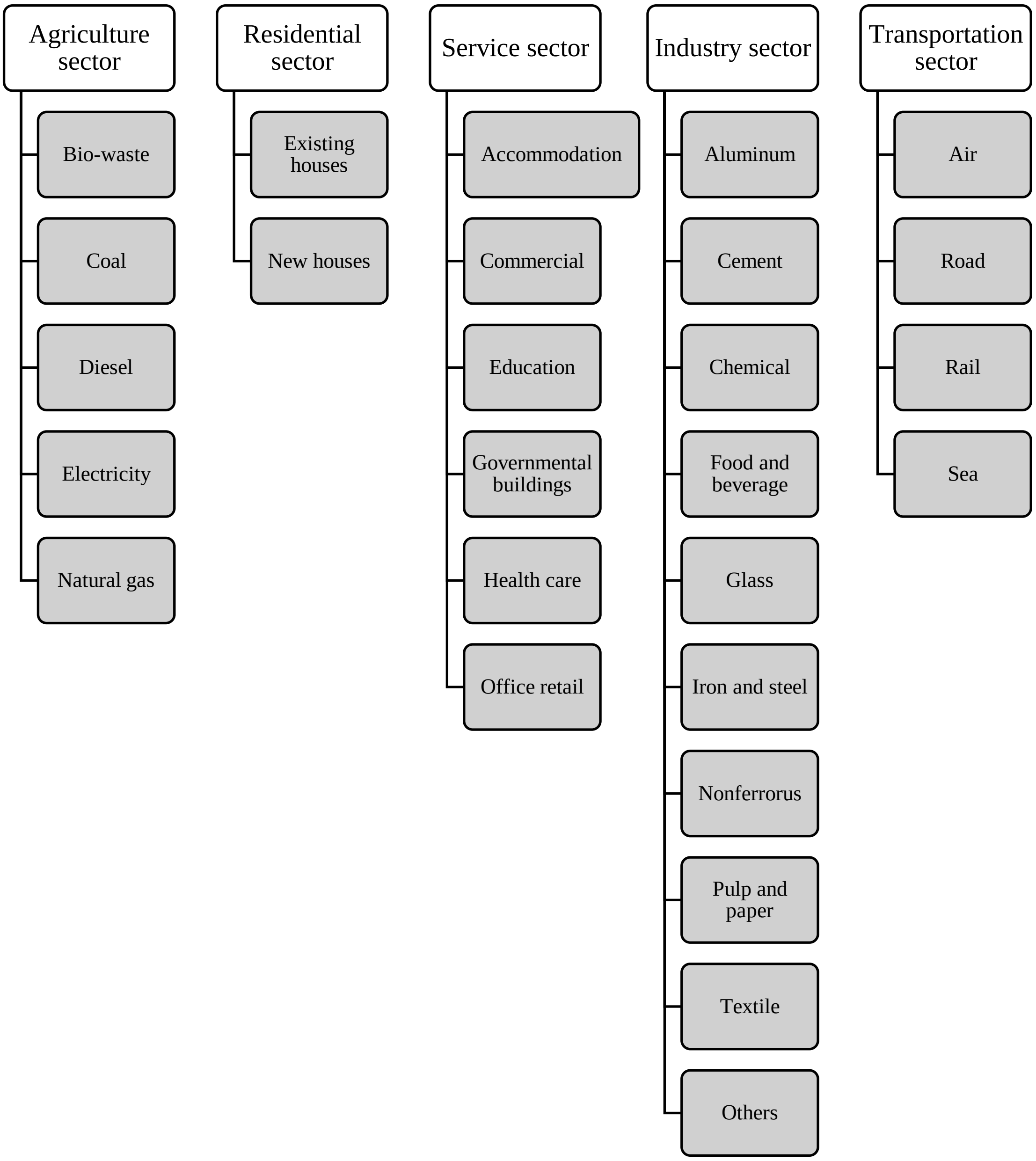


Figure 3.5. Main sub-categories of demand technologies.

Main sub-categories of demand technologies that are classified according to energy carriers, sub-sectors and/or types are diagrammatized in above Figure 3.5.

3.3. Variables

There exists two types of variables in BUEMS. One is optimization variables used in optimization process and other one is accounting variables used for accounting and reporting goals.

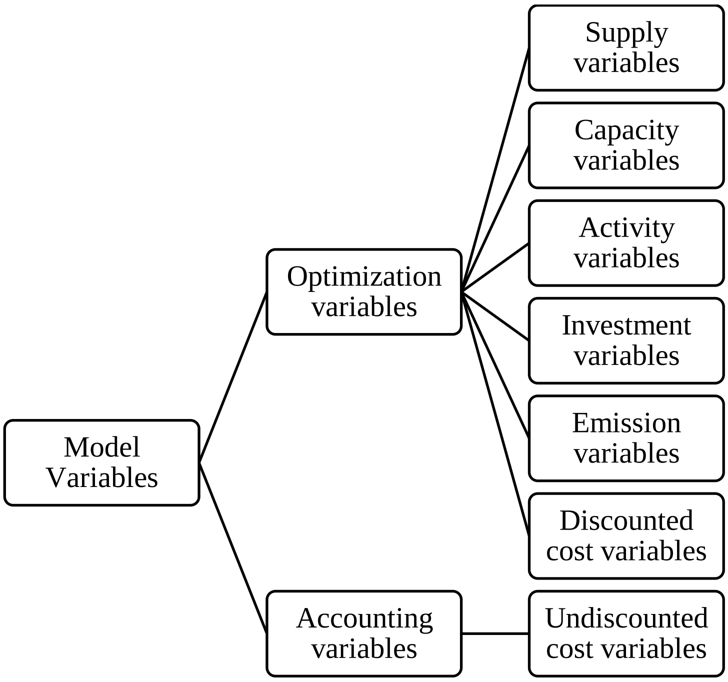


Figure 3.6. Types of variables.

Discounted and undiscounted costs variables composes cost variables together. But they have different functions in BUEMS. Undiscounted costs are for accounting and reporting purposes while discounted costs take part in the objective function.

“r_tsep” indicating the supply (resource) level of technology for each period is only decision variable of supply technologies. Its unit is PJ (petajoule) per period for all supply technologies.

Energy conversion and demand technologies have both capacity (“r_cap”) and investment (“r_inv”) decision variables showing capacity level and new capacity addition for each period respectively. In common with “r_tsep”, unit of “r_cap” is PJ per period for all technologies. But, unit of “r_inv” may vary by technology types. As units, billion vehicle-kilometers for transport sector demand technologies, GW for electricity conversion technologies, million tons for industry sector demand technologies and PJ for other technologies are used in the model.

Moreover, energy conversion technologies have activity (“r_act”) decision variable which indicates activity level of technology in addition to “r_cap” and “r_inv”. Unit of activity level decision variable is PJ for all technologies.

Lastly, emission variable represented by “r_em” shows emission levels of each technology for each period.

Table 3.4. Description of variables.

Variable	**Description**
r_tsep(m,t)	supply level of technology m at period t
r_cap(m,t)	installed capacity (capacity level) of technology m in period t
r_inv(m,t)	new capacity addition (investment level) for technology m in period t
r_act(m,t)	activity level of technology m in period t
r_em(m,t)	emission level for emission type v in period t

3.4. Objective Function and Total Annual Cost

The objective function is minimization of the sum of discounted annual costs for each period in BUEMS framework. Sum of the discounted annual costs of periods gives value of the total system cost. Therefore, in other words, the objective of BUEMS is to minimize the total system cost.

$$totcost = \sum_t disanntcost(t) \qquad (3.1)$$

where

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

Sum of undiscounted annual supply, investment, environmental, operational (fix and variable) and other costs for a period gives the value of undiscounted annual total system cost of that period. Then from this value, discounted annual total system cost can be calculated for each period of the planning horizon. In BUEMS, each period comprises of exactly 5 years.

Undiscounted annual total system cost can be expressed in closed-form as follows:

$$\begin{gathered}\mathit{undanntcost}\ (t) = \mathit{undannsupcost}(t) + \mathit{undanninv}(t) \\ + \mathit{undannothcost}(t) + \mathit{undannenvcost}(t)\end{gathered} \tag{3.2}$$

where

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

Structural formula of undiscounted annual total system cost is stated below.

$$\begin{gathered}\mathit{undanntcost}(t) = {}_{m}\Sigma\ (\mathit{scost}(m,t)*\mathit{r\_tsep}(m,t)) + {}_{m}\Sigma\ (\mathit{edistom}(m,t)*\mathit{r\_act}(m,t)) \\ + {}_{m}\Sigma\ (\mathit{etranom}(m,t)*\mathit{r\_act}(m,t)) + {}_{m}\Sigma\ (\mathit{dtranom}(m,t)*\mathit{r\_act}(m,t)) \\ + {}_{m}\Sigma_{u}{}^{t}\,\Sigma\ (\mathit{costinv}(m,u)*\mathit{r\_inv}(m,u)) \\ + {}_{m}\Sigma\ (\mathit{fixom}(m,t)*\mathit{r\_cap}(m,t)) + {}_{m\in kUc}\Sigma\ \mathit{varom}(m,t)*\mathit{r\_act}(m,t)) \\ + {}_{m\in d}\Sigma\ \mathit{capunit}(m,t)*\mathit{cf}(m,t)*\mathit{varom}(m,t))*\mathit{r\_cap}(m,t)/\mathit{eff}(m,t)) \\ + {}_{v}\Sigma\ (\mathit{envcost}(v,t)*\mathit{r\_em}(v,t))\end{gathered} \tag{3.3}$$

where

- first two lines indicate undiscounted annual total supply cost at period t

- undiscounted annual total investment cost at period t is represented in the third line
- fourth and fifth lines express undiscounted annual total other cost at period t
- undiscounted annual total environmental cost at period t is indicated in the last line

There is also a formulation to indicate undiscounted total system cost which has a varied notation to express investment cost and a salvage cost in its formulation different than undiscounted annual total system cost. This undiscounted total system cost is represented below.

$$
\begin{gathered}
\mathit{undtcost}(t) = {}_{m}\Sigma\ (\mathit{scost}(m,t) * \mathit{r\_tsep}(m,t)) + {}_{m}\Sigma\ (\mathit{edistom}(m,t) * \mathit{r\_act}(m,t)) \\
+ {}_{m}\Sigma\ (\mathit{etranom}(m,t) * \mathit{r\_act}(m,t)) + {}_{m}\Sigma\ (\mathit{dtranom}(m,t) * \mathit{r\_act}(m,t)) \\
+ {}_{m}\Sigma((\mathit{invcost}(m,t) + \mathit{edistinv}(m,t) + \mathit{etraninv}(m,t) + \mathit{dtraninv}(m,t)) * \mathit{r\_inv}(m,t)/5) \\
+ {}_{m}\Sigma\ (\mathit{fixom}(m,t) * \mathit{r\_cap}(m,t)) + {}_{m \in kUc}\Sigma\ (\mathit{varom}(m,t) * \mathit{r\_act}(m,t) \\
+ {}_{m \in d}\Sigma\ (\mathit{capunit}(m,t) * \mathit{cf}(m,t) * \mathit{varom}(m,t)) * \mathit{r\_cap}(m,t)/\mathit{eff}(m,t)) \\
+ {}_{v}\Sigma\ (\mathit{envcost}(v,t) * \mathit{r\_em}(v,t)) \\
- {}_{m}\Sigma\ (\mathit{salvinv}(m,t) * \mathit{r\_inv}(m,t))
\end{gathered}
\tag{3.4}
$$

where

- undtcost(t) : undiscounted total system cost

In formulation (3.4) the third line represents investment cost. However, this investment cost is not expressed in annualized form; therefore, based upon technology lifetime, capital recovery factor is used to annualize. Annualized form of the third line becomes as shown below through multiplying by capital recovery factor.

$$
\mathit{costinv}(m,t) = \mathit{crf}(m) * (\mathit{invcost}(m,t) + \mathit{edistinv}(m,t) + \mathit{etraninv}(m,t) + \mathit{draninv}(m,t)) \tag{3.5}
$$

where

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

After that, discounted annual total system cost is obtained through multiplying undiscounted annual total system cost by period discount factor.

$$\begin{aligned}
disanntcost(t) = {} & \sum_{m} (pdf(t)*scost(m,t)*r\_tsep(m,t)) + \sum_{m} (pdf(t)*edistom(m,t)*r\_act(m,t)) \\
& + \sum_{m} (pdf(t)*etranom(m,t)*r\_act(m,t)) + \sum_{m} (pdf(t)*dtranom(m,t)*r\_act(m,t)) \\
& + \sum_{m} (priinv(m,t)*r\_inv(m,t)) \\
& + \sum_{m} (pdf(t)*fixom(m,t)*r\_cap(m,t)) + \sum_{m \in kUc} pdf(t)*varom(m,t)*r\_act(m,t)) \\
& + \sum_{m \in d} pdf(t)*capunit(m,t)*cf(m,t)*varom(m,t))*r\_cap(m,t)/eff(m,t)) \\
& + \sum_{v} (pdf(t)*envcost(v,t)*r\_em(v,t))
\end{aligned} \tag{3.6}$$

where

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

In the end, formula (3.6) expresses annual discounted total system cost and sum of this formula for each period provides the total system cost in the objective function of BUEMS.

3.4.1. Supply Cost

Supply cost is all costs related to procurement of energy carriers to the system including transmission and distribution of energy carriers. Costs of mining (extraction), renewable and importation supply technologies for each period are added to total annual supply cost as positive values while exportation supply technologies come up as revenues for the system; therefore, they are included in total annual supply cost with a minus sign.

Both delivery costs of energy carriers as inputs, transmission and distribution costs of energy carriers as outputs are included into total supply cost with a positive sign in energy conversion technologies.

$$\begin{aligned}
undannsupcost(t) = {} & \sum_{m \in s} (scost(m,t)* r\_tsep(m,t)) \\
& + \sum_{ce \in s} edistom(m,t)*outent(m,t)*r\_act(m,t) \\
& + \sum_{ce \in s} etranom(m,t)*outent(m,t)*r\_act(m,t) \\
& + \sum_{ch \in s} dtranom(m,t)*outent(m,t)*r\_act(m,t)
\end{aligned} \tag{3.7}$$

where

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

In formulation (3.7), first line represents total cost of supply through multiplying unit supply cost by supply level in all periods for each supply technology.

Total costs of electricity distribution and transmission are expressed in the second and third lines which are obtained by multiplication of activity levels and unit operational costs in all periods for energy conversion technologies.

In the last line, total cost of LTH transmission is calculated through multiplying unit operational cost by activity level in each period for LTH generation technologies.

After that, to obtain total discounted annual supply cost, total undiscounted annual supply cost is multiplied by period discount factor and the following formulation comes out.

$$disannsupcost(t) = pdf(t) * undannsupcost(t) \tag{3.8}$$

where

- disannsupcost(t): discounted annual total supply cost at period t

Structural formula of period discount factor is as follows:

$$pdf(t)= {}_{y=1}{}^{nyrsper} \Sigma\ (1+discount)^{-(y-1)} * (1+discount)^{-(startyrs+nyrsper*(t-1))} \tag{3.9}$$

where

- nyrsper: number of years per period

- discount: discount factor

Discounted cost of each year in the period is calculated by the first multiplier while total discounted cost of period is discounted to the start of planning horizon with the second multiplier.

3.4.2. Investment Cost

Investments can cover a year, couple of years, period or couple of periods. For instance institution of a power plan can take a period. Therefore, annualization of investment costs is required. Investment cost describes the necessary amount of financing per unit of new capacity addition. This necessary amount should be distributed over the lifetime of the technology that invested by using capital recovery factor.

$$crf(m) = discount(m)/(1-(1+discount(m)))^{-life(m)} \tag{3.10}$$

where,

- crf : capital recovery factor
- discount(m) : discount rate of technology m
- life(m) : life time of technology m

Investment cost of a period consists of the costs of new investments in that period and investments that realized in previous periods but still last. The reason for a previously realized investment constituting a cost for following periods is its lifetime. The payment for investment cost is over when lifetime of the technology related to this investment ends.

Total undiscounted annually adjusted investment cost is calculated through annually adjusted investment cost multiplied by investment levels of technologies. Methods of calculation for annually adjusted investment cost and total undiscounted annually adjusted investment cost are below.

$$costinv(m,u)=crf(m)*(invcost(m,t)+edistinv(m,t)+etraninv(m,t)+dtraninv(m,t)) \tag{3.11}$$

where,

- costinv(m,u): annually adjusted investment cost of technology m at period u
- invcost(m,t) : unit investment cost of technology m at period t
- edistinv(m,t) : unit investment cost for electricity distribution system of technology m at period t
- etraninv(m,t) : unit investment cost for electricity transmission system of technology m at period t
- dtraninv(m,t) : unit investment cost for LTH transmission system of technology m at period t

$$undanninv(t)= {}_{m}\Sigma\ {}_{u}^{t}\Sigma(costinv(m,u)*r\_inv(m,u)) \qquad (3.12)$$

where

- undanninv(t): undiscounted annually adjusted total investment cost at period t
- “t-u”: interval for available investments of technology m at period t

When the lifetime of technology that is invested does not cover all years of a period, investment cost can be expressed a fraction of last period. This fraction rate is calculated using the lifespan of technology and number of years in that period.

$$fraclife(m)=(life(m)/nyrsper)-t \qquad (3.13)$$

To obtain total undiscounted annually adjusted investment cost for electricity distribution, electricity transmission and LTH transmission, their unit investment costs are summed by using same method. But, salvage cost should be included in calculations as a revenue this time. Salvage cost is obtained when a technology lifetime is over and added to the total system cost with a minus sign.

After calculating undiscounted annually adjusted investment cost, we need to obtain total discounted annually adjusted investment cost. Summation of discounted and annually adjusted investment costs of technologies at period t gives total discounted annually adjusted investment cost.

First of all, periodic discount factor which will be used for annualization and discounting purposes is calculated. With this factor, discounted actual investment cost is calculated. Then, total discounted annually adjusted investment cost is obtained by the help of discounted actual investment cost.

$$pridisc(m,t) = crf(m)*(1/(1+discount))^{(-startyrs+nyrsper*(t-1))} \tag{3.14}$$

where

- pridisc(m,t): periodic discount factor other than invesment for technology m at period t

In formula (3.14) "crf(m)" notation provides annualization while second multiplier discounts the annualized cost to the beginning of the planning horizon.

$$\begin{gathered} priinv(m,t) = pridisc(m,t)*(invcost(m,t)+edistinv(m,t)+etraninv(m,t) \\ +dtraninv(m,t)- salvinv(m,t)) \end{gathered} \tag{3.15}$$

where

- priinv(m,t): annually adjusted and discounted unit investment cost of technology m at period t
- salvinv(m,t) : salvage component of the invesment for technology m at period t

After pridisc(m,t) and priinv(m,t) are obtained, total discounted annually adjusted investment cost can be calculated by multiplication of annually adjusted, discounted unit investment cost of technology m at period t and investment level of technology m at period t.

$$disanninv(t) = m\Sigma\ (priinv(m,t)*r\_inv(m,t)) \tag{3.16}$$

where

- disanninv(t) : total discounted annually adjusted investment cost

3.4.3. Other Cost

Other cost composes of fixed and variable operation & maintenance costs. Fixed operation & maintenance cost is related to capacity levels of technologies while variable operation & maintenance cost is related to activity levels of technologies. Capacity utilization factor is used to determine activity levels of demand technologies hence they do not have activity level decision variables. Besides, unit conversion factor is used in case of capacity and activity units of demand technologies are different. Undiscounted total other cost is calculated as follows.

$$\begin{aligned} undother(t) = {}& _{m \in kUcUd} \Sigma\, fixom(m,t)*r\_cap(m,t) \\ &+ _{m \in kUc} \Sigma\, varom(m,t)*r\_act(m,t) \\ &+ _{m \in d} \Sigma\, (capunit(m,t)*cf(m,t)*varom(m,t))*r\_cap(m,t)/eff(m,t)) \end{aligned} \tag{3.17}$$

where

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

Total fixed operation and maintenance cost of all technologies for each period is calculated in the first line of formula (3.17). Then, other lines indicate different calculations of variable operation and maintenance cost since variable operation and maintenance cost is obtained based on activity levels which differ from technology type, particularly energy conversion and demand technologies. Therefore, second line represents calculation of variable operation and maintenance cost for energy conversion technologies while formula for variable operation and maintenance cost of demand technologies can be seen in third line. Capacity utilization factor exists in third line due to getting involved in calculations when needed.

To calculate total discounted annual other cost, undiscounted total other cost is multiplied by period discount factor.

$$disother(t)= pdf(t) * undother(t) \tag{3.18}$$

where

- disother(t): total discounted annual other cost (fix and variable operation & maintenance costs)

3.4.4. Environmental Cost

Environmental cost does not directly affect objective function of BUEMS as long as a penalty is not defined for emissions. This penalty (environmental cost) can be assigned for emissions arising from energy production, consumption, transmission and distribution activities of the system. Calculation method for undiscounted annual total environmental cost is shown below.

$$undannenvcost(t) = {}_{v}\Sigma\, envcost(v,t\,)*r\_em(v,t) \tag{3.19}$$

where

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

For calculating discounted form of environmental cost, undiscounted annual total environmental cost is multiplied by periodic discount factor.

$$disannenvcost(t) = pdf(t)*undannenv(t) \tag{3.20}$$

where

- disannenvcost(t) : total discounted annual environmental cost

3.5. Equations and Constraints

BUEMS aims to optimize its objective function by satisfying the model constraints in triangle of energy, environment and economy. The model constraints can be grouped as follows.

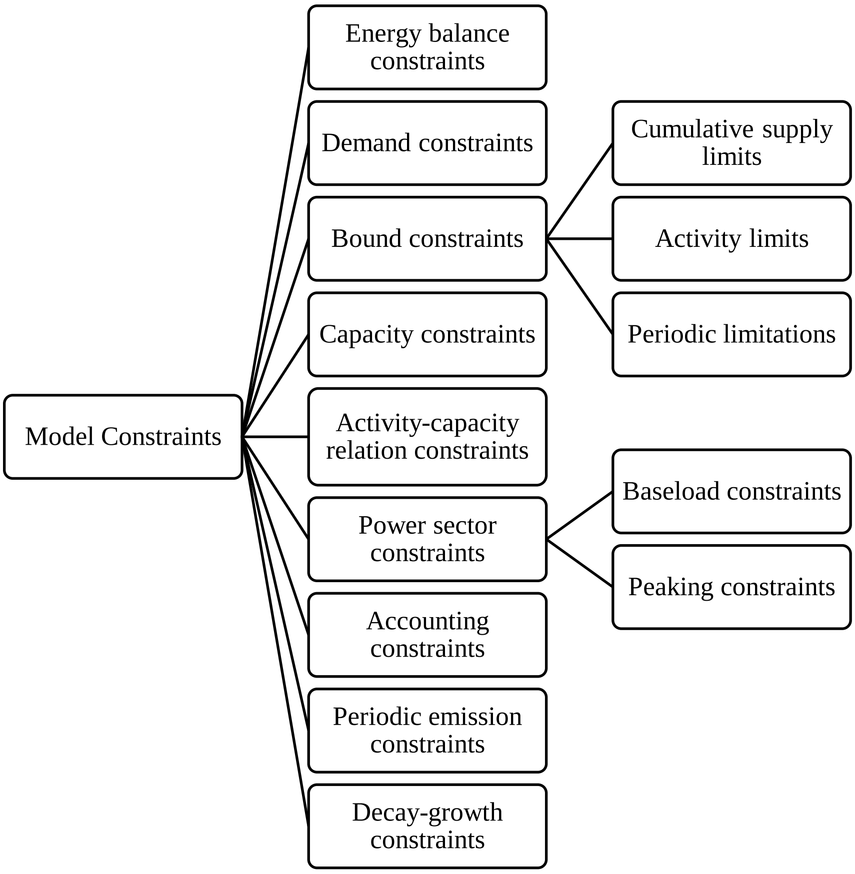


Figure 3.7. Model constraints of BUEMS.

3.5.1. Energy Balance Constraints

Energy balance constraints ensure that total usage of an energy source always remains equal or below its total supply level. Each energy carrier has this constraint. Extraction and importation technologies belonging to supply technologies and generation part of energy conversion technologies are expressed in left hand side while right hand side represents exportation technologies belonging to supply technologies, demand technologies and consumption part of energy conversion technologies.

“Inpent(m,t)” notation indicates input requirement level per unit activity of technology m at period t and is located on right hand side whereas output generation level per unit activity of technology m at period t is represented by “outent(m,t)” and takes place on left hand side of the constraint.

$$\begin{aligned} &{}_{m \in s}\Sigma\, r\_tsep(m,t) + {}_{m \in kUc}\Sigma\, r\_act(m,t)*outent(m,t) \geq \\ &+{}_{m \in s}\Sigma\, inpent(m,t)*r\_tsep(m,t) + {}_{m \in kUc}\Sigma\, inpent(m,t)*r\_act(m,t) \\ &+ {}_{m \in d}\Sigma\, inpent(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/eff(m,t) \end{aligned} \tag{3.21}$$

where

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

3.5.2. Demand Constraints

Demand constraints ensure that demand necessity is always satisfied by available capacity. Therefore, total activity levels of energy utilization sectors as end-use technologies are always equal to or greater than the demand requirements.

$${}_{m \in d}\Sigma\, (outent(dm)(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)) \geq demand(dm,t) \tag{3.22}$$

where

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

3.5.3. Capacity Constraints

At a period t, summation of investments (realized at current periods and at past periods but still last because of its lifetime) and capacities (installed in prior time and still have additional lifespan) equals to the available capacity is guaranteed by these capacity transfer constraints.

If an investment completes its lifetime, then it is does not exist anymore; therefore, its capacity should be excluded from the total capacity.

$$t' = t\text{-}life(m,l)/nyrsper \tag{3.23}$$

where

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

Capacity transfer constraints represented below indicate total available capacity for each technology at a period. Residual capacities whose investments were realized at the beginning of planning horizon do not have investment costs.

$$r\_cap(m,t) = resid(m,t) + {}_{x=t'}{}^{t}\,\Sigma\; r\_inv(m,x) \tag{3.24}$$

where

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

3.5.4. Activity-Capacity Relation Constraints

Activity level of an energy conversion technology is always less than or equal to its available capacity by force of activity-capacity relation constraints. This constraint is only practicable for energy conversion technologies because demand technologies do not have activity levels. As end-use technologies their activity level is in direct proportion to their available capacities.

$$r\_act(m,t) \leq capunit(m,t)*af(m,t)*r\_cap(m,t) \qquad (3.25)$$

where

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

If units of capacity level and activity level is different, unit conversion factor is used.

3.5.5. Cumulative Supply Limit

Several limitations exist for supply technologies. For instance, importation technologies have import limits, mining (extraction) technologies have reserve limits and renewable technologies have weather condition limits. Cumulative supply limit ensures that total supply level of a supply (resource) technology is always less than or equal to its cumulative supply level. Therefore, this limitation constraint is only applicable for supply technologies.

$$_t\Sigma\ (nyrsper*r\_tsep(s,t)) \leq cum(s,cm) \qquad (3.26)$$

where

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

3.5.6. Activity Limit

This activity limitation constraint is for technologies which have multiple output such as refinery sector. With activity limitation, it is guaranteed that total generation of multiple output technologies for its each output equals to a fraction of total activity level for each output.

$$limit(m,t)*r\_act(m,t) = {}_{e}\Sigma\,(r\_act(m,t)*outent(m,e,t)) \tag{3.27}$$

where

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

3.5.7. Periodic Limitations

Periodic limit constraints ensure to restrict supply, activity, capacity and investment levels of technologies. Supply technologies can just have periodic limitations related to their supply levels because of having only supply level decision variables. On the other hand, demand technologies cannot have periodic limits for their activity levels since they do not have activity decision variables.

$$r\_x(m,t) \leq bound\_x\_upper(m,t) \tag{3.28}$$

$$r\_x(m,t) = bound\_x\_fix(m,t) \tag{3.29}$$

$$r\_x(m,t) \geq bound\_x\_lower(m,t) \tag{3.30}$$

where

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

3.5.8. Peaking Constraints

The highest electricity and LTH demand requirement has to be met by total generation capacity at any time. Therefore, peaking constraints for electricity and LTH guarantee that sufficient available capacity is always ready to meet peak demand requirements for electricity and LTH.

Peaking constraint for electricity:

$$\begin{gathered}
{}_{m \in s} \Sigma\, teent(e,t)*peakcon(m,t)*r\_tsep(m,t)) + \\
{}_{m \in ce} \Sigma teent(e,t)*peakcon(m,t)*outelc(m,t)*capunit(m,t)*af(m,t)*r\_cap(m,t))) \geq \\
{}_{m \in s} \Sigma\, inpelc(m,t)*r\_tsep(m,t)) \\
+ {}_{m \in k} \Sigma\, inpelc(m,t)*r\_act(m,t)) \\
+ {}_{m \in c} \Sigma\, inpelc(m,t)*r\_act(m,t)) \\
+ {}_{m \in d} \Sigma\, inpelc(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/(eff(m,t))*(1+ereserv(e,t))
\end{gathered} \tag{3.31}$$

where

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

Peaking constraint for LTH:

$$\begin{gathered}
{}_{m \in ch} \Sigma\, peakcon(m,t)*outlth(m,t)*capunit(m,t)*af(m,t)*r\_cap(m,t)) \geq \\
{}_{m \in s} \Sigma\, inplth(m,t)*r\_tsep(m,t)) \\
+ {}_{m \in k} \Sigma\, inplth(m,t)*r\_act(m,t)) \\
+ {}_{m \in c} \Sigma\, inplth(m,t)*r\_act(m,t)) \\
+ {}_{m \in d} \Sigma\, inplth(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/(eff(m,t))*(1+hreserv(e,t))
\end{gathered} \tag{3.32}$$

where

- ch: LTH generation technology
- outlth(m,t): LTH generation level per unit activity of technology m at period t
- inplth(m,t): LTH demand level per unit activity of technology m at period t
- hreserv(e,t): LTH reserve parameter for LTH generation technology at period t

Total electricity and LTH demand requirements of related technologies are indicated in right hand side of formulas (3.31) and (3.32) while left hand side represents ready to meet capacity of electricity and LTH generation for peak demand. Peaking contribution parameter is used to specify reserved capacity for peak time of electricity and LTH demand requirements (Fraction of capacity in peak equations is given in the Appendix CD folder).

3.5.9. Baseload Constraints

Some power plants may not be able to operate in a flexible mode by several factors. Therefore, they are called baseload power plants such as coal-fired or nuclear power plants. Ever-changing generation amounts are not feasible for them due to operational costs, machine depreciation etc. However, total demand declines at nights and sudden ups and downs happen at night time demand requirements. Thus, in case of a sudden down in night time demand non-baseload power plants are deactivated since a significant difference occurs between production and night time demand (Day time and night time shares are given in the Appendix CD folder).

To prevent base load power plants be damaged because of demand fluctuations, this constraint guarantees that certain percentage of total night time demand is met by baseload power plants.

$$\begin{aligned} {}_{m\in ce}\Sigma\, outelc(m,t)*qhr\_n(m,t)*r\_act(m,t)*baseload(e,t)) \geq \\ {}_{m\in ce \cap cbs\_e}\Sigma\, qhr\_n(m,t)*outelc(m,t)*r\_act(m,t)) \end{aligned} \tag{3.33}$$

where

- baseload(e,t): the highest percentage of the baseload power plants in total electricity generation at period t

- qhr_n(m,t): night time share of electricity generation from technology m at period t
- cbs_e(m): baseload electric conversion technology indice

3.5.10. Periodic Emission Constraints

Emission levels of technologies are monitored by periodic emission constraints which have different equations for every technology. Emission level per unit supply for a supply technology is calculated as follows.

$$\sum_{s} (envsep(s,t) * r\_tsep(s,t)) = r\_em(v,t) \qquad (3.34)$$

where

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

Emission levels per unit activity for energy conversion technologies are represented below.

$$\sum_{m \in c} envact(m,t) * r\_act(m,t) = r\_em(v,t) \qquad (3.35)$$

where

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

Emission levels per unit activity for demand technologies are tracked by using capacity utilization factor to determine their activity levels.

$$\sum_{m \in d} envact(m,t) * capunit(m,t) * cf(m,t) * r\_cap(m,t) = r\_em(v,t) \qquad (3.36)$$

The level of total emissions emitted from all technologies is monitored by following equation.

$$totemis(t) = {}_{v}\Sigma\, r\_em(v,t) \tag{3.37}$$

where

- totemis(t): total system emissions at period t

3.5.11. Decay-Growth Constraints

For a supply technology supply level, for any technology capacity and activity levels can be restricted by decay and growth constraints when switching between periods.

For supply level:

$$r\_tsep(s,t+1) \geq r\_tsep(s,t)*(decayr(s,t+1)**nyrsper) \tag{3.38}$$

$$r\_tsep(s,t+1) \leq r\_tsep(s,t)*(growthr\ (s,t+1)**nyrsper) \tag{3.39}$$

where

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

For capacity level:

$$r\_cap(m,t+1) \geq r\_cap(m,t)*(decay(m,t+1)**nyrsper) \tag{3.40}$$

$$r\_cap(m,t+1) \leq r\_cap(m,t)*(growth(m,t+1)**nyrsper) \tag{3.41}$$

where

- m ∈ kUcUd
- decay(m,t): decay rate of a technology capacity between consecutive periods
- growth(m,t): growth rate of a technology capacity between consecutive periods

For activity level:

$$r\_act(m,t+1) \geq r\_act(m,t)*(decay(m,t+1)**nyrsper) \tag{3.42}$$

$$r\_act(m,t+1) \leq r\_act(m,t)*(growth(m,t+1)**nyrsper) \tag{3.43}$$

where

- $m \in kUc$
- decay(m,t): decay rate of a technology activity between consecutive periods
- growth(m,t): growth rate of a technology activity between consecutive periods

Lastly, there exists accounting constraints just for reporting purposes and comparing results of different scenarios in BUEMS. These constraints are presented in Appendix A.

4. MODEL CALIBRATION

In this study, BUEMS which estimates CO_2 emissions, energy technologies and primary energy supply levels for each 5-year time period between 2012 and 2052 is calibrated according to the latest Turkish energy and transport data.

On the side of BUEMS transport sector data, the model inputs for the years 2012 and 2017 are updated according to the latest statistics, having been gathered from various sources including the Statistical Institute of Turkey (TUIK), Ministry of Transport and Infrastructure (MoTI), Ministry of Energy and Natural Resources (MENR), Turkey Electricity Transmission Company (TEIAS), General Directorate of Highways (KGM), International Energy Agency (IEA) Publications, Turkish Airlines Annual Reports, Annual Reports of Municipalities and Istanbul Electric Tramway and Tunnel Establishments (IETT).

The base scenario built in BUEMS within the scope of this study reflects the current energy system of Turkey with its business-as-usual assumptions. In the same way, various electric vehicle diffusion and policy scenarios are carried out and results of these alternative scenarios are compared with the base scenario.

Within the scope of calibration, data related to annual bounds on capacity, bounds on scenario constraints, cumulative emissions, sectoral demands, O&M costs and residual capacities of transport sector in BUEMS are updated. The existing data for other sectors are left unchanged.

This chapter includes two main sections. In the first section, the BUEMS transport sector structure is explained thoroughly. Moreover, applied model extensions to build varied scenarios and to compare their results during this study are summarized briefly. The second section explains how the data used in calibration are gathered, verified and organized for the model.

4.1. Transport Sector Structure

In BUEMS, the transport sector is grouped into four major modes: air, maritime, rail and road transportations. These major modes are also divided into sub-modes as shown in Figure 4.1 below.

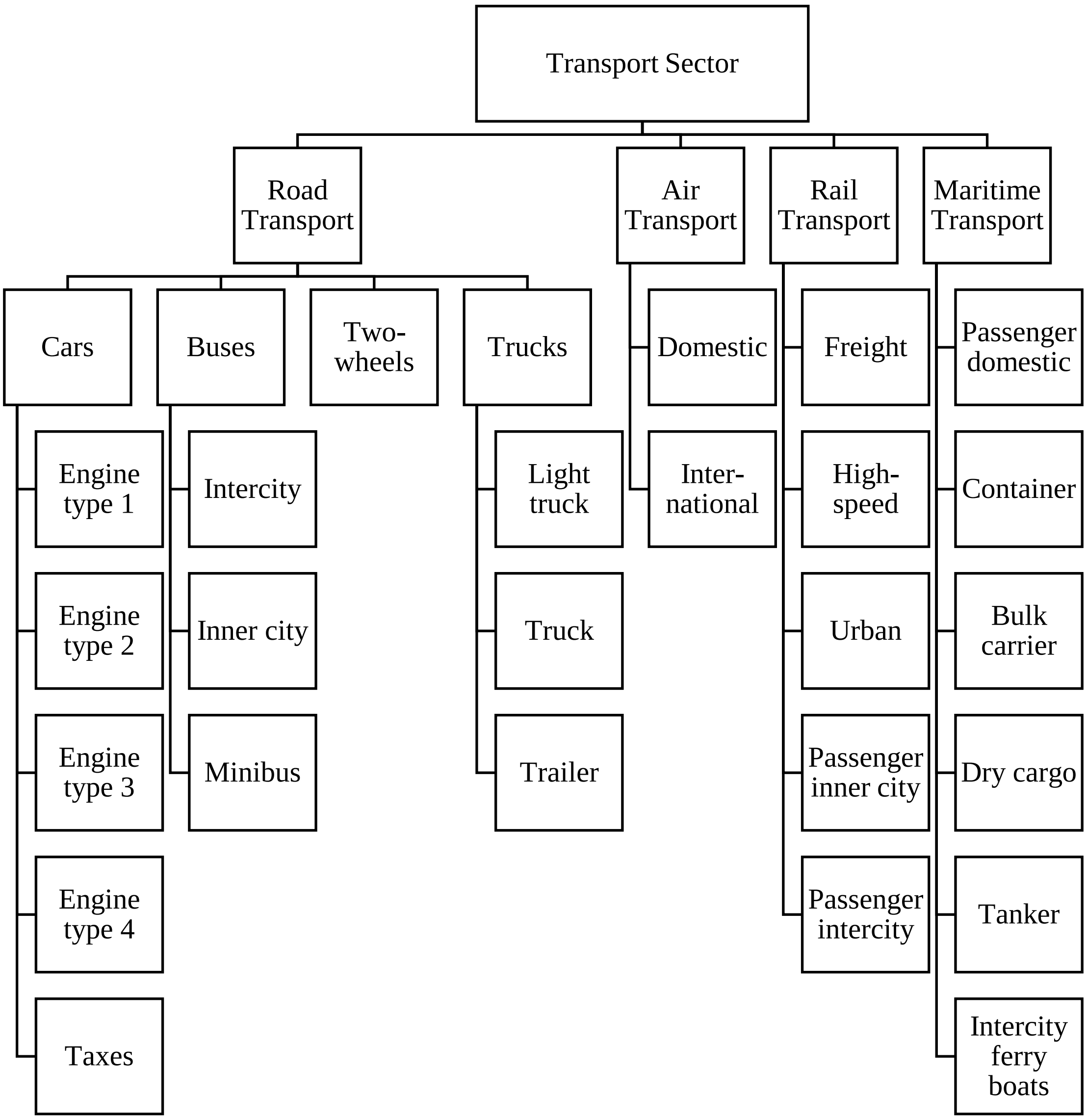


Figure 4.1. Sub-modes of the transport sector in BUEMS.

In the road transport mode, ICE cars are separated into four groups according to their engine type. From engine type 1 to engine type 4, they represent 1000-1400 cc, 1400-1600 cc, 1600-2000 cc and 2000+ cc respectively. The fifth group of cars denotes taxis. On the other hand, buses are divided into three categories: inner city buses, intercity buses and minibuses. The reason behind this categorization is variations of parameters (total vehicle kilometers, fuel efficiencies, fixed and variable operation and maintenance costs and prices) between these bus types. Also, trucks are grouped into three classes: truck, light truck and trailer due to same reasons.

Air transport is divided into two sub-modes: domestic and international flights. Since BUEMS is a national model, international flights are not included completely in the model. Only, these international flights whose departure is from Turkey are considered.

Freight, high-speed, urban, passenger-inner city and passenger-intercity are sub-modes of rail transport. Passenger-intercity indicates the mainline conventional railways except for high-speed. Rail urban includes metro and tramway trains in the cities while passenger inner city denotes suburban trains.

Maritime transport is separated into six sub-modes: passenger domestic, container, dry cargo, bulk carrier, tanker and intercity ferry boats. For the categorization of freight ships based on freight types, container, dry cargo, bulk carrier and tanker sub-modes are constituted. Passenger domestic indicates ships and boats which provide inner city service while intercity ferry boats are for intercity vessels.

For all twenty-five sub-modes, BUEMS requires total billion vehicle kilometers traveled per year as sectoral demand data of transport sector. These data are the most critical data for transport sector when different policy scenarios are applied and scenario results are compared. Demand data, total billion vehicle kilometers traveled, are calculated as total distance independently of passenger number or freight amount carried on the vehicle.

Table 4.1. Identifiers of sectoral demand for transport sector in BUEMS.

No	Mode	Identifier	Description
1	Air	TRA_AIRPD	passenger domestic
2	Air	TRA_AIRPI	passenger international
3	Road	TRA_BUSPC	inner city buses
4	Road	TRA_BUSPO	intercity buses
5	Road	TRA_CARPC	car engine type 1
6	Road	TRA_MINPC	minibus
7	Rail	TRA_RAIF	rail freight
8	Rail	TRA_RAIS	rail high speed
9	Rail	TRA_RAIU	rail urban
10	Rail	TRA_RAIPC	rail passenger inner city
11	Rail	TRA_RAIPO	rail passenger intercity
12	Maritime	TRA_SHPFD	shipping intercity ferry boats
13	Maritime	TRA_SHPPC	shipping passenger domestic
14	Maritime	TRA_SHPDY	shipping bulk carrier
15	Maritime	TRA_SHPCT	shipping container
16	Maritime	TRA_SHPKY	shipping dry cargo
17	Maritime	TRA_SHPT	shipping tanker
18	Road	TRA_TRUF	heavy truck
19	Road	TRA_TTRUF	trailer
20	Road	TRA_TRULF	light truck
21	Road	TRA_TWHP	two wheels
22	Road	TRA2_CARPC	car engine type 2
23	Road	TRA3_CARPC	car engine type 3
24	Road	TRA4_CARPC	car engine type 4
25	Road	TRAX_CARPC	taxi

Fuel efficiencies, fixed and variable operation and maintenance costs, lifetimes, residual capacities, capacity bounds, activity levels, availability factors, investment prices, investment bounds are other input requirements for transport sector technologies in BUEMS. These input requirements are displayed in the Appendix CD folder. There exists 950 transport technologies in the model (they are listed in the Appendix CD). All the data required by the model for transport sector are compiled for the base year 2012 and year 2017 according to the gathered data. Then, data between 2017 and 2052 are estimated based on strategic plan of MoTI and expert consultation. Input data types and their units for transport sector in BUEMS are given in Table 4.2.

Table 4.2. Input data types and their units for transport sector in BUEMS.

Data Description	**Identifier**	**Unit**
demand	demanddata	billion vehicle kms
activity levels (upper/ fix/ lower)	actboundfxdata	billion vehicle kms
	actboundlodata	billion vehicle kms
	actboundupdata	billion vehicle kms
availability factor	afdata	percantage
capacity bounds (upper/ fix/ lower)	capboundfxdata	billion vehicle kms
	capboundlodata	billion vehicle kms
	capboundupdata	billion vehicle kms
efficiency rate (fuel efficiency)	effdata	percantage
fixed O&M cost	fixomdata	US million dollars per billion vehicle kilometers
investment bounds (upper/ fix/ lower)	iboundfxdata iboundlodata iboundupdata	billion vehicle kms
investment cost	invcost	US million dollars per billion vehicle kilometers
useful lifetime	lifedata	years
residual capacity	residdata	billion vehicle kms
variable O&M cost	varomdata	US million dollars per billion vehicle kms

4.1.1. Electric Vehicles

To force electric vehicles deployment in BUEMS, electric vehicle equations/constraints are defined separately. With these constraints, upper and lower bounds are set according to the diffusion rate of electric vehicles and associated electricity needs. As depicted in Figure 4.2 electric vehicles are classified in three categories: electric cars, electric buses and electric rail vehicles.

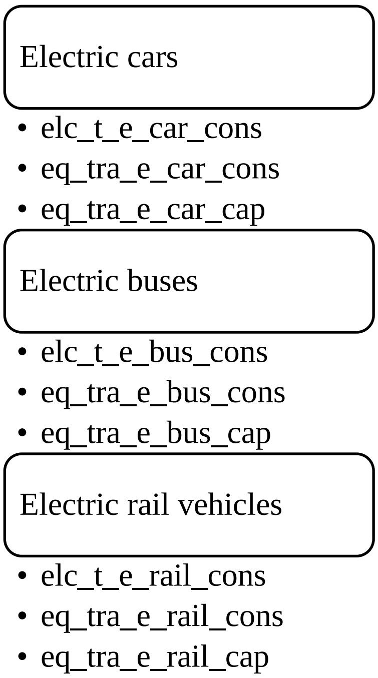


Figure 4.2. Additional electric vehicle equations/constraints in BUEMS.

These electric vehicle equations/constraints take part in base and all other alternative scenarios. Thus, behavior and effects on the energy system of electric vehicles deployment are observed under different diffusion and policy scenarios in this study.

Capacities of electric cars, electric buses and electric rail vehicles (eq_tra_e_car_cap, eq_tra_e_bus_cap, eq_tra_e_rail_cap respectively) in the transport sector are expressed with the following equations for BUEMS.

$$\begin{gathered}\textit{eq\_tra\_e\_car\_cap(t)..} \qquad \textit{elc\_t\_e\_car\_cons(t) =e=} \\ \textit{sum(m\$(ket\_c(m) and d(m)),inpelct(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/eff(m,t))}\end{gathered} \tag{4.1}$$

$$\begin{gathered}\textit{eq\_tra\_e\_bus\_cap(t)..} \qquad \textit{elc\_t\_e\_bus\_cons(t) =e=} \\ \textit{sum(m\$(ket\_b(m) and d(m)),inpelct(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/eff(m,t))}\end{gathered} \tag{4.2}$$

$$\begin{gathered}\textit{eq\_tra\_e\_rail\_cap(t)..} \qquad \textit{elc\_t\_e\_rail\_cons(t) =e=} \\ \textit{sum(m\$(ket\_r(m) and d(m)),inpelct(m,t)*capunit(m,t)*cf(m,t)*r\_cap(m,t)/eff(m,t))}\end{gathered} \tag{4.3}$$

where

- capunit(m,t): unit conversion factor of technology m at period t
- cf(m,t): capacity utilization factor of technology m at period t
- d(m): demand technologies
- eff(m,t): efficiency rate of technology m at period t
- elc_t_e_bus_cons(t): electricity consumption level of electric buses at period t
- elc_t_e_car_cons(t): electricity consumption level of electric cars at period t
- elc_t_e_rail_cons(t): electricity consumption level of electric rail vehicles at period t
- inpelct(m,t): level of input requirement
- ket_b(m): transportation bus electricity demand technologies
- ket_c(m): transportation car electricity demand technologies
- ket_r(m): transportation rail electricity demand technologies
- r_cap(m,t): capacity level of technology m at period t

Upper and lower electricity consumption bounds of electric cars, electric buses and electric rail vehicles in the transport sector are set with the following constraints. These upper and lower bounds are defined according to the prediction of electricity consumption values for electric vehicles. For electric cars, only a lower bound is used while upper and lower bounds are both used for electric buses and electric rail vehicles.

eq_tra_e_car_cons(t)..   elc_t_e_car_cons(t) =g= bounds("ELC_T_CAR",t) (4.4)

eq_tra_e_bus_cons(t)..   elc_t_e_bus_cons(t) =g= bounds("ELC_T_BUS_LO",t) (4.5)

eq_tra_e_bus_cons_1(t).. elc_t_e_bus_cons(t) =l= bounds("ELC_T_BUS_UP",t) (4.6)

eq_tra_e_rail_cons(t)..   elc_t_e_rail_cons(t) =g= bounds("ELC_T_RAIL_LO",t) (4.7)

eq_tra_e_rail_cons_1(t).. elc_t_e_rail_cons(t) =l= bounds("ELC_T_RAIL_UP",t) (4.8)

where

- bounds("ELC_T_BUS_LO",t): set of lower bounds for electric buses consumption
- bounds("ELC_T_BUS_UP",t): set of upper bounds for electric buses consumption
- bounds("ELC_T_CAR",t): set of lower bounds for electric cars consumption
- bounds("ELC_T_RAIL_LO",t): set of lower bounds for electric rail vehicles consumption
- bounds("ELC_T_RAIL_UP",t): set of upper bounds for electric rail vehicles consumption
- eq_tra_e_bus_cons(t): equation for lower electricity consumption bound of electric buses at period t
- eq_tra_e_bus_cons_1(t): equation for upper electricity consumption bound of electric buses at period t
- eq_tra_e_car_cons(t): equation for lower electricity consumption bound of electric cars at period t
- eq_tra_e_rail_cons(t): equation for lower electricity consumption bound of electric rail vehicles at period t
- eq_tra_e_rail_cons_1(t): equation for upper electricity consumption bound of electric rail vehicles at period t

4.2. Demand Data

This section describes the demand data sources, their compilation and associated assumptions.

4.2.1. Road Transport

Demand data, billion vehicle kilometers, for years 2012 and 2017 are taken from Traffic and Transportation Information Reports published by KGM. In this report, total kilometer values of years 2012 and 2017 are available for inner city buses, intercity buses, trucks, light trucks, and trailers. On the other hand, total kilometers of cars for all engine types, taxis and minibuses take part as a single value in the report. Besides, no data are available for two-wheelers.

To separate and recompile data for cars, taxis and minibuses, annual number of vehicles data (number of road motor vehicles by aim of use) are taken from TUIK for each vehicle type. Total annual kilometers per vehicle data are created according to expert consultations. Then, total vehicle kilometer values are calculated by multiplication of these two data and the shares of each vehicle type in total vehicle kilometers are figured out. With these shares, billion vehicle kilometer values for cars, taxis and minibuses are obtained separately from Traffic and Transportation Information Reports of KGM.

Table 4.3. Annual number of vehicles and total kilometer per vehicle data for cars, taxis and minibuses (based on TUIK data and expert guess).

	number of vehicles			km per year		
year	car	taxi	minibus	car	taxi	minibus
2012	15,722,658	110,871	396,119	20,000	90,000	65,000
2013	16,556,218	111,257	421,848	20,000	90,000	65,000
2014	17,363,125	112,726	427,264	20,000	90,000	65,000
2015	18,412,290	114,746	449,213	20,000	90,000	65,000
2016	19,443,816	113,568	463,933	20,000	90,000	65,000
2017	20,509,828	113,816	478,618	20,000	90,000	65,000

To distribute demand data for all cars to each engine type, data for share of engine types in total cars are taken from a preceding graduate study focusing on the transport sector (Cirit, 2008). Then total vehicle kilometer data are divided into sub-totals for each engine type based on percentages. The distribution of cars according to engine type is as follows:

Table 4.4. Shares of cars by engine type.

Engine Type	**Share**
1000-1400 cc	38%
1400-1600 cc	50%
1600-2000 cc	10%
2000+ cc	2%
Total	100%

On the side of two wheelers, to calculate the demand data for two wheelers, annual number of vehicles data (number of road motor vehicles by aim of use) are taken from TUIK and total kilometers data are assumed to be as 2000 km per year. Based on these figures, the total billion vehicle kilometers data are obtained.

Data for years 2012 and 2017 are calculated as mentioned above. However, demand data, billion vehicle kilometers, of future years are predicted based on expert consultation in the transport sector.

As a result of all demand calculations and estimations for road transport sub-modes, billion vehicle kilometers for each period are obtained in the below table.

Table 4.5. Demand data (in billion vehicle kilometers) of road transportation.

Sub-mode	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
TRA_BUSPC	0.074	0.084	0.089	0.094	0.100	0.106	0.112	0.119	0.126
TRA_BUSPO	2.448	2.368	2.406	2.444	2.483	2.523	2.564	2.605	2.646
TRA_CARPC	25.765	32.136	40.170	50.212	62.766	78.457	98.071	122.589	153.236
TRA2_CARPC	33.902	42.284	52.882	66.069	82.586	103.233	129.041	161.301	201.627
TRA3_CARPC	6.708	8.457	10.571	13.214	16.517	20.647	25.808	32.260	40.325
TRA4_CARPC	1.356	1.691	2.114	2.643	3.303	4.129	5.162	6.452	8.065
TRAX_CARPC	1.959	2.112	2.207	2.306	2.410	2.518	2.632	2.750	2.874
TRA_MINPC	5.432	6.414	4.939	3.803	2.928	2.255	1.736	1.337	1.029
TRA_TRUF	12.806	11.824	12.013	12.205	12.401	12.599	12.801	13.005	13.214
TRA_TTRUF	9.824	12.466	12.815	13.174	13.543	13.922	14.312	14.712	15.124
TRA_TRULF	5.384	8.161	8.292	8.424	8.559	8.696	8.835	8.976	9.120
TRA_TWHP	5.660	6.206	6.826	7.509	8.260	9.086	9.994	10.994	12.093

4.2.2. Air Transport

As mentioned before, in the part of air transport, only domestic flights are not taken in consideration. The international flights with departures from Turkey are also included into the calculations together with whole domestic flights to obtain more accurate results.

Finding data for demand predictions in total kilometers for air flights is a challenging task. Therefore, Turkish Airlines (TK) Annual Reports are useful sources to calculate demand data for air transport. TK is the airway company with the largest market share in Turkey.

First of all, “number of landings and take-offs” and “distance flown km” data of TK are imported from TK Annual Reports for the past years. Then data of “Domestic and international transport and the number of arrivals-departures on the airports” are taken from TUIK. TUIK has only total number of landings and take-offs. Finally, total distance flown is calculated from TK distance flown by ratio of “TK-number of landings and take-offs / Total number of landings and take-offs”.

Table 4.6. Total distance flown (million kilometer) of domestic flights.

Domestic flights	**Total - number of landings and take-offs**	**TK - number of landings and take-offs**	**TK distance flown km (million)**	**TOTAL distance flown km (million)**
2012	600,818	128,541	78	363
2013	682,685	157,363	98	424
2014	754,259	172,307	108	473
2015	832,958	191,500	118	512
2016	886,228	195,522	121	550
2017	909,332	207,621	131	574

In the calculations of international flights part, only total landings and take-offs data of Turkish aircrafts are imported since BUEMS is a national model. Then, calculated total distance flown is divided into two to be able to include just one way trips into the model since total distance flown data consist of round trips.

Table 4.7. Total distance flown (million km) of international flights take-off from Turkey.

International flights	**Total - number of landings and take-offs**	**TK - number of landings and take-offs**	**TK distance flown km (million)**	**TOTAL distance flown km (million)**	**TOTAL distance flown km (million) of departures from Turkey**
2012	284,898	179,843	465	736	368
2013	323,780	220,037	593	872	436
2014	360,634	250,214	684	986	493
2015	397,526	271,267	747	1,094	547
2016	406,254	279,781	797	1,157	579
2017	412,743	275,691	799	1,196	598

Air transport demand data for years 2012 and 2017 are calculated as mentioned above. Demand data for future years are estimated according to expert consultations in the transport sector.

In consequence of all demand calculations and predictions for domestic and international flights of air transport, total billion kilometer distance flown for each period is compiled as follows:

Table 4.8. Demand data (total distance flown in billion kilometers) of air transport.

Sub-mode	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
TRA_AIRPD	0.464	0.574	0.648	0.719	0.784	0.839	0.881	0.907	0.917
TRA_AIRPI	0.485	0.598	0.688	0.777	0.863	0.940	1.006	1.056	1.099

4.2.3. Rail Transport

Demand data, train kilometers, for sub-modes of rail transport except for rail urban are compiled from TUIK website. Train kilometers for freight, high speed, passenger inner city (suburban) and passenger intercity (mainline-conventional) are available in “length of railways, train kilometers, tonne kilometers and freight transport” statistics of TUIK. Same information also exists in Turkish Railways Annual Statistics Book of The Turkish State Railways (TCDD). TCDD is the authority for all railways operations in Turkey and publications about railways operational statistics.

However, there exist no statistics related to rail urban sub-mode includes metro and tramway trains in the cities. Therefore, this information gathered one by one through municipality websites of the cities which have metro and/or tramway infrastructure. The reason for adding urban rail systems as a sub-mode of rail transport is increasing number of cities that have urban rail systems.

There exists twelve cities which have metro systems, light rail systems and/or tramway systems as urban rail systems that are publicly available. These cities as follows: Istanbul, Izmir, Ankara, Bursa, Eskisehir, Kayseri, Samsun, Konya, Antalya, Gaziantep, Adana and

Kocaeli. The city Kocaeli joins this group in recent years. It does not have any urban rail systems infrastructure until the year 2017.

Line routes, total line lengths, daily trip numbers and commissioning dates are recorded for each rail system of these twelve cities from municipality websites. Then total vehicle kilometers are calculated by multiplication of line lengths and total number of trips in related years which urban rail systems are in service. Each new line that starts operation at different times of the year included into total vehicle kilometers in proportion to time period which it is in service.

Table 4.9. Total million vehicle kilometers of urban rail systems in Turkey.

City	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Istanbul	13.38	17.27	19.51	20.42	20.67	21.14
Izmir	0.28	2.20	2.95	3.29	3.29	3.64
Ankara	2.25	2.25	4.30	4.63	4.63	5.36
Bursa	2.88	2.94	3.63	3.83	3.83	3.83
Eskisehir	8.10	8.10	10.68	14.28	14.28	14.28
Kayseri	1.89	1.99	3.94	4.29	4.40	4.78
Samsun	1.39	1.39	1.39	1.39	1.92	2.12
Konya	3.89	3.89	3.89	3.89	3.89	3.89
Antalya	0.59	0.59	0.59	0.59	0.59	0.59
Gaziantep	0.54	0.73	0.94	0.94	1.29	1.29
Adana	0.81	0.81	0.81	0.81	0.81	0.81
Kocaeli	-	-	-	-	-	0.78

After obtaining total vehicle kilometers of urban rail systems in each city as in Table 4.10 as a result of above methods, demand data for future years are estimated according to the growth prospects of experts in transport sector. Total vehicle kilometers of all rail transport sub-modes as demand data are finalized as follows.

Table 4.10. Demand data (billion train kilometers) of rail transport.

Sub-mode	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
TRA_RAIF	0.018	0.022	0.023	0.024	0.026	0.027	0.029	0.031	0.032
TRA_RAIS	0.004	0.007	0.007	0.007	0.007	0.007	0.007	0.008	0.008
TRA_RAIU	0.050	0.063	0.066	0.070	0.074	0.079	0.084	0.089	0.094
TRA2_RAIPC	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
TRA3_RAIPO	0.012	0.012	0.013	0.014	0.015	0.015	0.016	0.017	0.018

4.2.4. Maritime Transport

Maritime transport consists of intercity ferry boats, passenger domestic, tankers, bulk carriers, dry cargo and container ships as sub-modes. Only domestic operations of these six sub-modes are taken into consideration in demand data calculations of maritime transport.

General Directorate of Maritime Affairs (DTGM) is the responsible authority for maritime statistics. However, getting detailed information for maritime transport is a difficult process. Therefore, demand data for each sub-mode are calculated according to the obtained general data from DTGM and TUIK. Total million vehicle kilometers statistics by years of maritime transport in Turkey is represented below table.

Table 4.11. Total million vehicle kilometers of maritime transport in Turkey.

Year	**Vehicle km (million)**
2012	125
2013	137
2014	144
2015	154
2016	148
2017	153

Information about number of vessels by type for each year is taken from “Number Development of Turkish Maritime Fleet by Ship Type” statistics of DTGM. After obtaining annual vessel numbers by types, annual total kilometers by vessel type are compiled based on expert consultation in transport sector and total vehicle kilometer for each vessel type show up in the following tables 4.12 and 4.13.

Table 4.12. Numbers and total kilometers of intercity ferry boats, passenger domestics and bulk carriers by years.

intercity ferry boats			**passenger domestic**			**bulk carrier**		
#	**thousand km per year**	**total thousand km**	#	**thousand km per year**	**total thousand km**	#	**thousand km per year**	**total thousand km**
149	90	13,410	90	65	5,850	115	240	27,600
150	90	13,500	93	65	6,045	109	240	26,160
158	90	14,220	91	65	5,915	102	240	24,480
166	90	14,940	92	65	5,980	85	240	20,400
178	90	16,020	95	65	6,175	80	240	19,200
181	90	16,290	97	65	6,305	64	240	15,360

Table 4.13. Numbers and total kilometers of tankers, container and dry cargo ships by years.

container			**dry cargo**			**tanker**		
#	**thousand km per year**	**total thousand km**	#	**thousand km per year**	**total thousand km**	#	**thousand km per year**	**total thousand km**
72	240	17,280	489	240	117,360	214	240	51,360
72	240	17,280	473	240	113,520	213	240	51,120
74	240	17,760	447	240	107,280	196	240	47,040
78	240	18,720	390	240	93,600	194	240	46,560
72	240	17,280	379	240	90,960	190	240	45,600
75	240	18,000	353	240	84,720	184	240	44,160

Finally, total vehicle kilometers by sub-modes are calculated from total vehicle kilometers of maritime transport by ratio of “total km of a sub-mode / total km of all sub-modes”.

Maritime transport demand data for years 2012 and 2017 are calculated as mentioned above. Demand data for future years are estimated according to the expert consultation in the transport sector.

In consequence of all demand calculations and predictions for each sub-mode of maritime transport, total billion vehicle kilometers for each period are compiled as follows:

Table 4.14. Demand data (billion vehicle kilometers) of maritime transport by sub-modes.

Sub-mode	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
TRA_SHPFD	0.010	0.014	0.014	0.015	0.016	0.017	0.018	0.019	0.020
TRA_SHPPC	0.004	0.005	0.006	0.006	0.006	0.006	0.007	0.007	0.008
TRA_SHPDY	0.015	0.013	0.013	0.014	0.015	0.016	0.017	0.018	0.019
TRA_SHPCT	0.012	0.015	0.016	0.017	0.018	0.018	0.019	0.021	0.022
TRA_SHPKY	0.069	0.070	0.074	0.078	0.082	0.087	0.092	0.097	0.102
TRA_SHPT	0.032	0.037	0.039	0.041	0.043	0.045	0.048	0.050	0.053

4.3. Electric Vehicles Consumption Data

To obligate electric vehicles deployment in BUEMS, upper and lower bounds are set according to the prediction of consumption values for electric vehicles. Thus, behavior and effects on the energy system of electric vehicles deployment are observed under different diffusion and policy scenarios.

Electric vehicles are classified into three category: electric cars, electric buses and electric rail vehicles. This section describes how electricity consumption levels are determined for each category by adding additional constraints to BUEMS.

On the side of bounds determination of electric cars, only a lower bound is used for the model. Bounds for consumption levels of electric cars are based on an expert survey research conducted by Kumbaroğlu and Öztürk (2017). According to this research, 140,000 electric vehicles are estimated to be on the road in Turkey by year of 2022. For the base scenario of this study, this prediction is cut in half as the national electric vehicle manufacturing project has been progressing slower than anticipated. In other words, it is assumed that there will be 70,000 electric cars on the road in Turkey by year 2022.

Electricity consumption level predictions of electric cars are finalized according to the below assumptions:

- An increase of 19.1% per year in the number of electric cars.
- A consumption of 25 kWh of electricity per 100 kilometers (IEA, 2018).
- An annual mileage of 15,000 km.

In consequence of the above assumptions, finalized numbers and electricity consumption levels of electric cars which are included into BUEMS as lower bounds are provided below.

Table 4.15. Lower electricity consumption bounds (in PJ) and numbers for electric cars.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption	0.0001944	0.117	0.945	2.268	5.443	13.064	31.353	75.247	180.592
Number	14	8,640	70,000	168,000	403,200	967,680	2,322,432	5,573,837	13,377,208

In the part of bounds determination of electric buses, upper and lower bounds are used for the model. To determine current numbers of electric buses, a web search is conducted and municipality websites and news portals are examined. According to this search, there was no electric buses in 2012 while 42 electric buses are available by year of 2017. Location of these 42 electric buses are as follows: 4 buses in Eskisehir, 18 buses in Kayseri and 20 buses in Izmir. Until 2022, 15 electric buses in Elazig and 22 electric buses in Manisa are expected to be in service.

For the base and other alternative scenarios except “ISTBUS” and “NODIESEL_T” scenarios, below assumptions are used to determine upper and lower bounds for electricity consumption levels of electric buses.

Assumptions for lower bound:

- An estimation of 79 electric buses in Turkey by year of 2022 and an increase of 8% per year in the number of electric buses.
- A consumption of 135 kWh of electricity per 100 kilometers (IEA, 2018).
- Annual mileage of 50,000 km.

Assumptions for upper bound:

- An estimation of 99 electric buses in Turkey by year of 2022 and an increase of 16% per year in the number of electric buses.
- A consumption of 150 kWh of electricity per 100 kilometers (IEA, 2018).
- Annual mileage of 50,000 km.

As a result of the above assumptions, finalized numbers and electricity consumption levels of electric buses which are included into BUEMS as upper and lower bounds are represented below.

Table 4.16. Upper and lower electricity consumption bounds (in PJ) and numbers of electric buses.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption - low	0	0.0113	0.0192	0.0282	0.0415	0.0610	0.0896	0.1318	0.1937
Number - low	0	42	79	116	171	251	369	542	797
Consumption - up	0	0.0113	0.0267	0.0561	0.1179	0.2475	0.5198	1.0917	2.2925
Number - up	0	42	99	208	437	917	1,925	4,043	8,491

On the side of bounds determination of electric rail vehicles, upper and lower bounds are prepared for the model. Consumption levels of electric rail vehicles except for rail urban sub-mode are based on Turkish Railways Annual Statistics Book of TCDD. From 2012 to 2017, electricity consumptions of railways are available in this book. Thus, a ratio for future periods is calculated from current data in terms of kWh per billion km.

For the part of rail urban, electricity consumption values of urban rail systems in Ankara is found from the municipality website. Then, a general ratio is obtained from Ankara data in terms of kWh per km to use it for electricity consumption calculations for all urban rail systems.

For upper bound a higher rate of electricity consumption per kilometer is preferred while a lower rate of electricity consumption per kilometer is applied for lower bound.

In consequence of the above methods, finalized electricity consumption levels of electric rail vehicles which are included into BUEMS as upper and lower bounds are obtained as follows:

Table 4.17. Upper and lower electricity consumption bounds (in PJ) of electric rail vehicles.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption - low	2.659	4.344	4.605	4.881	5.174	5.484	5.813	6.162	6.532
Consumption - up	2.820	4.570	4.844	5.135	5.443	5.769	6.116	6.483	6.871

4.4. Other Data

As stated before, BUEMS requires total billion vehicle kilometers traveled per year as sectoral demand data of transport sector and these data are the most critical data for transport sector when different policy scenarios are applied and scenario results are compared.

Fuel efficiencies, fixed and variable operation and maintenance costs, lifetimes, residual capacities, capacity bounds, activity levels, availability factors, investment prices, investment bounds are other input requirements for transport sector technologies in BUEMS.

5. SCENARIOS AND RESULTS

5.1. Definition of Scenarios

For the base scenario (“BASE”) definition, the current energy system of Turkey is represented with its business-as-usual assumptions, together with a modest prediction for electric vehicles. In the base scenario, electric cars are expected to rise to 70 thousand in 2022 and grow with a 19.1% rate per year.

As the first alternative scenario (“MOREECAR”), the consumption of electric cars is estimated by more demanding prediction as 140 thousand cars in 2022 and 19.1% growth per year to analyze the effects of electric vehicles deployment on the model. Electricity consumption levels of this alternative scenario with the same assumptions with BASE are as follows:

Table 5.1. Lower electricity consumption bounds (in PJ) for electric cars in MOREECAR scenario.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption	0.0001944	0.117	1.890	4.536	10.886	26.127	62.706	150.494	361.185
Number	14	8,640	140,000	336,000	806,400	1,935,360	4,644,864	11,147,674	26,754,417

The case of no electric cars between 2022-2052 years in Turkey is handled in the second alternative scenario (“NOECAR”) to compare results of extinction and deployment of electric vehicles.

In the next chapter, the scenario results will show that with the increase in number of electric cars in each period, electricity generation sector CO_2 emissions increase while transport sector CO_2 emissions decrease. Therefore, as the third alternative scenario (“COALLIM_E”), coal-based electricity generation is restricted to direct energy production for electric cars to renewable energy. Electric vehicles demand is taken same with BASE and coal-based electricity generation is limited to levels of the NOECAR.

With the intent of evaluating the relationship of power generation, transport sector and CO_2 emissions, an extreme case is handled in the fourth alternative scenario (“NONEWCOAL_E”). In this scenario, electric vehicles prediction remains same with the Base scenario, but coal based electricity generation is restricted in the way that generation would not show an increase by 2027.

The fifth alternative scenario (“ISTBUS”) is built on the consideration of what will happen if all the buses in Istanbul are electric vehicles by year 2027. Therefore, according to the inner city bus transport data of Istanbul, electric buses’ bounds of the model are revised. Then coal based electricity generation is restricted once again to direct growing electricity demand of electric buses to renewable energy. Total number of buses and total annual mileage values are calculated through information on websites of Istanbul Bus Company, Istanbul Public Bus Company and IETT and also from 2017 Annual Report of IETT. Then total electricity consumptions are estimated in case of all the buses in Istanbul city are electric vehicles. For lower bound, 135 kWh of electricity consumption per 100 kilometers is assumed while 170 kWh of electricity consumption per 100 kilometers is supposed for upper bound. Other assumptions are same with BASE scenario assumptions. According to the calculated inner city buses transport data of Istanbul, consumption levels of Istanbul buses are obtained as follows:

Table 5.2. Upper and lower electricity consumption bounds (in PJ) for electric buses in Istanbul.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption - low	0	0	0	3.6135	6.6728	13.3318	27.8719	59.6698	129.2598
Consumption - up	0	0	0	4.5503	8.4028	16.7881	35.0980	75.1398	162.7716

Lastly, electric buses bounds are revised in ISTBUS alternative scenario by adding Istanbul data to current data of electricity consumption of electric buses. Thus, finalized upper and lower electricity consumption bounds of electric buses in ISTBUS scenario are indicated below.

Table 5.3. Upper and lower electricity consumption bounds (in PJ) for electric buses in ISTBUS scenario.

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption - low	0	0.0102	0.0192	3.6417	6.7143	13.3927	27.9616	59.8016	129.4535
Consumption - up	0	0.0188	0.0442	4.6432	8.5978	17.1977	35.9582	76.9461	166.5650

To see effects of banning diesel powered vehicles, the sixth scenario (“NODIESEL_T”) is created. Therefore, usage of diesel cars and buses are banned by year of 2027 in the model. Diesel consumption of cars and buses is identified as zero starting with year 2027 by adding fix levels to the model for them. Then coal base electricity generation is restricted once again to direct growing electricity demand of transport sector to renewable energy.

As the seventh alternative scenario (“CO2LIM25%_T”), emission restrictions are applied to the transport sector in the base scenario. In this regard, transport emissions are restricted so as to be 25% below the BASE scenario emissions.

Lastly, a carbon tax (0.05$ per kiloton of CO_2) is introduced into the base scenario in three different ways starting from year 2032. Based upon the interdependent relationship of power generation, transportation and CO_2 emissions, firstly 0.05$ per kiloton of CO_2 emission tax is applied to the transport sector only (“CO2TAX50_T” scenario). Then this tax is placed on the electricity generation sector solely (“CO2TAX50_E” scenario). After that electricity generation and transport sectors are subjected to this carbon tax together in the base scenario (“CO2TAX50_TE” scenario).

Table 5.4. Scenarios and their definitions in the study.

Scenario	Definition
BASE	Business-as-usual assumptions Estimation of 70 thousand electric cars in 2022 and 19.1% growth per year
MOREECAR	Same assumptions with BASE except for electric cars Estimation of 140 thousand electric cars in 2022 and 19.1% growth per year
NOECAR	The case of no electric cars between 2022 and 2052 years in Turkey
COALLIM_E	Same assumptions with BASE except for coal-based electricity generation Coal-based electricity generation is limited to levels of NOECAR
NONEWCOAL_E	Same assumptions with BASE except for coal-based electricity generation Coal-based electricity generation is restricted in the way that generation would not show an increase by 2027
ISTBUS	The case of all the buses in Istanbul are electric vehicles by year 2027 Coal-based electricity generation is restricted in the way that generation would show an 10% increase at most after 2027
NODIESEL_T	The case of banning diesel powered vehicles, usage of diesel cars and buses, by year of 2027 Coal-based electricity generation is restricted in the way that generation would show an 10% increase at most after 2027
CO2LIM25%_T	Transport emissions are restricted so as to be 25% below BASE scenario emissions
CO2TAX50_T	0.05$ per kiloton of CO2 emission tax is applied to the transport sector only
CO2TAX50_E	0.05$ per kiloton of CO2 emission tax is placed on the electricity generation sector only
CO2TAX50_TE	Electricity generation and transport sectors are subjected to 0.05$ per kiloton of CO2 emission tax together

Abbreviations which are used in following subsections related to results and comparison of the scenarios are explained below.

Table 5.5. Definition of abbreviations in chapter 5.

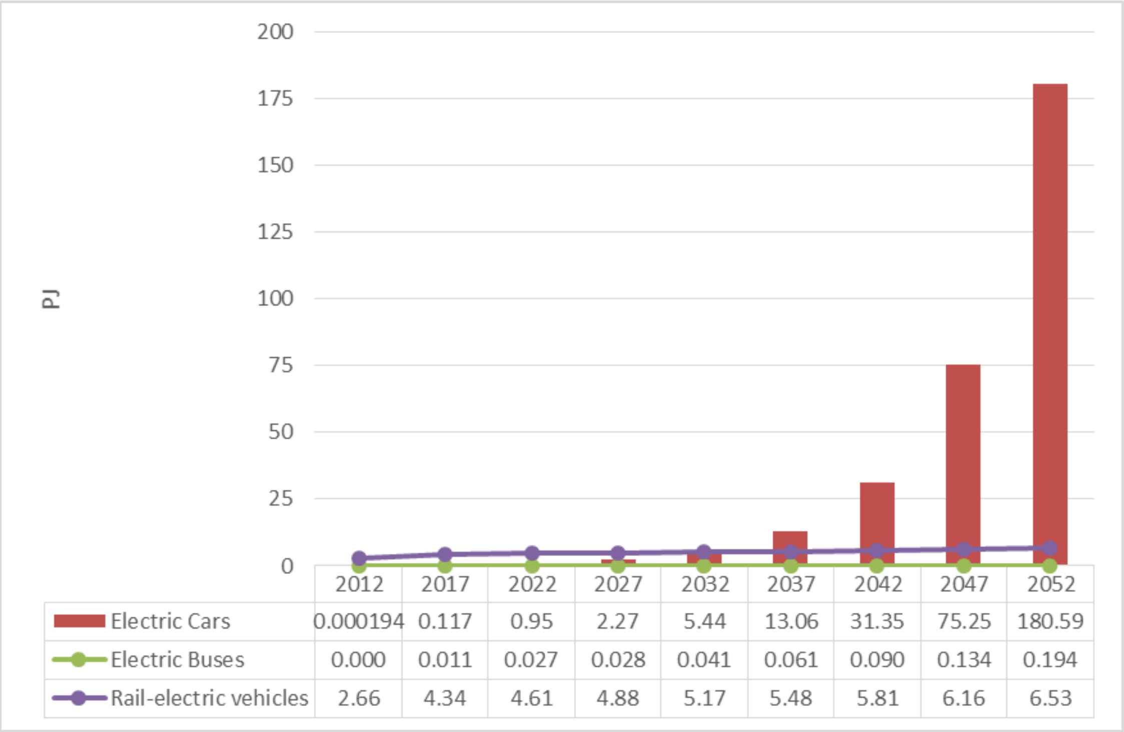
Abbreviation	**Definition**
emiss_elc	periodic emissions from electricity sector technologies
emiss_tra	periodic emissions from transport sector technologies
natgas gen	natural gas based power generation
coal gen	coal based power generation
solar and wind gen	power generation from solar and wind
pet_t_cons	petroleum consumption of transport sector
elc_t_bus	electricity consumption of buses
renewables	power generation from hydro, solar and wind
renewables %	share of power generation from hydro, solar and wind in total power generation

5.2. Base Scenario

The base scenario is built to reflect the current energy system of Turkey with its business-as-usual assumptions, together with a modest prediction for electric vehicles. In the base scenario, electric cars are expected to rise to 70 thousand in 2022 and to grow 2.4 times for each period.

5.2.1. Electricity Consumption of Transport Sector

Electric cars dominate the electricity consumption of transport sector in each period. Electricity consumption of electric cars is almost zero in 2012 and 0.117 PJ in 2017 whereas it reaches 75.247 PJ in 2047 and PJ 180.592 in 2052.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
🟥 Electric Cars	0.000194	0.117	0.95	2.27	5.44	13.06	31.35	75.25	180.59
● Electric Buses	0.000	0.011	0.027	0.028	0.041	0.061	0.090	0.134	0.194
● Rail-electric vehicles	2.66	4.34	4.61	4.88	5.17	5.48	5.81	6.16	6.53

Figure 5.1. Electricity consumption levels of transport sector predicted in BASE scenario.

5.2.2. Energy Consumption of Transport Sector

In the model, total energy consumption of transportation includes electricity, petroleum, diesel, biodiesel, hydrogen, jet fuel, CNG, LPG, ethanol and methanol as fuel types. According to the results of the base scenario, diesel fuel is the dominant fuel from the beginning of planning horizon, 56.36% in 2012 and 53.44% in 2017. But its share in total transport energy consumption decreases over time, 31.48% in 2047 and 22.48% in 2052 due to rise in electricity share particularly. Electricity consumption in transportation gradually increases because of electric car deployment where its share is 0.32% in 2012, 0.47% in 2017, 6.29% in 2047 and 13.76% in 2052. Hydrogen fuel gets involved in 2052 with a consumption of 1.614 PJ. While jet fuel and petroleum consumptions continue to grow depending on the increase of transport demand, methanol consumption decreases for each period. Lastly, LPG consumption is 127.5 PJ in 2012 then drops over time and becomes zero by year 2047 due to considerable increase in electric cars.

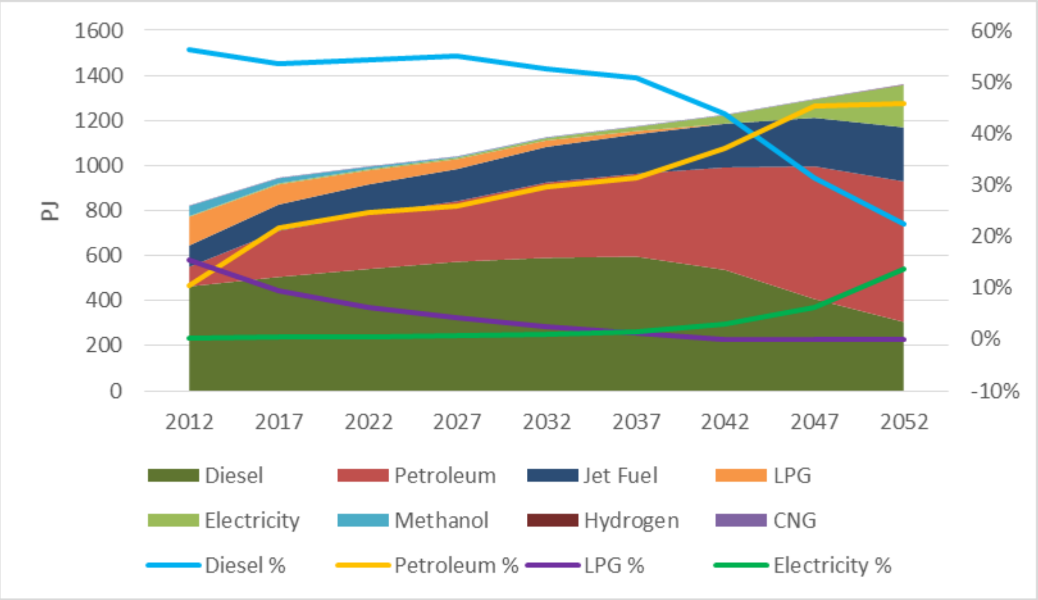


Figure 5.2. Energy consumption levels of transport sector by fuel types: BASE Scenario.

5.2.3. Electricity Generation

Electricity generation obtains from coal, natural gas, hydropower, solar, wind, geothermal, oil products and nuclear sources in the model. While coal is the second dominant after natural gas energy source in the beginning (244 PJ in 2012 and 351 PJ in 2017), it becomes the dominant fuel by 2027. Coal usage reaches 439.698 PJ in 2027 and 3720.846 PJ in 2052. While electricity generation from natural gas is 376 PJ in 2012 and 389.4 PJ in 2017, it decreases over time and drops to 335.602 PJ in 2052. Natural gas's share decreases from 43.66% in 2012 to 9.39% in 2052.

On the side of renewables, electricity generation from solar begins in 2017 with 4.29 PJ and wind begins in 2012 with 21.09 PJ. The solar and wind energy share reaches its maximum in 2027 with a 2.28% and 11.41% respectively then they decrease gradually in the rest of the periods because new investments for solar and wind are not realized in the base scenario after 2027. Hydropower accounts 24.15% for of total electricity generation in 2012 and drops to 9.32% in 2052 while geothermal energy reaches its peak point in 2037 with 3.10% share and becomes 1.49% in 2052.

Nuclear energy gets involved in 2027 with a share of 10% of total electricity generation. Since additional capacity is not be realized in the base scenario for next periods, its share decreases because of its unchanging capacity and significant increase of coal. Total electricity production increase from 861.12 PJ in 2012 to 4507.09 PJ in 2052.

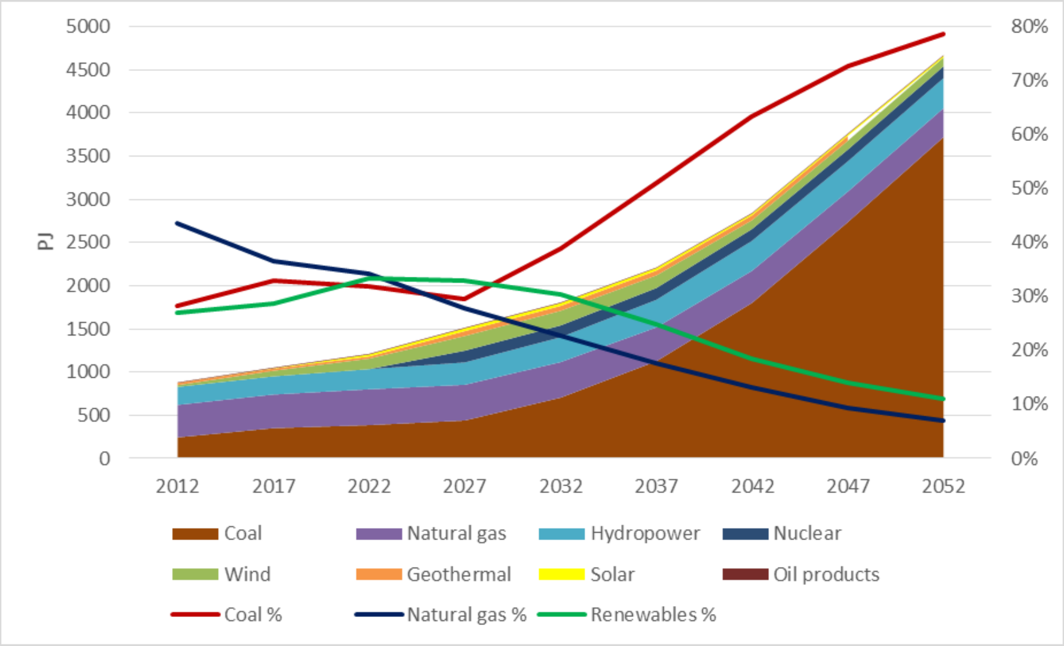


Figure 5.3. Electricity generation levels by sources: BASE Scenario.

5.2.4. Installed Capacities

Installed capacities of power plants are presented in Table 5.6. Coal fired power plants have 12.6 GW capacity in 2012 and reach 138.6 GW capacity in 2052 and coal becomes the dominant energy source. Capacity of natural gas fired power plants is 20.4 GW at the beginning of planning horizon while it drops after 2022 and will be 22.5 GW in 2052. Nuclear energy has 4.8 GW installed capacity in 2027 and preserves its capacity in next periods.

On the other hand, solar and wind power begin in 2017 with 1.36 GW capacity and in 2012 with 2.3 GW capacity respectively and their capacities decrease after 2032.

Table 5.6. Installed capacities (in GW) predicted in the base scenario.

Energy Sources	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Coal	12.600	20.068	22.200	24.770	39.049	53.445	75.935	106.987	138.599
Natural Gas	20.400	23.100	29.300	29.181	29.062	27.583	26.203	24.893	22.466
Hydropower	19.600	27.200	31.530	29.917	28.315	27.356	27.547	27.812	27.586
Wind	2.300	6.400	11.803	16.524	16.524	14.224	10.124	9.957	9.957
Solar	-	1.362	8.262	8.262	8.262	7.112	4.979	4.979	4.979
Geothermal	0.160	1.060	1.153	1.153	2.540	2.540	2.540	2.540	2.540
Nuclear	-	-	-	4.800	4.800	4.800	4.800	4.800	4.800
Petroleum	1.040	0.315	0.315	0.315	0.315	0.315	1.000	0.994	0.997

5.2.5. Emission Levels

Total CO_2 emission level is 272.1 Mton in 2012 and reaches 1408.5 Mton in 2052. Total CO_2 emissions almost increase by 5.2 times from the beginning to the end of the planning horizon due to significant rise in coal based electricity generation and decrease in solar and wind energy after 2032.

Considering the sectoral shares of total CO_2 emissions, the main contributor is electricity generation with 31.48%, followed by the industry sector with 26.78% share as the second largest emitter in 2012. The electricity generation sector protects its place throughout the planning horizon as the largest emitter and reaches 47.87% share caused by burning fossil fuels, especially coal. As the third largest emitter, the transport sector accounts for 20.28% of total CO_2 emission in 2012, then declines period by period due to electric vehicles deployment and drops to a 7.71% share in the last period.

Refinery sector emission levels are 5.5 Mton in 2012 and 6.4 Mton in 2017, and reach 9.5 Mton in 2052 due to ordinary increase in petroleum products demand. However, the share of refinery sector CO_2 emissions decreases over time since demand of petroleum products growing at a decreasing rate because of the rise in the use of electric vehicles.

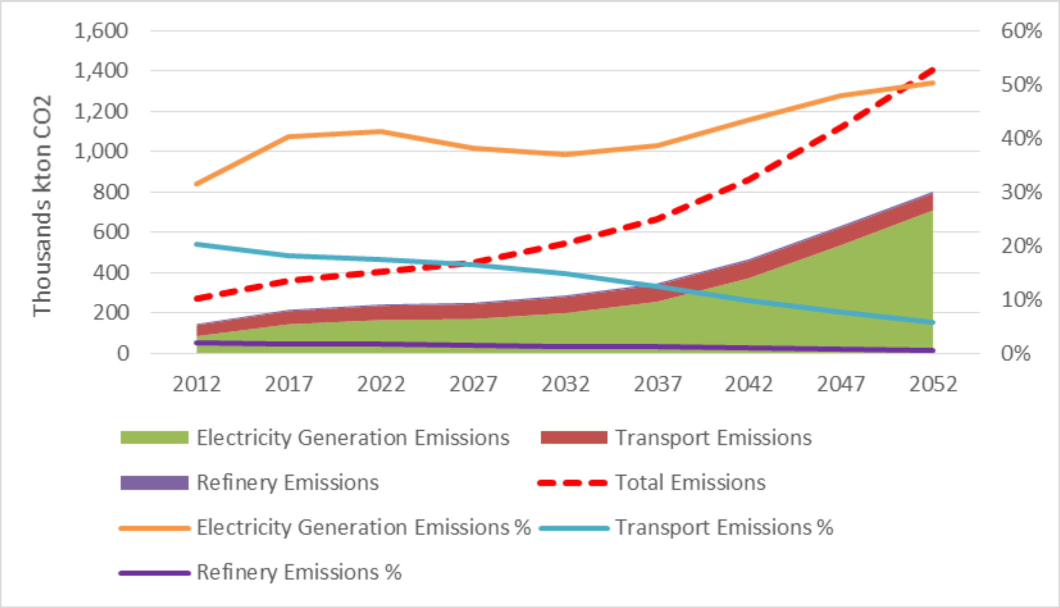


Figure 5.4. CO_2 emission levels by sectors: BASE Scenario.

5.3. Electric Car Scenarios

In the MOREECAR scenario, electric cars prediction is made as 140 thousand cars in 2022 and 2.4 times growth for each period while the case of no electric cars between 2022-2052 years in Turkey is handled in the NOECAR scenario.

5.3.1. Electricity Consumption of Transport Sector

According to the demand prediction of electric cars throughout the planning horizon, the estimated consumption values of electric cars are indicated in Figure 5.5. Estimated consumption values of electric buses and rail vehicles are same in all three scenarios; therefore, total electricity consumption of transportation changes particularly depending on estimated consumption values of electric cars in all scenarios.

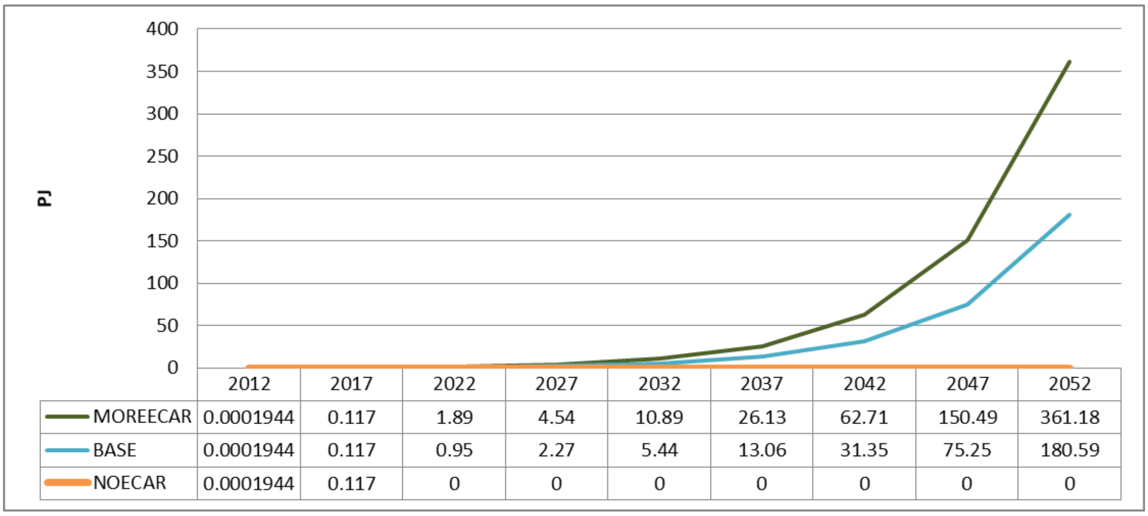


Figure 5.5. Electric cars consumption levels.

Total electricity consumptions and consumptions of buses and rail vehicles between 2012 and 2052 for each scenarios are given below table.

Table 5.7. Electricity consumption levels (in PJ).

	Scenario	2012	2017	2022	2027	2032	2037	2042	2047	2052
Buses	**MOREECAR**	0.000	0.011	0.027	0.028	0.041	0.061	0.090	0.134	0.194
	BASE	0.000	0.011	0.027	0.028	0.041	0.061	0.090	0.134	0.194
	NOECAR	0.000	0.011	0.027	0.028	0.041	0.061	0.090	0.134	0.194
Rail vehicles	**MOREECAR**	2.659	4.344	4.605	4.881	5.174	5.484	5.183	6.162	6.532
	BASE	2.659	4.344	4.605	4.881	5.174	5.484	5.183	6.162	6.532
	NOECAR	2.659	4.344	4.605	4.881	5.174	5.484	5.183	6.162	6.532
Total	**MOREECAR**	2.659	4.472	6.522	9.449	16.105	31.675	68.613	156.786	367.906
	BASE	2.659	4.472	5.577	7.177	10.658	18.609	37.256	81.543	187.318
	NOECAR	2.659	4.472	4.632	4.909	5.215	5.545	5.903	6.296	6.726

5.3.2. Energy Consumption of Transport Sector

As it can be seen from Figure 5.6, when the demand for electric vehicles increases, the needed amount of petroleum for transport sector decreases. By year 2027, petroleum consumption of transport sector is 268.539 PJ in BASE while 260.477 PJ in MOREECAR and 271.859 PJ in NOECAR. For 2027, petroleum consumption of transport sector is reduced by 3% in MOREECAR and increased by 1.2% in NOECAR in comparison with BASE. As the difference of electric vehicles demand grows between the scenarios over time, the need for petroleum for transportation changes significantly. For instance, in 2052 petroleum fuel consumption for transportation is 623.885 PJ in BASE, but it drops to 496.893 PJ in MOREECAR and reaches 748.646 PJ in NOECAR. For 2052, petroleum consumption of transport sector is reduced by 20% in MOREECAR and increased by 20% in NOECAR in comparison with BASE.

Considering the share of petroleum fuel consumption to the total energy consumption of transport sector, by year 2027 shares are 25.78% in BASE, 25.15% in MOREECAR and 26.08% in NOECAR while in 2052 they are 45.83%, 35.12% and 57.35% respectively. In the model, other fuel demands (diesel, LPG etc.) are not be affected from electricity demand changes of transport sector.

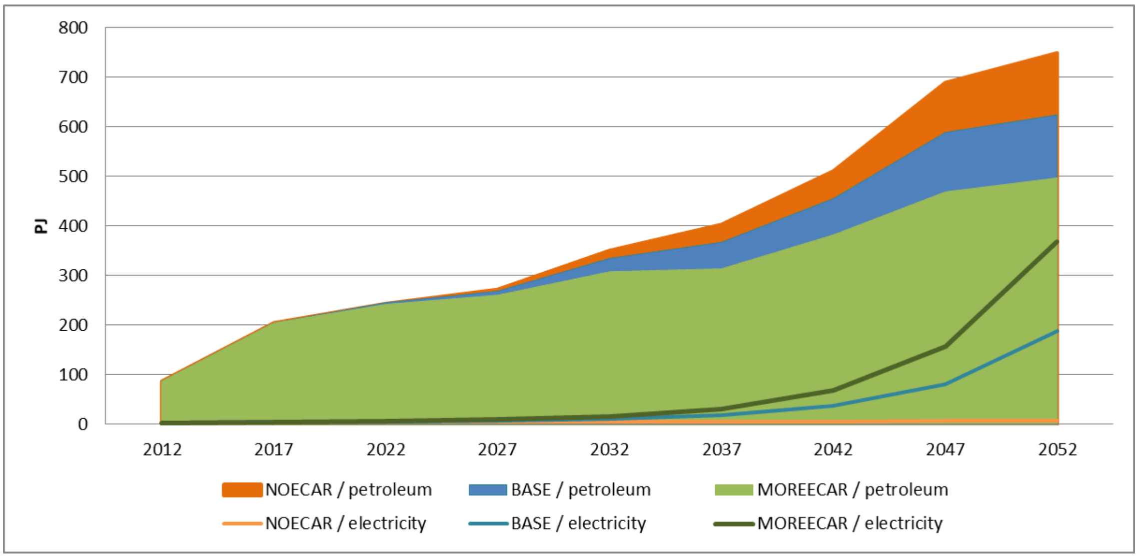


Figure 5.6. Electricity and petroleum consumption levels of the transport sector.

5.3.3. Electricity Generation

Three scenario results show that the system meets growing electricity demand due to the increase in the number of electric cars from coal-based electricity generation because of the model's "to minimize total system cost" objective and Turkey's current coal policy which is introduced to the BUEMS. Therefore, while growing number of electric cars provides considerable emission reductions in transport sector emissions, it causes a significant growth in total system emissions because of the coal-based electricity generation.

For year 2027 coal based electricity generation is 439.698 PJ in BASE, 448.869 PJ in MOREECAR and 429.853 PJ in NOECAR while in 2052 it is 3720.846 PJ, 3938.967 PJ and 3501.134 PJ respectively. In 2027, coal based electricity generation is reduced by 2.2% in NOECAR and increased by 2% in MOREECAR according to the BASE. On the other hand, coal based electricity generation is reduced by 6% in NOECAR and increased by 5.9% in MOREECAR according to the BASE in 2052.

The model meets increasing electricity demand of transportation from coal-based electricity generation only and electricity generation by other sources remains same in these three scenarios. Therefore, emission levels of electricity generation sector increase when burning fossil fuels caused by coal-based electricity generation increment go up. For 2027, emission level of electricity generation sector is 170440 kton CO_2 in BASE, 172830 kton CO_2 in MOREECAR and 168040 kton CO_2 in NOECAR whereas by 2052 the emission level is 709530 kton CO_2, 748460 kton CO_2 and 670380 kton CO_2 respectively. The share of electricity generation sector emission level increase from 38.14% in 2027 to 50.37% in 2052 for BASE, from 38.51% in 2027 to 51.99% in 2052 for MOREECAR and from 37.53% in 2027 to 48.29% in 2052 for NOECAR.

The shares of coal based electricity generation to total electricity generation in each period of the scenarios go parallel with each other since all electricity demand increase is satisfied with coal based generation in each scenarios.

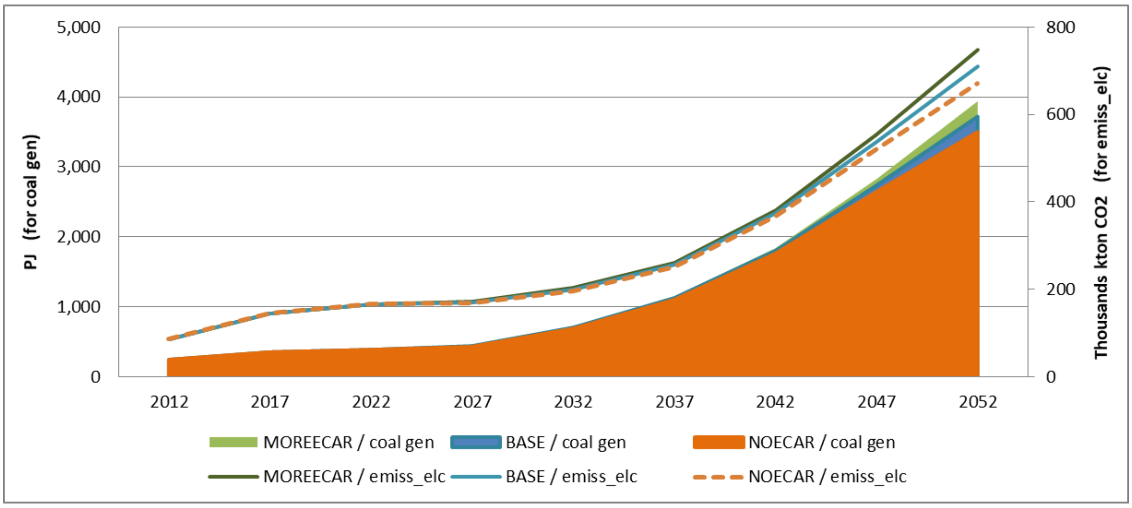


Figure 5.7. Coal based electricity generation and emission levels of electricity generation.

5.3.4. Emission Levels

With the increase in the number of electric cars in each period transport sector CO_2 emissions decrease compared to base scenario. On the other hand, the system meets growing electricity demand due to the increase in the number of electric cars from coal-based electricity generation because of the model's "to minimize total system cost" objective and Turkey's current coal policy which is introduced to the BUEMS. Therefore, while growing number of electric cars provides considerable emission reductions in transport sector emissions, it causes a significant growth in total system emissions in the system because of burning fossil fuels originating from the coal-based electricity generation.

In the same way, removing electric cars from the model causes an increase in transport sector CO_2 emissions compared to base scenario. But, the drop in electricity demand for transportation in the absence of electric cars reduces the coal-based electricity generation and electricity generation sector CO_2 emissions at the same time. Thus, especially for the last periods of the planning horizon whereas the impact of electric vehicles deployment is seen more particularly, total system emission is the least in NOECAR scenario and total emission of MOREECAR scenario is larger than BASE due to the burning fuels factor to meet electricity demand.

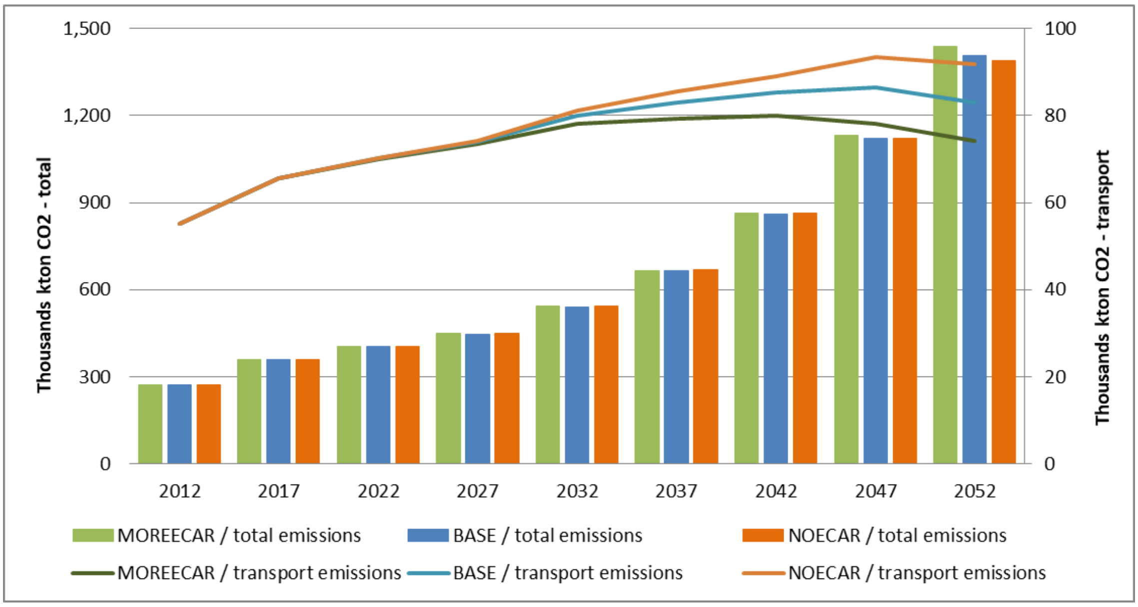


Figure 5.8. Total and transport sector emission levels.

In 2022, while transport sector emission is 70,299 kton CO_2 in BASE, it increases to 70,164 kton CO_2 in NOECAR and decreases to 70,062 kton CO_2 in MOREECAR. By year 2052, the BASE scenario emits 83,103 kton CO_2 while NOECAR emits 91,837 and MOREECAR emits 74,214 kton CO_2. On the other hand, electricity generation sector emission and total emission are 166,010 and 403,140 kton CO_2 respectively in BASE while they are 166,080 and 404,320 kton CO_2 in NOECAR and 166,020 and 402,940 kton CO_2 in MOREECAR for year 2022. In 2052, electricity generation sector emission is 709,530 kton CO_2 for BASE, 670,380 kton CO_2 for NOECAR, and 748,460 kton CO_2 for MOREECAR while total emission is 1,408,500 kton CO_2 for BASE, 1,388,300 kton CO_2 for NOECAR, and 1,439,600 kton CO_2 for MOREECAR.

On the side of total emissions, they are increased by 2.2% for MOREECAR and reduced by 1.4% for NOECAR in 2052 according to the BASE.

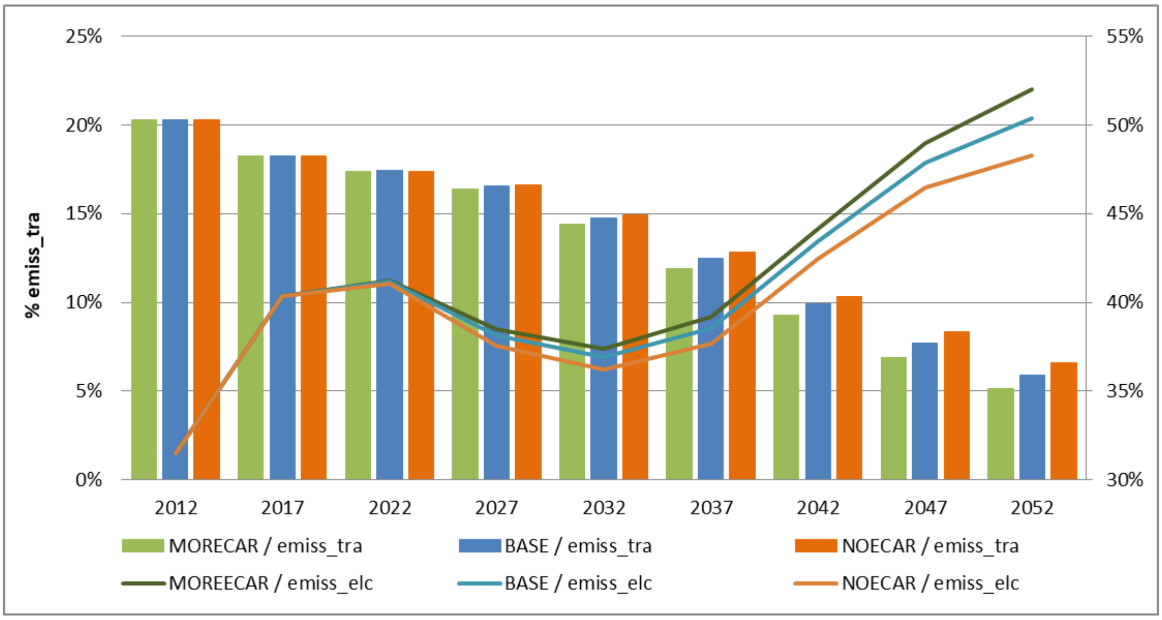


Figure 5.9. Shares of electricity generation and transport sectors emission levels.

5.4. Coal Restriction Scenarios

When coal-based electricity generation is restricted, it can be seen that the growing electricity demand with the increase of electric cars is met from renewable energy, fully from solar and wind based electricity generation. Comparison of the Base and Coal Restrictions scenarios, the results indicates that total system emissions of the Coal Restriction Scenarios is lower than the Base as a consequence of directing renewables to meet the energy demand of electric cars.

5.4.1. Electricity Consumption of Transport Sector

In these two scenarios electric cars consumption levels are taken same with the base scenario to see the importance of co-development of electric vehicles and renewable energy. Comparison of these three scenarios will show how the electric vehicle deployment impact differs in the system with the same electrical vehicles demand but different energy portfolios.

Table 5.8. Electric cars consumption levels (in PJ).

Year	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Consumption	0.0001944	0.117	0.945	2.268	5.443	13.064	31.353	75.247	180.592

5.4.2. Energy Consumption of Transport Sector

Energy consumption levels of transportation by fuel types (electricity, petroleum, diesel, LPG etc.) in both COALLIM_E and NONEWCOAL_E scenarios are same with BASE since all demand predictions of transport sector remain same with the base scenario.

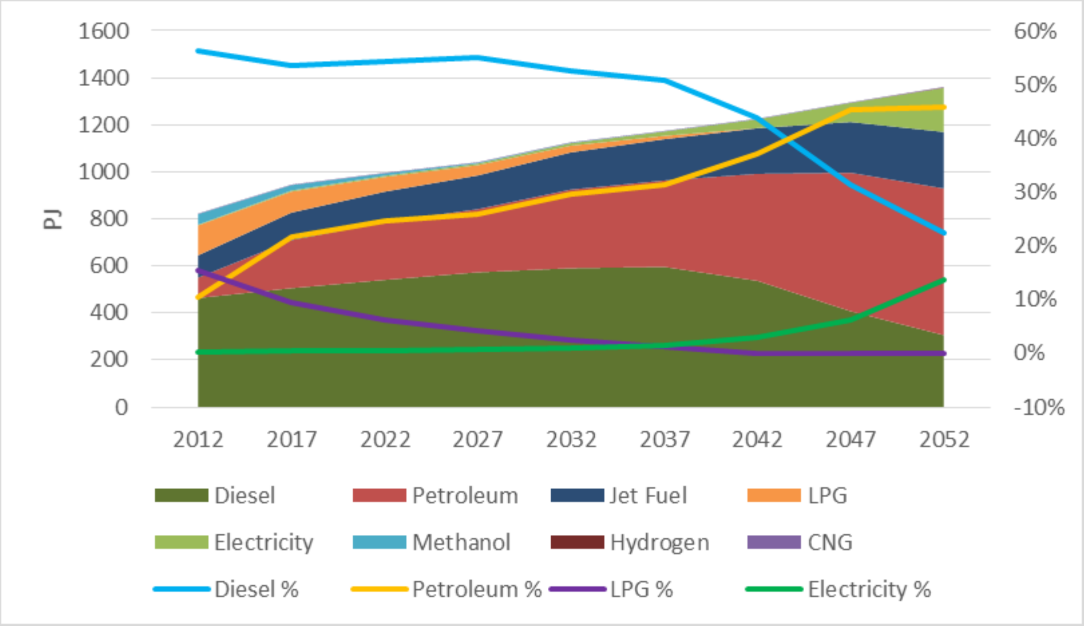


Figure 5.10. Energy consumption levels of transport sector by fuel types: BASE, COALLIM_E and NONEWCOAL_E Scenarios.

5.4.3. Electricity Generation

In COALLIM_E scenario, coal based electricity generation is restricted to be same as coal based electricity generation in NOECAR. On the other hand, in NONEWCOAL_E scenario coal based electricity generation is fixed starting from year 2027 as so no increment is on coal based generation after 2027. In COALLIM_E scenario, coal based electricity generation increases from 429.853 PJ in 2027 to 3501.134 PJ in 2052 while it is 439.698 PJ in 2027 and 2052.

With the decline in coal based electricity generation, system meets unsatisfied energy need by generating electricity from renewable energy, actually wind and solar energy for both alternative scenarios. Sudden and significant decrease of coal based electricity generation in NONEWCOAL_E scenario forces the system to close demand and supply gap by using natural gas based electricity generation also.

For year 2022 electricity generation from solar is 24.195 PJ in BASE scenario while it is 24.247 PJ in COALLIM_E and 39 PJ in NONEWCOAL_E. In year 2052, solar based power generation is 20.41 PJ for BASE when it is 20.753 PJ for COALLIM_E and 293.652 PJ for NONEWCOAL_E. Thus, solar based electricity generation is increased by 0.2% in COALLIM_E and 6.1% in NONEWCOAL_E for 2022 while it is increased by 1.7% and 13 times respectively for 2052 in comparison with the BASE.

On the side of wind based power generation, BASE scenario has 120.973 PJ generation and COALLIM_E has 121.149 PJ generation in 2022 while electricity generation from wind is 102.052 PJ and 103.767 PJ respectively in year 2052. In NONEWCOAL_E scenario wind based power generation shows a significant increase. It is 195 PJ in 2022, 535.08 PJ in 2037 and 1468.26 PJ in 2052. Residual supply gap, which cannot be met by solar and wind based power generation in NONEWCOAL_E scenario, is closed by power generation from natural gas sources. As a result, wind based electricity generation is increased by 0.1% in COALLIM_E and 6.1% in NONEWCOAL_E for 2022 while it is increased by 1.7% and 13 times respectively for 2052 according to the BASE.

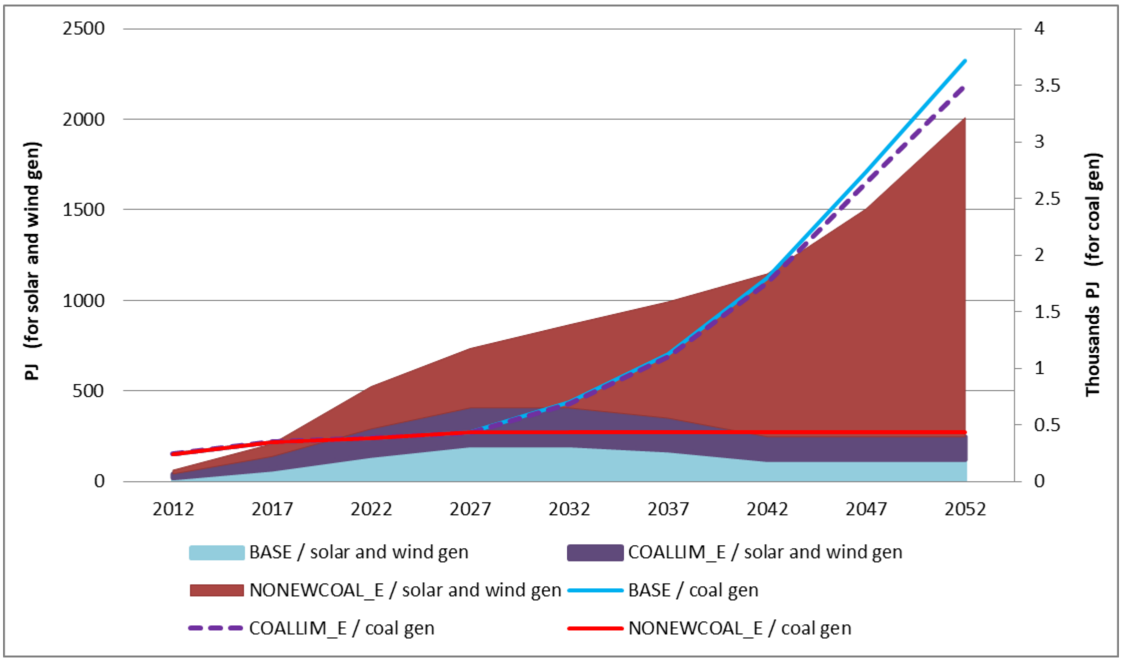


Figure 5.11. Coal based and solar & wind electricity generation levels: BASE, COALLIM_E and NONEWCOAL_E Scenarios.

Comparison of natural gas based power generations for BASE and NONEWCOAL_E scenarios is figured below. Power generation amounts from natural gas of both scenarios are same between the periods of 2012 and 2037. As from 2042 natural gas based power generation show an increase according to the base scenario. In 2042, power generation from natural gas is 371.858 PJ for BASE and 393.391 PJ for NONEWCOAL_E while it is 335.602 PJ in BASE and 716.820 PJ in NONEWCOAL_E scenarios for year 2052. Natural gas based power generation of NONEWCOAL_E is increased by 5.8% in 2042 and 1.14 times in 2052 in comparison with the BASE.

For both scenarios, COALLIM_E and NONEWCOAL_E, directing energy supply from coal to renewables and natural gas which is cleaner than coal results in a decrease in total emissions depending on a decline in emissions from electricity sector technologies according to the base scenario.

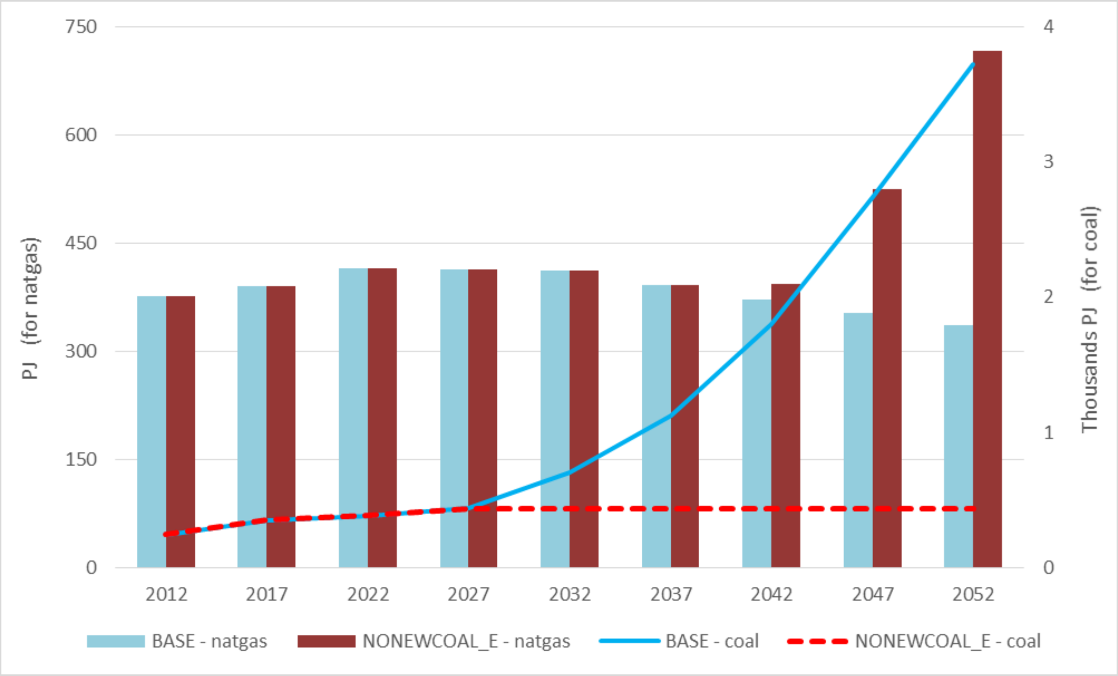


Figure 5.12. Coal and natural gas based electricity generation: BASE and NONEWCOAL_E Scenarios.

5.4.4. Emission Levels

For both scenarios, COALLIM_E and NONEWCOAL_E, directing energy supply from coal to renewables and natural gas results in a decrease in total emissions depending on a decline in emissions from electricity sector technologies according to the base scenario.

COALLIM_E scenario and BASE scenario do not have a significant difference with regard to coal based power generation. Hence, decrease in emissions from electricity sector technologies, correspondingly in total emissions, is not noticed prominently. Indeed, emissions from electricity sector technologies is 170,440 kton CO_2 for BASE and 167,900 kton CO_2 for COALLIM_E in 2027 while it is 709,530 kton CO_2 and 670,290 kton CO_2 respectively in 2052. In BASE scenario, total emission is 447,030 kton CO_2 in 2027 and 1,408,500 kton CO_2 in 2052 when it is 446,460 kton CO_2 in 2027 and 1,371,500 kton CO_2 in 2052 in NONEWCOAL_E scenario. In 2027 total emissions of COALLIM_E are reduced by just 0.1% while they are reduced by 0.3% in 2052 according to total emissions of BASE.

However, a significant change is observed in total emissions and electricity sector emissions when results of BASE and NONEWCOAL_E scenarios are compared. Total emissions decrease to 881,730 kton CO_2 in 2052 while electricity sector emissions show decrease from 709,530 to 151,550 kton CO_2 in 2052 based on the base scenario. As a result, total emissions of NONEWCOAL_E are reduced by 37% for 2052 in comparison with total emissions of BASE.

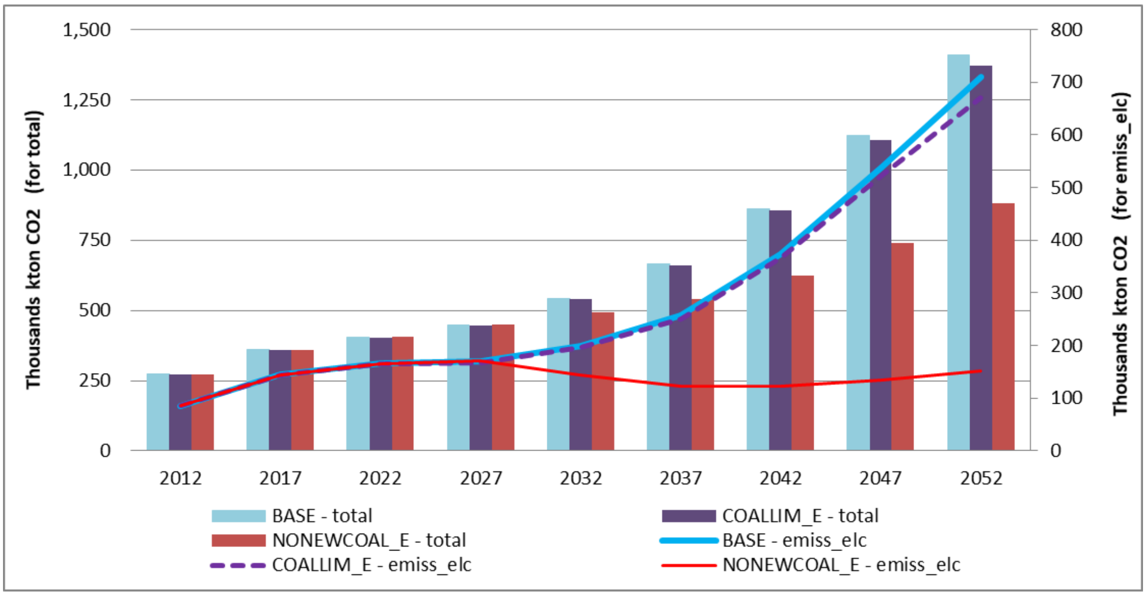


Figure 5.13. Total and electricity generation sector emission levels: BASE, COALLIM_E and NONEWCOAL_E Scenarios.

Since demand data for transport sector technologies remain unchanged in three scenario, transport sector emission values are same for all three scenarios. However, its share in total emissions gradually increase over years in COALLIM_E and NONEWCOAL_E scenarios because of the decline in total emissions according to the base scenario.

For year 2037, in BASE scenario the share of transport sector emission in total emissions is 12% while it is 13% in COALLIM_E and 15% in NONEWCOAL_E. In 2052, it is 5.9% for BASE, 6.1% for COALLIM_E and 9.4% for NONEWCOAL_E.

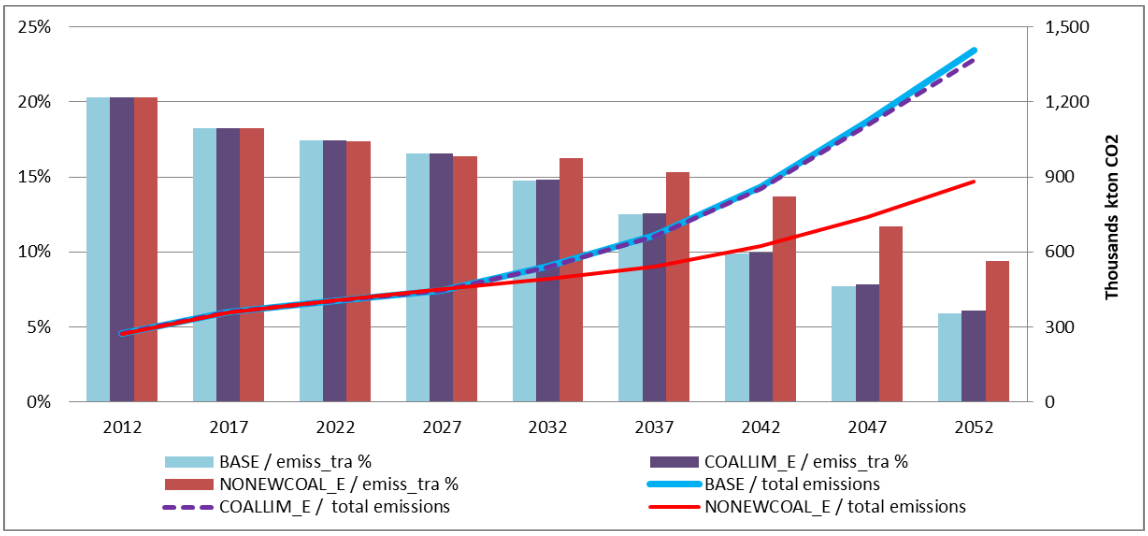


Figure 5.14. Total emission levels and transport sector emission shares: BASE, COALLIM_E and NONEWCOAL_E Scenarios.

5.5. Electric Bus Scenario

This scenario ("ISTBUS") is created on the consideration of what will happen if all the buses in Istanbul are electric vehicles by year 2027. Therefore, according to the inner city buses transport data of Istanbul, electric buses bounds of the model are revised. Then coal base electricity generation is restricted once again to direct growing electricity demand of electric buses to renewable energy.

5.5.1. Electricity Consumption of Transport Sector

Estimated consumption values of electric cars and rail vehicles are same in both scenarios, base and ISTBUS. Therefore, total electricity consumption of transportation changes particularly depending on estimated consumption values of electric buses.

Total electricity consumptions and consumptions of electric buses between 2012 and 2052 for each scenarios are given below table.

Table 5.9. Electricity consumption levels (in PJ) of the transport sector.

	Scenario	2012	2017	2022	2027	2032	2037	2042	2047	2052
Buses	**ISTBUS**	0.000	0.011	0.027	4.643	6.714	13.393	27.962	59.802	129.454
	BASE	0.000	0.011	0.027	0.028	0.041	0.061	0.090	0.134	0.194
Tranpsort total	**ISTBUS**	2.659	4.472	6.522	11.792	17.331	31.941	65.128	141.211	316.578
	BASE	2.659	4.472	5.577	7.177	10.658	18.609	37.256	81.543	187.318

5.5.2. Energy Consumption of Transport Sector

As it can be seen from Figure 5.15, when the number of electric buses increases, the needed amount of petroleum for transport sector decreases. With case of all buses in Istanbul are electric vehicles by year 2027, only consumption of electricity and petroleum fuels change in transport sector.

For year 2047, petroleum consumption of transport sector is 455.206 PJ in the BASE and 441.252 PJ in ISTBUS. As the difference of electric buses fuel demand grows between the scenarios over time, the need for petroleum for transportation changes significantly. For instance, in 2052 petroleum fuel consumption for transportation is 623.885 PJ in BASE and it drops to 576.232 PJ in ISTBUS. Consequently, petroleum consumption of transport sector in ISTBUS is decreased by 3% for 2047 and 7.6% for 2052 in comparison with BASE scenario results.

In the model, other fuel demands (diesel, LPG etc.) are not be affected significantly from electricity demand changes of electric buses.

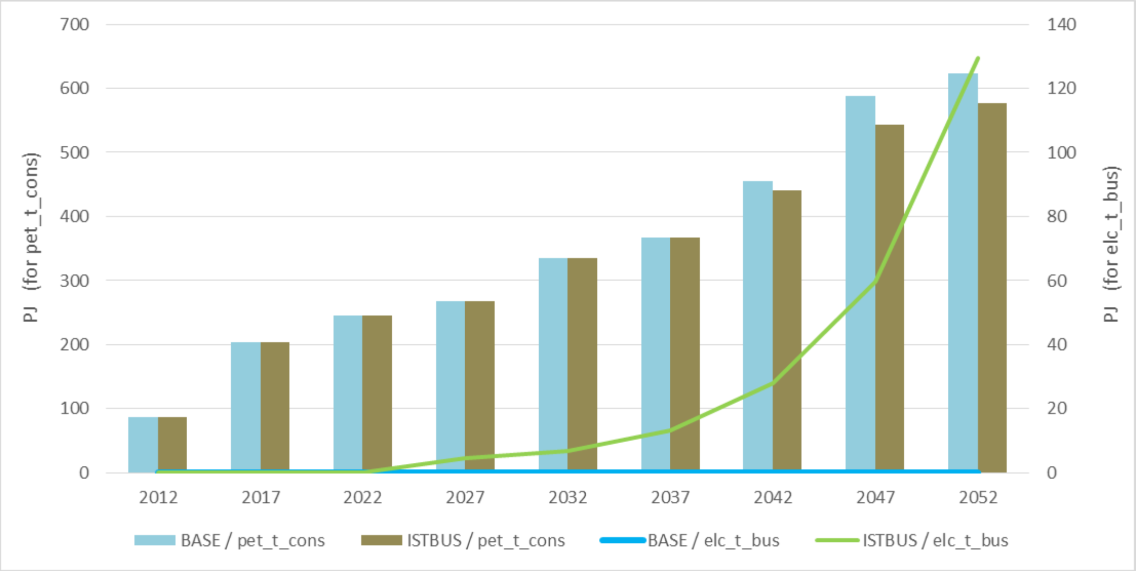


Figure 5.15. Electricity and petroleum consumption levels of transport sector: BASE and ISTBUS Scenarios.

5.5.3. Electricity Generation

In ISTBUS scenario, coal based electricity generation is restricted to 10% increment every period from 2027 to direct increasing electricity demand of transport sector to clean energy. In 2032, coal based electricity generation is 703.517 PJ for BASE and 483.67 PJ for ISTBUS while it is 3720.846 PJ for BASE and 708.14 PJ for ISTBUS in 2052.

With the decline in coal based electricity generation, system meets unsatisfied electricity need by generating electricity from natural gas for ISTBUS scenario. Sudden and significant decrease of coal based electricity generation forces the system to close demand and supply gap by using hydropower, wind and solar energy also.

From year 2037, natural gas based power generation of ISTBUS shows an increase according to BASE scenario. In 2037, power generation from natural gas is 391.43 PJ for BASE and 670.672 PJ for ISTBUS when it is 335.602 PJ for BASE and 1817.403 PJ for ISTBUS in 2052. As a result, natural gas based power generation of ISTBUS is increased by 71% for 2037 and 4.4 times for 2052 according to the BASE scenario results.

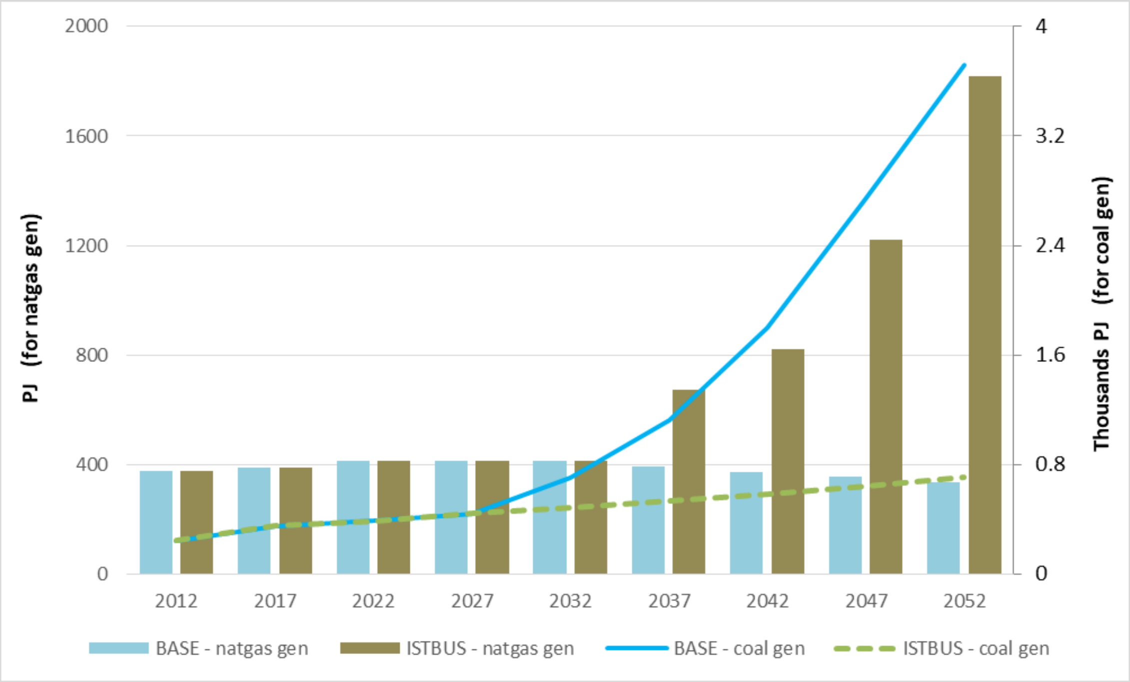


Figure 5.16. Natural gas and coal based energy generations: BASE and ISTBUS Scenarios.

On the side of renewables, share of hydro, wind and solar based power generation in total energy production is 31% for both scenarios in 2027 while it decreases to 9.95% for BASE and 25.22% for ISTBUS in 2052.

Energy generation from hydropower shows an increase from year 2042 in ISTBUS according to BASE scenario. In 2042, hydropower generation is 347.49 PJ for BASE and 355.637 PJ for ISTBUS while it is 347.978 PJ for BASE and 439.058 PJ for ISTBUS in 2052. Therefore, increase in energy generation from hydropower of ISTBUS is 2.3% in 2042 and 26.2% in 2052 based on BASE scenario results.

In BASE scenario power generation from wind and solar is 146.168 PJ for 2022 and 122.462 PJ for 2052 whereas it is 145.396 PJ in 2022 and 480.857 PJ in 2052 for ISTBUS scenario.

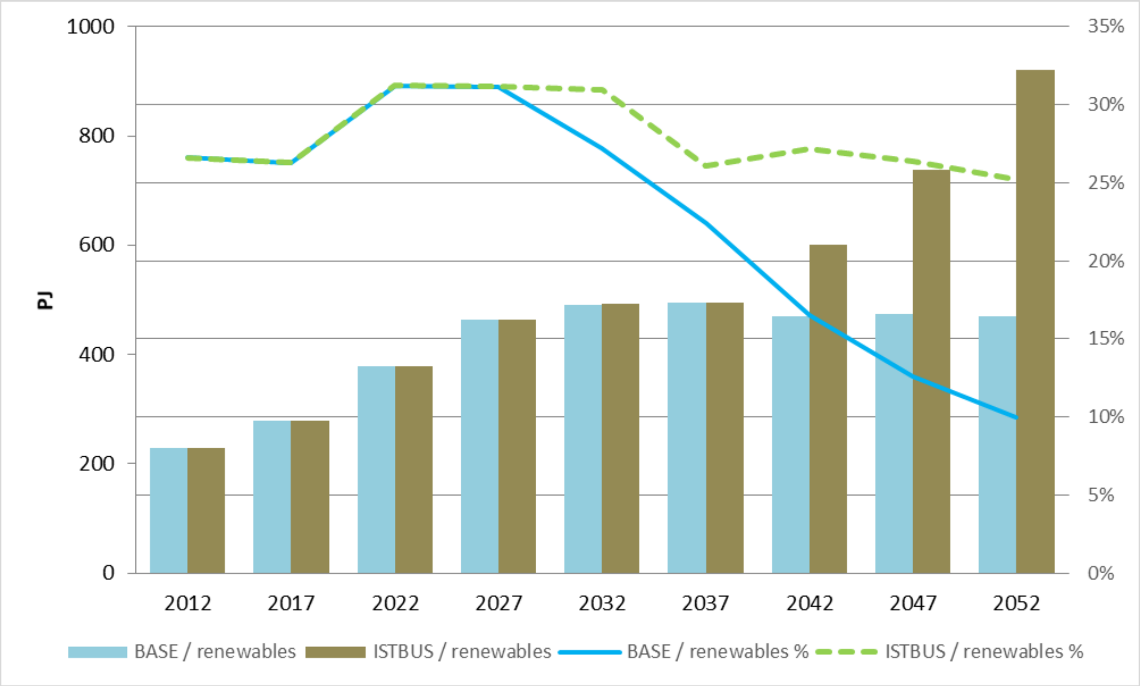


Figure 5.17. Power generation from renewable sources: BASE and ISTBUS Scenarios.

5.5.4. Emission Levels

Directing energy supply from coal to renewables and natural gas results in a decrease in total emissions depending on a decline in emissions from electricity sector technologies and introducing electric buses of Istanbul to the system provides a decline in transport sector emissions in ISTBUS scenario.

A significant change by introducing more electric buses to the system is clearly seen after year 2042. Transport sector emissions are 85,231 kton CO_2 for BASE and 84,254 kton CO_2 for ISTBUS in 2042 while they are 83,103 kton CO_2 and 79,767 kton CO_2 respectively in 2052. These results provides 1.1% decrease in 2042 and 4% decrease in 2052 for ISTBUS according to the BASE.

In BASE scenario, total emission is 541,580 kton CO_2 in 2032 and 1,408,500 kton CO_2 in 2052 when it is 509,170 kton CO_2 in 2032 and 1,013,900 kton CO_2 in 2052 in ISTBUS scenario.

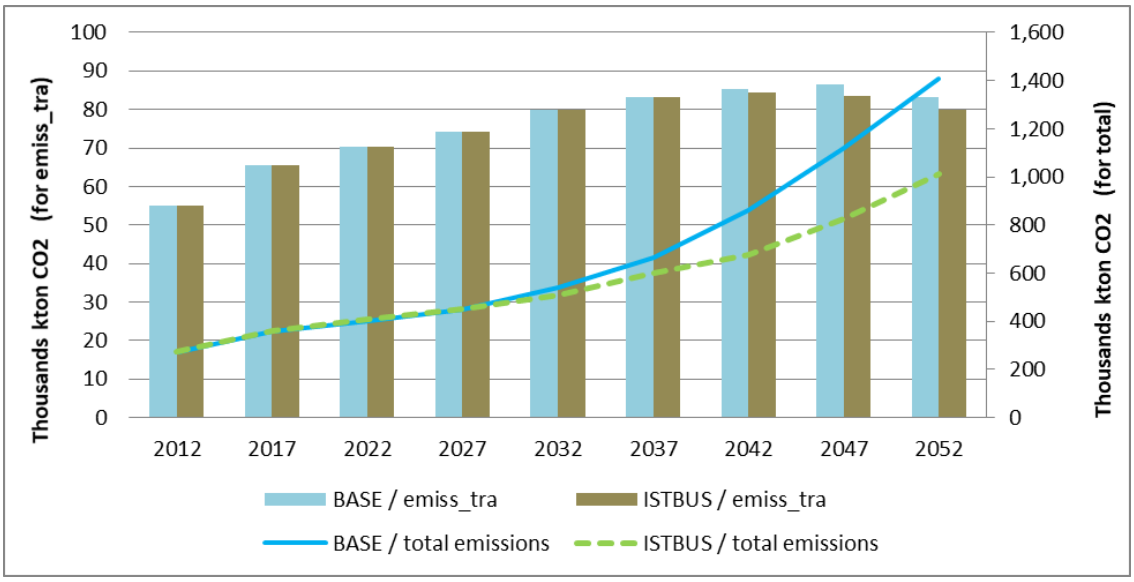


Figure 5.18. Transport sector and total emissions: BASE and ISTBUS Scenarios.

For ISTBUS directing energy supply from coal to renewables and natural gas results in a decrease in total emissions depending on a decline in emissions from electricity sector technologies according to the base scenario.

ISTBUS scenario and BASE scenario have a significant difference in electricity sector emissions with regard to coal based power generation. Decrease in emissions from electricity sector technologies, correspondingly in total emissions, is noticed particularly after 2027.

Emissions from electricity sector technologies is 200,020 kton CO_2 for BASE and 161,560 kton CO_2 for ISTBUS in 2032 while it is 709,530 kton CO_2 and 292,710 kton CO_2 respectively in 2052. As a result, electricity generation emissions of ISTBUS are reduced by 19.2% for 2032 and 58.7% for 2052 in comparison with electricity generation emissions of BASE.

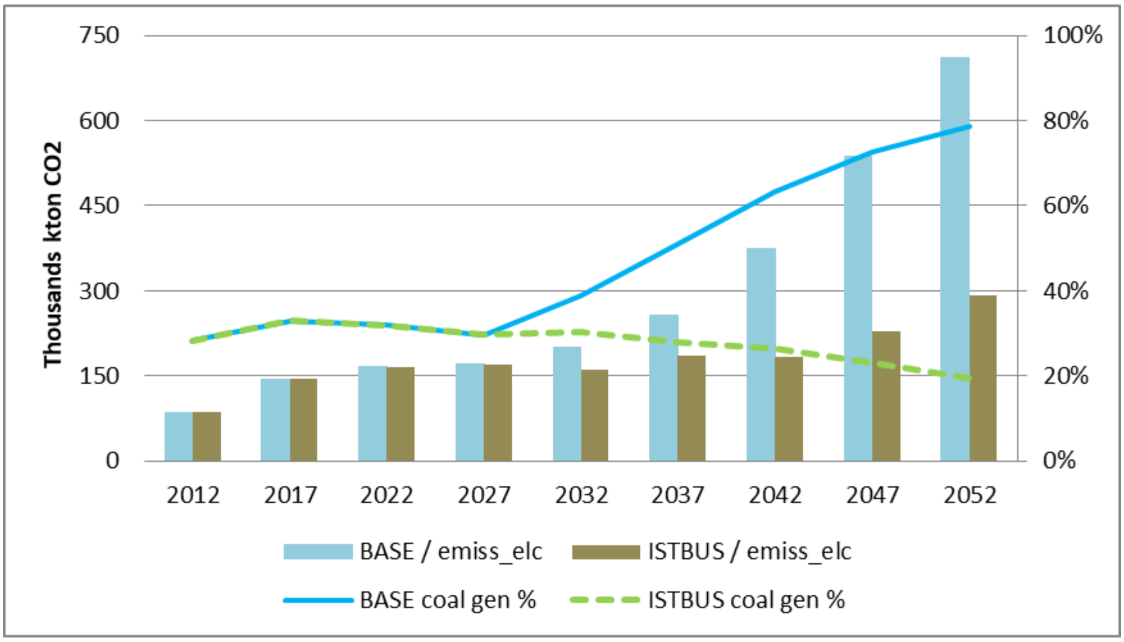


Figure 5.19. Electricity sector emissions and coal based power generation shares: BASE and ISTBUS Scenarios.

5.6. Diesel Ban Scenario

To see effects of banning diesel powered vehicles, usage of diesel cars and buses are banned by year of 2027 in the model. Diesel consumption of cars and buses is identified as zero starting with year 2027 by adding fix levels to the model for them in NODIESEL_T scenario. Then coal based electricity generation is restricted once again to direct growing electricity demand of electric buses to renewable energy.

5.6.1. Electricity Consumption of Transport Sector

With the banning diesel powered cars and buses by year of 2027, estimated consumption values of electric cars and buses significantly differ from each other, BASE and NODIESEL_T. Therefore, total electricity consumption of transportation changes totally depending on estimated consumption values of electric cars and buses.

As from 2047 consumption values of electric cars and buses are same in both scenarios since electric vehicle demand is peaking, therefore diesel fuel is already not required by cars and buses between the years of 2047-2052.

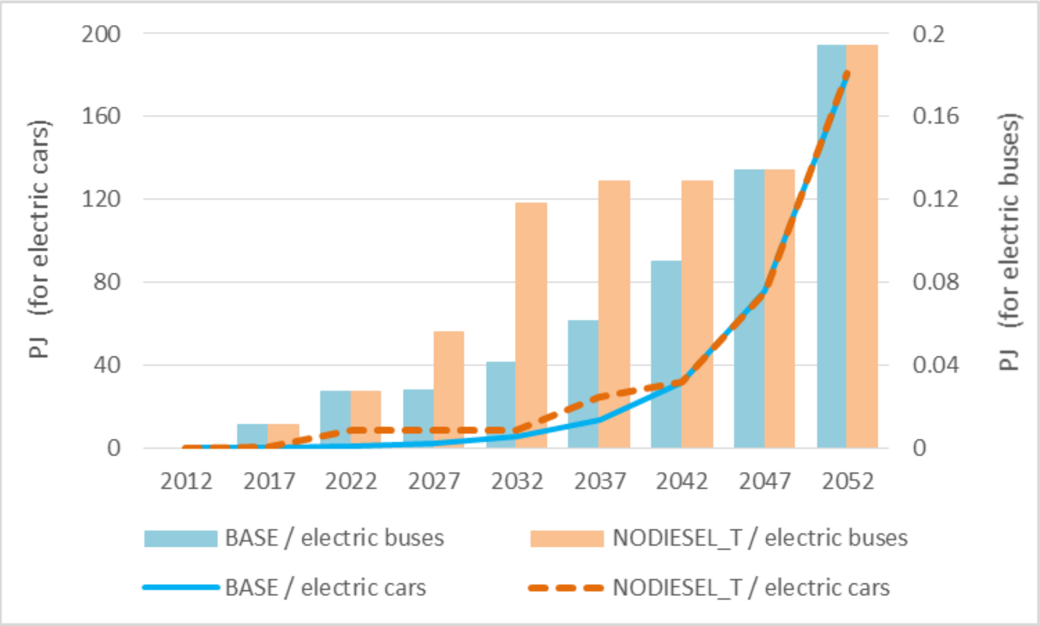


Figure 5.20. Electricity consumption levels (in PJ) for electric cars and buses: BASE and NODIESEL_T Scenarios.

5.6.2. Energy Consumption of Transport Sector

Until 2022, petroleum and diesel consumption levels in transport sector for both scenarios, Base and NODIESEL_T, is at same levels. With the banning diesel cars and buses by year of 2027, fuel consumption levels of transport sector for both scenarios significantly differ from each other.

Petroleum consumption is 245.232 PJ in BASE and 213.639 PJ in NODIESEL_T for year 2022. In 2027, it increases to 268.539 PJ for BASE and 288.290 for NODIESEL_T. The reason for higher consumption of petroleum fuel in NODIESEL_T is the ban for diesel consumption. With the banning diesel cars and buses by year of 2027, fuel demand for buses and cars is met by electricity and petroleum in NODIESEL_T scenario. In 2052, share of petroleum consumption is 46% for BASE and 44% for NODIESEL_T.

On the other hand, diesel consumption of transport sector is 541.014 PJ for BASE and 377.804 PJ for NODIESEL_T in 2022. In 2027 it increases to 573.475 PJ for BASE and decreases to 215.694 PJ for NODIESEL_T. Then, for 2052 diesel consumption is 306.049 PJ in BASE and 113.167 PJ in NODIESEL_T. Therefore, NODIESEL_T provides 30% decrease for 2022 while it provides 1.2 times decrease for 2052 in the diesel consumption of transport sector according to the BASE. In despite of diesel ban in NODIESEL_T, diesel consumption in this scenario is originated from diesel fuel demand of other transport vehicles such as rail vehicles, trucks etc.

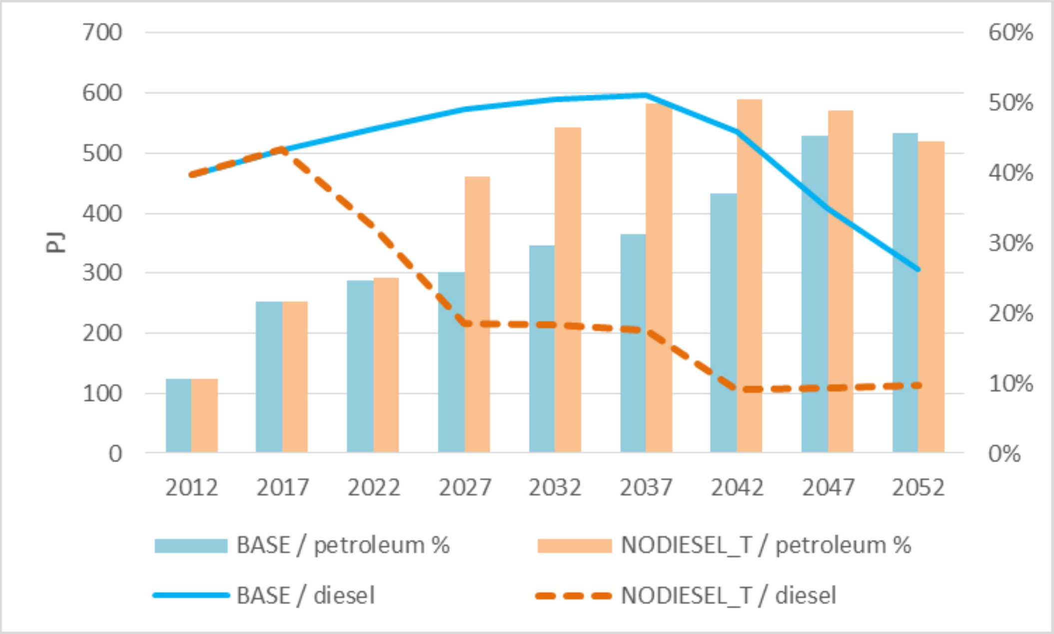


Figure 5.21. Fuel consumption levels of transport sector: BASE and NODIESEL_T Scenarios.

5.6.3. Electricity Generation and Emission Levels

Electricity demand as a fuel for transport sector is increased subsequent to ban for diesel cars and buses by year of 2027 and this ban provides a decline in transport sector emissions in NODIESEL_T scenario. Electric vehicle deployment because of diesel ban in NODIESEL_T scenario provides a significant decrease in transport sector emissions compared to BASE scenario. Share of transport sector emissions in total emissions is 17% for BASE and 12% for NODIESEL_T in 2027 while it is 6% for both of them in 2052.

Electricity sector emissions are 170,440 kton CO_2 for BASE and 170,630 kton CO_2 for NODIESEL_T in 2027 while they are 709,530 kton CO_2 and 195,830 kton CO_2 respectively in 2052. When the results of NODIESEL_T and BASE scenarios are compared, electricity sector emissions are reduced by almost 72% in 2052.

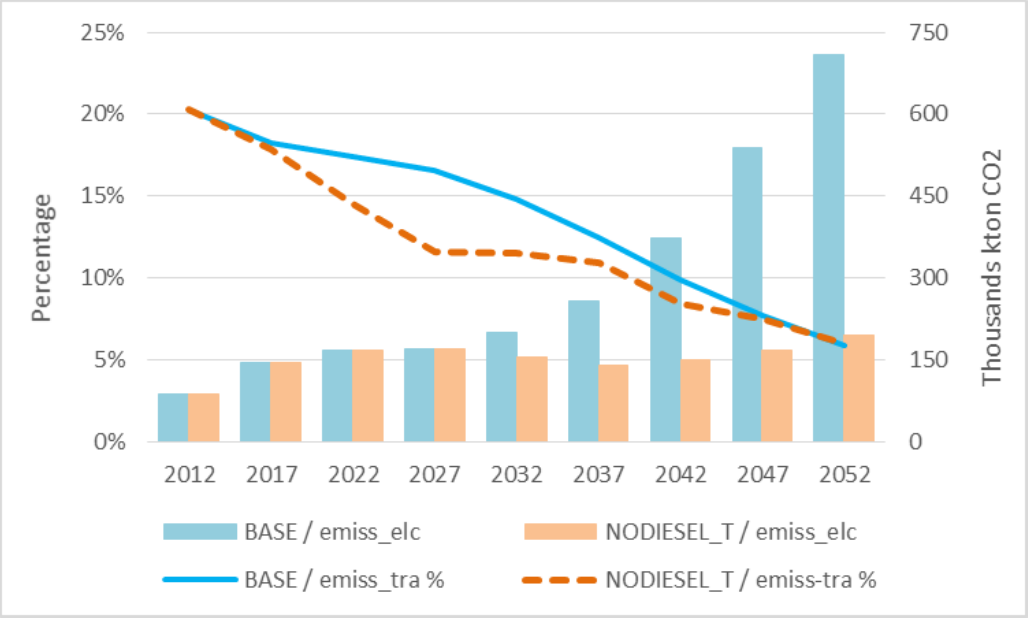


Figure 5.22. Emission levels comparison: BASE and NODIESEL_T Scenarios.

In NODIESEL_T scenario, coal based electricity generation is restricted to 10% increment every period from 2027 to direct increasing electricity demand of transport sector to clean energy. Directing energy supply from coal to renewables results in a decrease in total emissions depending on a decline in emissions from electricity sector technologies. In 2032, coal based electricity generation is 703.517 PJ for BASE and 483.67 PJ for NODIESEL_T while it is 3720.846 PJ for BASE and 708.14 PJ for NODIESEL_T in 2052. Sudden and significant decrease of coal based electricity generation forces the system to close demand and supply gap by using hydropower, wind and solar energy.

Noticeable change in diesel fuel consumption between BASE and NODIESEL_T scenarios and coal restriction for NODIESEL_T scenario provide a decrease in total emissions. In 2027, total emission of BASE scenario is 447,030 kton CO_2 and total emission of NODIESEL_T scenario is 428,380 kton CO_2 whereas they are 1,408,500 kton CO_2 and

925,400 kton CO_2 respectively in 2052. Thus, total emissions of NODIESEL_T scenario are decreased by 4.2% for 2027 and 34.3% for 2052 according to the BASE scenario results.

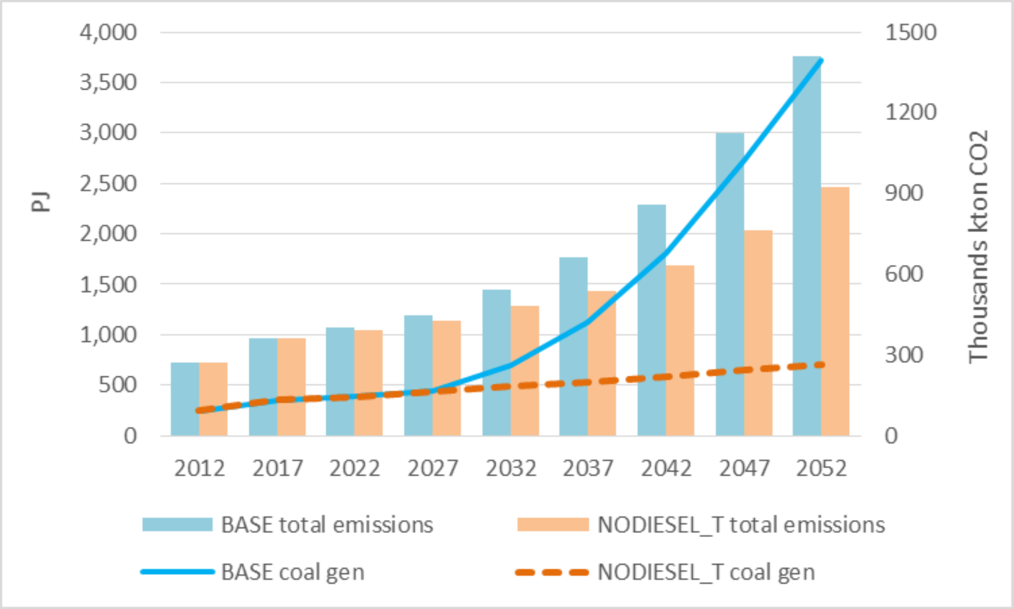


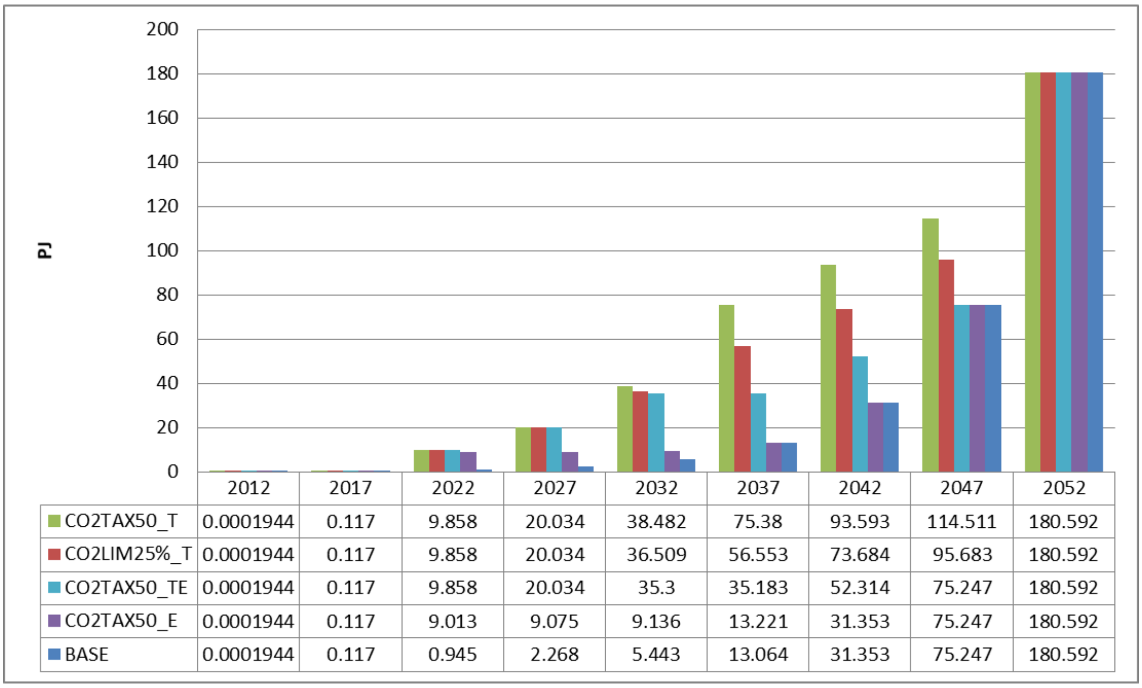
Figure 5.23. Total emission levels and coal based power generation: BASE and NODIESEL_T Scenarios.

5.7. Emission Restriction and Tax Scenarios

A reduction of 25% compared to the base scenario is applied to the transport emissions in CO2LIM25%_T scenario. After that, a carbon tax (0.05$ per kiloton of CO_2) is introduced into the base scenario in three different ways starting from year 2032. Firstly 0.05$ per kiloton of CO_2 emission tax is applied to the transport sector only (“CO2TAX50_T” scenario). Then this tax is placed on the electricity generation sector solely (“CO2TAX50_E” scenario). Lastly, electricity generation and transport sectors are subjected to this carbon tax together in the CO2TAX50_TE scenario.

5.7.1. Electricity Consumption of Transport Sector

By applying emission restriction and tax, just consumption values of electric cars show a change. Estimated consumption values of electric buses and rail vehicles are same in all five scenarios, CO2TAX50_T, CO2LIM25%_T, CO2TAX50_TE, CO2TAX50_E and BASE. Hence, total electricity consumption of transportation changes depending on consumption values of electric cars in all scenarios.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
🟩 CO2TAX50_T	0.0001944	0.117	9.858	20.034	38.482	75.38	93.593	114.511	180.592
🟥 CO2LIM25%_T	0.0001944	0.117	9.858	20.034	36.509	56.553	73.684	95.683	180.592
🟦 CO2TAX50_TE	0.0001944	0.117	9.858	20.034	35.3	35.183	52.314	75.247	180.592
🟪 CO2TAX50_E	0.0001944	0.117	9.013	9.075	9.136	13.221	31.353	75.247	180.592
🟦 BASE	0.0001944	0.117	0.945	2.268	5.443	13.064	31.353	75.247	180.592

Figure 5.24. Electricity consumption levels of electric cars.

5.7.2. Electricity Generation

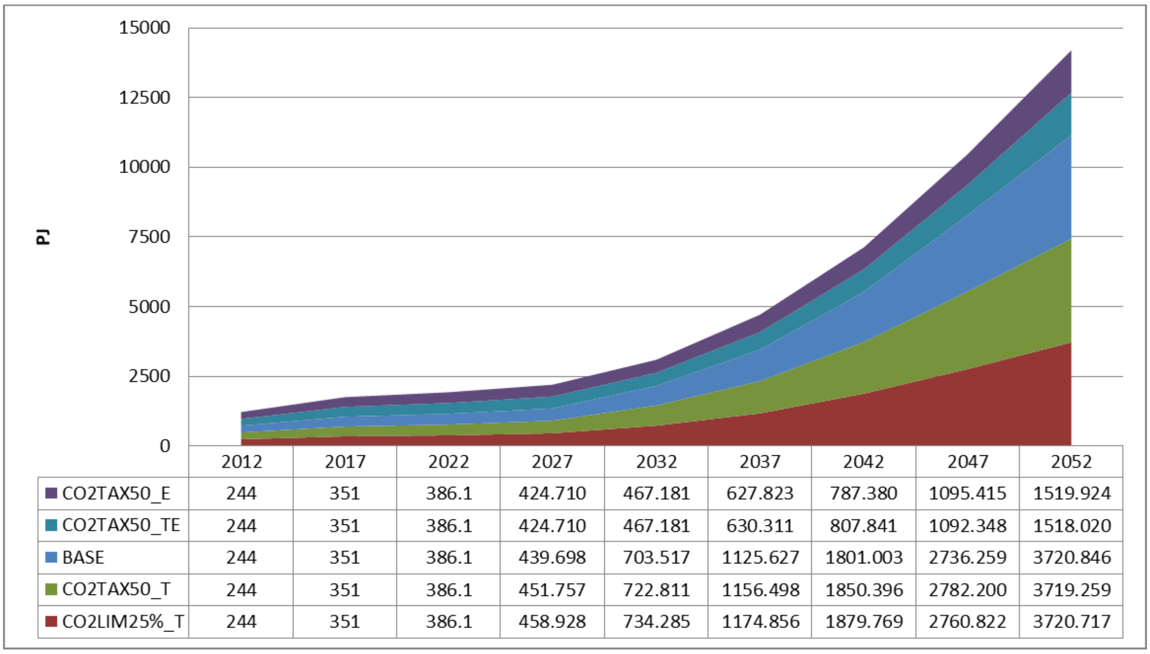
To apply emission restriction on transport sector emissions and tax scenarios on transport and/or electricity generation sectors only have impacts on coal based power generation in all four scenarios.

Placing a carbon tax (0.05$ per kiloton of CO_2) on only electricity generation sector (CO2TAX50_E) and electricity generation sector-transport sector together (CO2TAX50_TE) provides a decrease in coal based power generation for almost each period compared to BASE scenario since the model wants to reduce total emission because of its objective function (minimization of total system cost).

On the other hand, applying a carbon tax (0.05$ per kiloton of CO_2) on only transport sector (CO2TAX50_T) and emission restriction at the rate of 25% on transport sector (CO2LIM25%_T) causes an increase on coal based power generation compared to BASE scenario. Because transport sector moves in the direction of electric vehicle deployment to reduce its emissions. Then, growing electricity demand due to the increase in the number of electric cars is met from coal-based electricity generation because of the model's "to minimize total system cost" objective and Turkey's current coal policy which is introduced to the BUEMS.

Therefore, while growing number of electric cars provides considerable emission reductions in transport sector emissions in CO2TAX50_T and CO2LIM25%_T scenarios, it causes a rise in coal-based electricity generation.

Coal-based electricity generation levels in each period for all four scenarios and BASE scenario are presented in Figure 5.25.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
■ CO2TAX50_E	244	351	386.1	424.710	467.181	627.823	787.380	1095.415	1519.924
■ CO2TAX50_TE	244	351	386.1	424.710	467.181	630.311	807.841	1092.348	1518.020
■ BASE	244	351	386.1	439.698	703.517	1125.627	1801.003	2736.259	3720.846
■ CO2TAX50_T	244	351	386.1	451.757	722.811	1156.498	1850.396	2782.200	3719.259
■ CO2LIM25%_T	244	351	386.1	458.928	734.285	1174.856	1879.769	2760.822	3720.717

Figure 5.25. Coal based power generations of emission restriction and tax scenarios.

5.7.3. Emission Levels

As mentioned in previous section, in CO2TAX50_E and CO2TAX50_TE scenarios, coal based power generation decreases compared to BASE scenario since the model wants to reduce total emission because of its objective function (minimization of total system cost). Therefore, emissions from electricity generation sector in these two scenarios are less than in BASE scenario.

On the other hand, in CO2TAX50_T and CO2LIM25%_T scenarios, coal based power generation increases compared to BASE scenario. Because transport sector moves in the direction of electric vehicle deployment to reduce its emissions. Then, growing electricity demand due to the increase in the number of electric cars is met from coal-based electricity generation. Therefore, emissions from electricity generation sector in these two scenarios are more than in BASE scenario.

Briefly, order of emissions from electricity generation sector from less to more is as follows: CO2TAX50_E, CO2TAX50_TE, BASE, CO2TAX50_T and CO2LIM25%_T.

On the side of transport emissions, order from less to more is as follows: CO2TAX50_T, CO2TAX50_TE, CO2LIM25%_T, CO2TAX50_E and BASE. This order indicates the following result. Placing a carbon tax directly on transport sector emissions is the most effective way of reducing transport sector emissions rather than applying emission restriction on transport sector. Then, for sure applying emission restriction on transport sector is more solution-oriented for reducing transport emissions than placing a carbon tax on electricity generation sector emissions. As can be seen in the figure below, applying a carbon tax only on electricity generation sector is not an enough efficient way to reduce transport emissions. However, it has an incontrovertible indirect effect on transport emissions compared to BASE scenario.

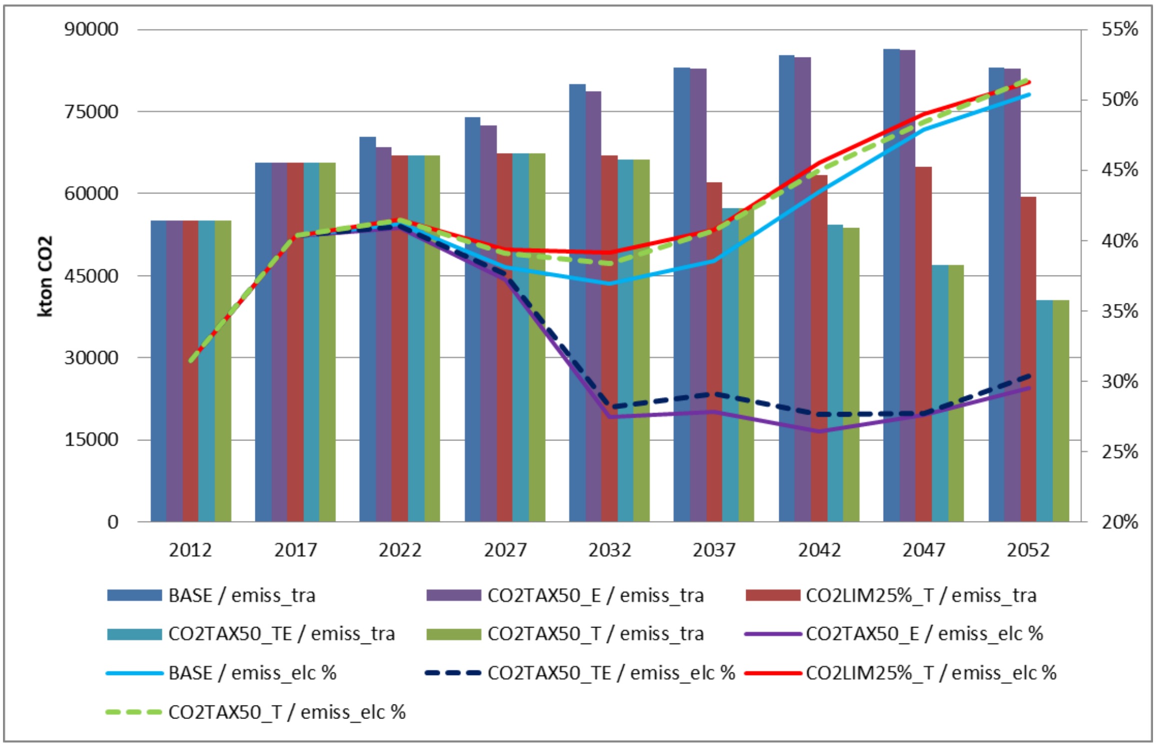


Figure 5.26. Emission levels of electricity generation and transport sectors.

5.8. Abatement Cost Comparison of Scenarios

The results of scenarios are presented in Table 5.10 as their total system cost and total emissions by summing up values from 2012 to 2052 for each scenario. Total system cost represents annual discounted total system cost in million US dollars while total emissions are presented in kton CO_2 in BUEMS. In Table 5.10, units are million US $ and million ton CO_2 respectively. Total system costs of scenarios are discounted to year 2019.

It can be seen that all alternative scenarios have lower total emissions than the BASE scenario except for MOREECAR. However, almost all of them have higher total system cost compared to BASE scenario. Only NODIESEL_T scenario has lower total system cost and lower total emissions at the same time than BASE scenario.

MOREECAR scenario has higher total system cost and higher total emissions at the same time than BASE scenario. The reason of this case is that: the system meets growing electricity demand due to the increase in the number of electric cars from coal-based electricity generation because of the model's "to minimize total system cost" objective and Turkey's current coal policy which is introduced to the BUEMS. Therefore, while growing number of electric cars provides considerable emission reductions in transport sector emissions, it causes a significant growth in total system emissions in the system because of burning fossil fuels originating from the coal-based electricity generation.

Table 5.10. Total system cost (million US $ - 2019) and total emissions (million ton CO_2) of the scenarios.

Scenarios	Total system cost	Total emissions
BASE	370,977	6,078
MOREECAR	371,254	6,126
NOECAR	371,824	6,065
COALLIM_E	371,050	6,016
NONEWCOAL_E	374,909	4,765
ISTBUS	376,346	5,116
CO2LIM25%_T	371,200	6,004
CO2TAX50_T	373,112	6,001
CO2TAX50_E	376,679	5,035
CO2TAX50_TE	381,440	4,943
NODIESEL_T	369,321	4,792

Total emissions and total system cost of each scenario between the years of 2012 and 2052 are also figured in Figure 5.27. As a result of this figure, it is observed that reducing system emissions causes an increase in total system cost. There exists one exception in all over the alternative scenarios: NODIESEL_T scenario. This scenario achieves savings in total system cost while reducing its total emissions.

On the other hand, when MOREECAR scenario is insulated, the least effective scenario is NOECAR. It increases total system cost from 370,977 million US $ to 371,254 million US $ while it provides just a little decline in total emissions, from 6,078 million ton CO_2 to 6,065 million ton CO_2.

Figure 5.27. Total emissions and total system cost of each scenario throughout the planning horizon.

To evaluate and compare total costs and emissions improvements of alternative scenarios an abatement cost is calculated for each scenario as an evaluation criteria. This cost is a ratio which is obtained by dividing total cost change to saving from CO_2 emissions for each scenario. Abatement costs of each scenario are presented in below table. These costs indicate “US $ / ton CO_2” rates of scenarios. The rates may be positive or negative depending on their total costs in case of being higher or lower than the base scenario.

Table 5.11. Abatement costs (cost increase / emission saving ratio) of each scenario according to the BASE.

Parameter	**CO_2 savings**	**Cost increase**	**Marginal abatement cost**
Unit	**million ton CO2**	**million US $**	**US $/ton CO2**
BASE	Ref. Point	Ref. Point	Ref. Point
NODIESEL_T	1,286	- 1,656	-1.29
COALLIM_E	62	73	1.18
NONEWCOAL_E	1,314	3,932	2.99
CO2LIM25%_T	74	223	3.01
CO2TAX50_E	1,043	5,702	5.47
ISTBUS	963	5,369	5.58
CO2TAX50_TE	1,136	10,463	9.21
CO2TAX50_T	78	2,135	27.37
NOECAR	13	847	65.15
MOREECAR	- 47	277	N/A

According to Table 5.11, NODIESEL_T, NONEWCOAL_E, CO2TAX50_E, ISTBUS and CO2TAX50_TE scenarios provide around 1,000 million ton CO_2 emission reduction over the planning horizon while other scenarios provide a reduction of less than 80 million tons.

To evaluate and compare cost and emission improvements of alternative scenarios for each period, abatement costs are calculated for each period from 2022 to 2052. This cost is obtained by dividing cost increase to saving from CO2 emissions. Abatement costs for each period are presented in below table. MOREECAR scenario does not have abatement costs since it has higher CO_2 emission levels than the BASE for each period. In addition, abatement cost could not be calculated for NOECAR scenario until the last two periods since NOECAR scenario has also higher CO_2 emission levels than the BASE for the period of 2022-2042. However, NOECAR provides 13 million ton CO_2 savings and causes 277 million US$ cost increase in total for the whole planning horizon due to emission savings and cost increase between the years of 2047 and 2052.

Table 5.12. Abatement costs of scenarios for each period according to the BASE.

Scenarios	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
COALLIM_E	-	-45.64	3.66	3.49	1.50	0.37	0.72
NONEWCOAL_E	-	-	15.75	7.13	4.05	2.73	1.88
ISTBUS	-	-	9.70	15.99	6.87	4.68	3.47
CO2LIM25%_T	9.56	158.46	65.23	23.26	16.13	-0.42	-2.90
CO2TAX50_T	9.75	78.14	132.55	44.49	58.65	49.24	1.18
CO2TAX50_E	-	-44.07	30.66	16.68	6.51	3.68	2.41
CO2TAX50_TE	-	45.33	47.02	23.46	10.19	5.33	3.14
NODIESEL_T	-56.92	-33.08	-4.53	1.37	1.98	2.17	1.74
NOECAR	-	-	-	-	-	33.33	-5.31
MOREECAR	-	-	-	-	-	-	-

In Table 5.12, negative values indicate cost decreases in some periods. NODIESEL scenario has cost decreases for some periods and for the total according to the BASE since bounds for diesel consumption of transport sector and coal based electricity generation are removed and/or revised.

Abatement costs for each period from 2022 to 2052 are also presented in Figure 5.28. This cost is obtained by dividing cost increase to saving from CO_2 emissions. While CO2LIM25%_T and CO2TAX50_T scenarios have higher abatement costs, NODIESEL_T and COALLIM_E scenarios have lower abatement costs among the all alternatives scenarios.

According to Figure 5.28, NONEWCOAL_E scenario which provides significant emission reduction (1,314 million ton CO_2) over the planning horizon in comparison with BASE scenario, starts with an abatement cost of 15.75 $ per ton CO_2 in 2032 and ends up with an abatement cost of 1.88 $ per ton CO_2 in 2052. Another scenario, NODIESEL_T, provides a reduction (1,314 million ton CO_2 and 850 million US $) both in emissions and total cost for whole planning horizon. However, an abatement cost, 1.37 $ per ton CO_2, arises for this scenario in 2037 and this cost increases to 1.74 $ per ton CO_2 in 2052.

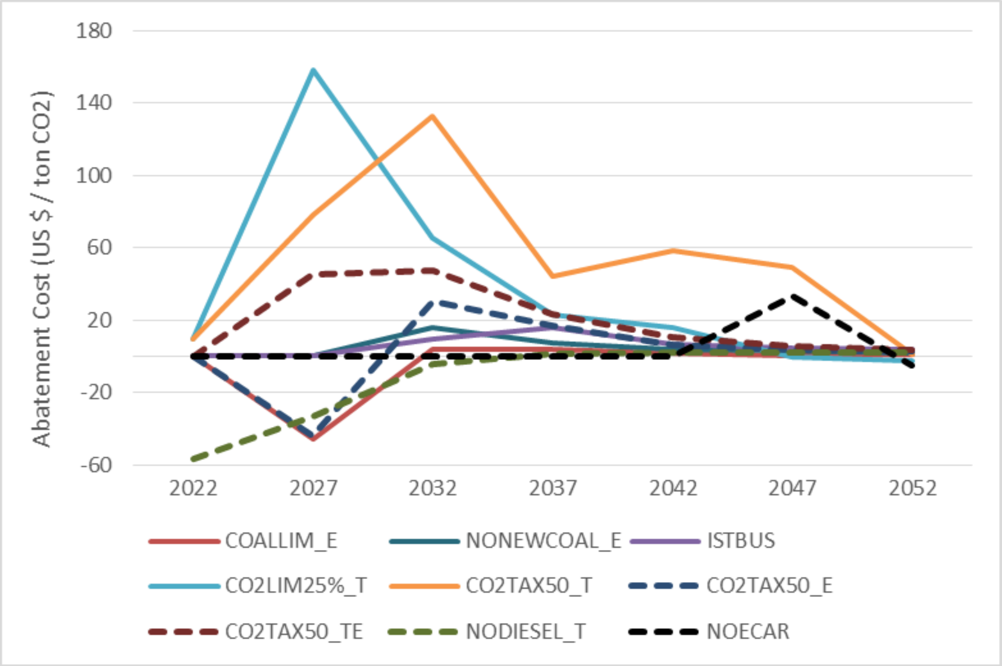


Figure 5.28. Abatement costs of scenarios for each period.

ISTBUS scenario which has a 963 million ton CO_2 reduction in total emissions in comparison with the BASE, starts with an abatement cost of 9.70 $ per ton CO_2 in 2032, then its abatement cost decreases to 3.47 $ per ton CO_2 in 2052. On the other hand, CO2TAX50_E scenario has 30.66 $ per ton CO_2 abatement cost in 2032 while this cost shows a significant decline in each period and decreases to 2.41 $ per ton CO_2 in 2052. Over the planning horizon, CO2TAX50_E scenario provides a 1,043 million ton emission reduction according to BASE scenario.

6. SENSITIVITY ANALYSIS

Transport sector demand data and cost of EVs are among the most important parameters affecting scenario results in this study. Therefore, the base scenario is run under different cost of EVs and transport demand values to see how sensitive model is for these values. Then total emissions and total system costs are compared for each different values of these two parameters.

Data for transport sector demand and cost of EVs in base scenario are decreased by 20% and 10% and also increased by 20% and 10%. Then, each obtained values is added to model separately and their impacts on total emissions and total system cost are evaluated according to the results of BUEMS with its current data.

According to Figure 6.1, transport sector demand changes have more significant impacts on total emissions than cost of EVs data changes.

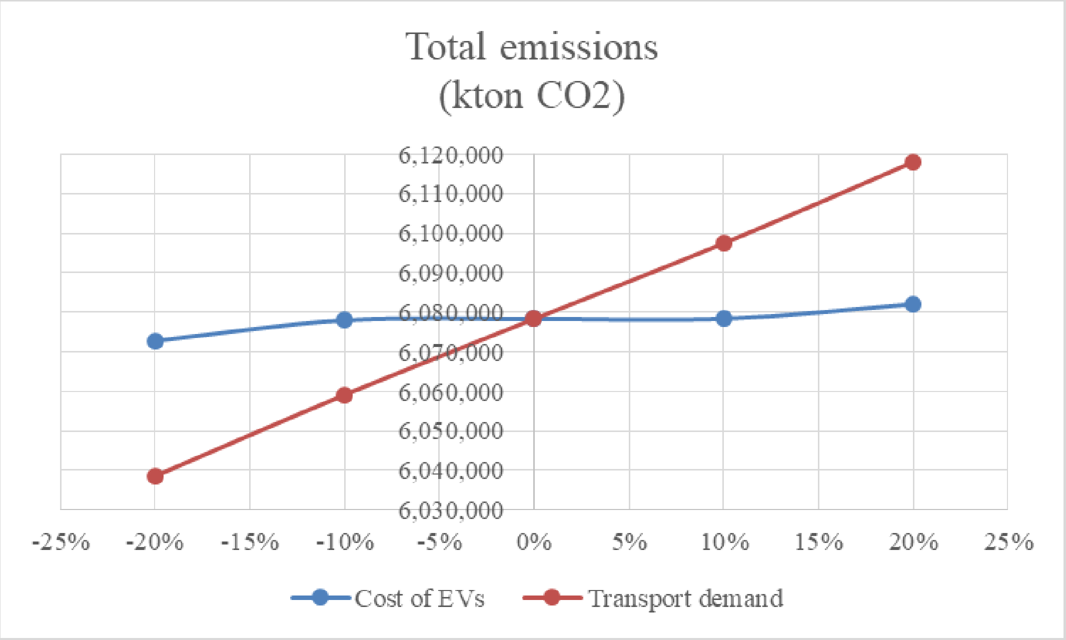


Figure 6.1. Total emissions change with different data for transport sector demand and cost of EVs in the base scenario.

As can be seen from Figure 6.2, transport sector demand changes have more significant impacts on total system cost than cost of EVs data changes, too.

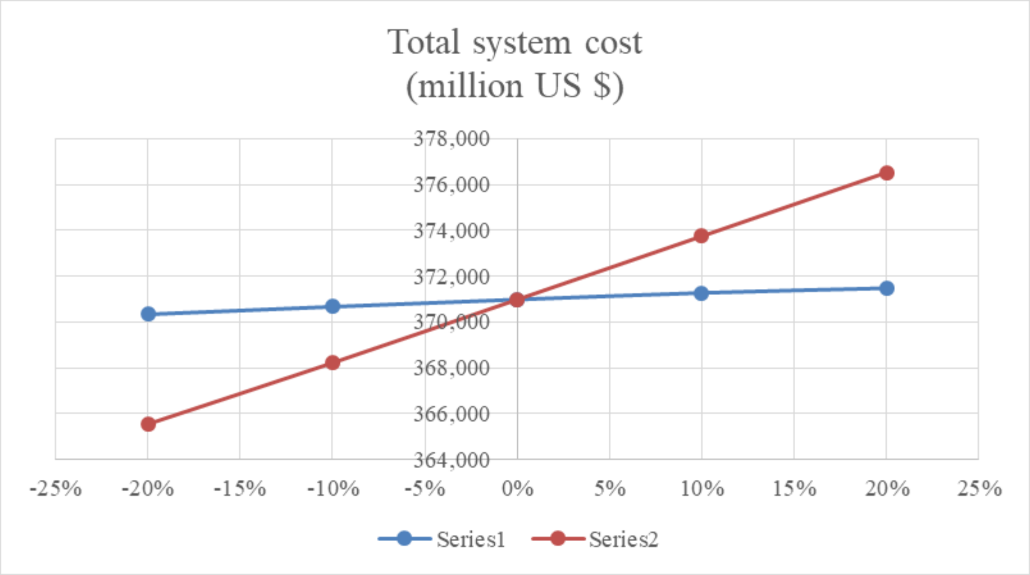


Figure 6.2. Total system cost change with different data for transport sector demand and cost of EVs in the base scenario.

In both figures, rise in transport sector demand and cost of EVs results in an increase on total emissions and total system costs. At the same time, fall in transport sector demand and cost of EVs results in a decrease on total emissions and total system costs. However, transport sector demand changes have a greater effect on total emissions and total system costs than cost of EVs changes.

7. CONCLUSIONS

Evaluation of electric vehicles deployment and CO2 emissions from electric vehicles is a challenging and multilateral task. Various electric vehicle diffusion and energy policy scenarios may lead to different results. Therefore, several scenarios from different perspectives have been carried out to reveal the underlying consequences in this study.

To evaluate these diffusion and policy scenarios and their long-term effects , a bottom-up model, BUEMS has been used and calibrated according to the latest Turkish energy and transport data for this study. BUEMS presents the energy sector in a technologically detailed way and estimates CO2 emissions, energy technologies and primary energy supply levels for each 5-year time period between 2012 and 2052. All the complex relationships of producing, transforming, transmitting and/or supplying energy sources according to the useful demand characteristics are represented with great technological detail. The objective is the minimization of the total energy system cost. The levels and prices of the various energy sources are in equilibrium in each period, which guarantees that the net total cost of supplying all levels of energy services are minimized, while satisfying a number of constraints, such as, system constraints (which are standard for any model application) regarding energy sources, demands, capacities, activities, electricity generations, emissions and other optional constraints such as user imposed policy constraints, including emissions restrictions, bounds on activities, capacities, and energy source supply levels.

The main scenario, BASE scenario, represents the current energy system of Turkey with its business-as-usual assumptions, together with a modest prediction for electric vehicles. Electric cars are expected to rise to 70 thousand in 2022 and to grow 2.4 times for each period in BASE. Then, in MOREECAR scenario, the electric cars prediction is made as 140 thousand cars in 2022 and 2.4 times growth for each period while the case of no electric cars between 2022-2052 years in Turkey is handled in NOECAR scenario. Results of these three scenarios show that with the increase in the number of electric cars transport sector CO2 emissions decrease compared to BASE scenario. On the other hand, the system meets growing electricity demand due to increasing number of electric cars from coal-based electricity generation because of the model's “to minimize total system cost” objective and

Turkey’s current coal policy introduced in BUEMS. Therefore, while a growing number of electric cars provides considerable emission reductions in the transport sector emissions, it causes a significant growth in total system emissions because of the coal-based electricity generation.

In order to direct power generation for electric cars to other sources of energy, in COALLIM_E scenario, coal-based electricity generation is restricted. When it is restricted, it is seen that the growing electricity demand with the increase of electric cars is met from renewable energy, fully from solar and wind based electricity generation. As a consequence, total system emissions of COALLIM_E become lower than BASE. With the intent of evaluating the relationship of power generation, transport sector and CO2 emissions, an extreme case is handled in NONEWCOAL_E scenario. In this scenario, electric vehicles prediction remains same with the BASE, but coal based electricity generation is restricted in the way that generation would not show an increase by 2027. Comparison of BASE, COALLIM_E and NONEWCOAL_E indicates that total system emissions of COALLIM_E and NONEWCOAL_E scenarios are lower than BASE as a consequence of directing renewables to meet the energy demand of electric cars. Moreover, the most prominent result is the variance of electric vehicle deployment impact in the system with the same electric vehicles demand but different energy portfolios.

ISTBUS scenario is built on the consideration of what will happen if all the buses in Istanbul are electric vehicles by year 2027. Therefore, inner city buses transport data of Istanbul are revised as if all buses are electric vehicles. Then coal based electricity generation is restricted to direct growing electricity demand of electric buses to renewable energy. Moreover, to see effects of banning diesel powered vehicles, NODIESEL_T scenario is created. In this scenario, the usage of diesel cars and buses are banned and diesel consumption of cars and buses is identified as zero starting with year 2027. Then coal base electricity generation is restricted once again to direct growing electricity demand of transport sector to renewable energy. Comparison of BASE, ISTBUS and NODIESEL_T indicates that total system and transport sector emissions of ISTBUS and NODIESEL_T scenarios are lower than BASE. Moreover, NODIESEL_T scenario has lower total system cost and lower total emissions at the same time than BASE.

In CO2LIM25%_T scenario, transport emissions are restricted so as to be 25% below BASE scenario emissions. As another scenario to reduce emissions, a carbon tax (0.05$ per kiloton of CO_2) is introduced into the BASE scenario in three different ways starting from year 2032. Firstly, 0.05$ per kiloton of CO_2 emission tax is applied to the transport sector only in CO2TAX50_T scenario, then this tax is placed on the electricity generation sector solely in CO2TAX50_E scenario, lastly electricity generation and transport sectors are subjected to this carbon tax together in CO2TAX50_TE scenario. In CO2TAX50_E and CO2TAX50_TE scenarios, coal based power generation decreases compared to BASE since the model wants to reduce total emission because of its objective function; therefore, emissions from electricity generation in these two scenarios are less than BASE. On the other hand, in CO2TAX50_T and CO2LIM25%_T scenarios, transport sector moves in the direction of electric vehicle deployment to reduce its emissions. Then, growing electricity demand due to the increase in the number of electric cars is met from coal-based electricity generation. Therefore, emissions from electricity generation sector in these two scenarios are higher than in the BASE scenario.

In the abatement cost comparison part, NODIESEL_T and NONEWCOAL_E scenarios become prominent. While they provide significant CO_2 emission reduction (1,286 and 1,314 million ton CO_2 respectively) over the planning horizon, their marginal abatement costs are lower than other scenarios at the same time. On the other hand, ISTBUS and CO2TAX50_E scenarios also have lower marginal abatement costs among the other scenarios except for NODIESEL_T and NONEWCOAL_E and provide 963 and 1,043 million ton CO_2 reduction in total respectively in comparison with BASE scenario.

All these scenario results explained above demonstrate interdependent relationship of power generation, transportation and CO2 emissions. Electric vehicles would not help to significantly reduce CO2 emissions solely, particularly in some countries which have heterogeneous power plant portfolio consisting of many thermal plants. Actually, it is needed to develop policies and measures to reduce CO2 emissions from electricity generation in conjunction with electric vehicles deployment incentives.

This study examines necessary steps needed to be achieved together with the deployment of electric vehicles. Electrical vehicles can succeed considerable emission reductions in a green power system. It is necessary to think about the transition to EVs with renewable energy. Otherwise, the additional emissions generated by the need for additional electricity is more than the emissions which are reduced by the savings in the use of petroleum products. The results of the BUEMS scenarios verify this.

If the charging systems using renewable energy become widespread, for instance grid-assisted photovoltaic charging stations that directly receive solar power or deployment of electric vehicles with support of sustainable development goals. The main focus should be installing and enhancing infrastructures that enable the use of renewable energy sources and preparing the grid for electric vehicles deployment and transition. As one of the best practices worldwide, in Norway, which is among the pioneers of the electric car revolution, 94% of electricity is produced from renewable sources with about 17 g/kWh of greenhouse gas emissions (GHG). In Turkey electricity generation from renewable sources is only 29% and approximately 520 g/kWh GHG is being produced. Thus, Turkey's electricity grid causes 30 times more greenhouse gas emissions than Norway’s by means of charging electric vehicles. In order to make the transition towards electric vehicles sustainable, electricity generation needs to be less carbon-intensive.

The main focus globally is to increase the use of renewable energy and to prepare the grid for a widespread adoption of electric vehicles. Practices such as free charging of electric vehicles in public areas offered by the municipalities will primarily increase the demand for the electric vehicles and bring along the charging station investments. Another issue is practicing incentives for the installment of new electric vehicle charging stations with fast-charging options and universal standards so that electric vehicle owners are freed from range anxiety. Therefore, developing incentive mechanisms in these areas is key to deploy electric vehicles.

As a future work for this study, model resolution can be increased so as to introduce a daily load duration curve and allow for optimization of instantaneous charging needs with network supply/demand balance. Also, the model can be developed into a price-elastic version to reflect the impact of price changes on the demand of electricity, other energy sources and technology choices. Furthermore, the intermittency of renewable power generation can be explored in more detail using a stochastic model extension.

In addition, BUEMS can be calibrated and run under various scenarios with revised policy constraints, end-use sector demands, energy supply prices, investment and O&M costs, bounds for other variables and technologies and policy const. Thus, new several comparisons and analyses can be conducted based on these revisions.

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APPENDIX A: ACCOUNTING CONSTRAINTS

Accounting constraints just exist for reporting purposes and comparing results of different scenarios in BUEMS.

For supply and energy conversion technologies total supply limit of an energy carrier is expressed by two equations below.

In supply technologies:

$$e\_supply(t) = {}_{m \in s\cap(\text{set of technologies producing } e)}\Sigma\ r\_tsep(m,t) \quad \text{(A.1)}$$

In energy conversion technologies:

$$e\_supply(t) = {}_{m \in c\cap(\text{set of technologies producing } e)}\Sigma\ outent(m,t) * r\_act(m,t) \quad \text{(A.2)}$$

where

- e_supply(t): total supply level of energy source e at period t.

Total installed capacities of electricity production plants from several energy sources are indicated as follows.

$$es\_e\_cap(t) = {}_{m \in c\cap(\text{set of technologies producing } e)}\Sigma\ r\_cap(m,t) \quad \text{(A.3)}$$

where

- es_e_cap(t): total installed capacity of a electricity generation plant from a specified energy source es at period t

Following energy consumption equation of electricity generation sector shows consumption level of an energy source to generate electricity.

$$es\_e\_cons(t) = {}_{m \in c\cap(\text{set of technologies producing } e)}\Sigma inpent(m,t) * r\_act(m,t) \quad \text{(A.4)}$$

where

- es_e_cons(t): consumption level of an energy source used for electricity generation at period t

Electricity generation levels of energy conversion technologies from an energy sources are indicated below equation.

$$es\_e\_gen(t) = {}_{m \in c \cap (\text{set of technologies producing } e)} \Sigma inpent(m,t) * r\_act(m,t) \qquad \text{(A.5)}$$

where

- es_e_gen(t): electricity generation levels of energy conversion technologies using an energy source at period t

Following equation is for total electricity production of all energy conversion technologies provided from all energy sources.

$$elc\_prod(t) = {}_{m \in ce} \Sigma\, r\_act(m,t) \qquad \text{(A.6)}$$

where

- elc_prod(t): total electricity production of the system at period t

Energy consumption levels of energy utilization sector by energy source types are expressed in the equation below.

$$es\_x\_cons(t) = {}_{m \in c \cap (\text{set of technologies producing } e)} \Sigma inpent(m,t) * r\_act(m,t) \qquad \text{(A.7)}$$

where

- es_x_cons(t): consumption level of energy source es in sector x at period t