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LUT School of Energy Systems
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100% RENEWABLE ENERGY SYSTEM FOR TURKEY AND THE SPECIAL ROLE OF SOLAR PHOTOVOLTAICS AND BATTERY STORAGE

Supervisor: Professor Christian Breyer, LUT
Examiner: Professor Lassi Linnanen, LUT

ABSTRACT

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Examiners: Professor Christian Breyer
Professor Lassi Linnanen

Keywords: Turkey, 100% renewable energy, energy model, energy demand, energy consumption, solar PV, wind, storage, regional electricity demand, water demand, industrial gas demand, non-energetic gas demand, economics.

Economic growth, increasing population, urbanisation and industrialisation are the macro effects on increasing global energy demand. These indicators values are increasing in Turkey as well and will continue at least for next 30 years. Turkey's energy policy is structured on energy supply security but in contrast to this, Turkey's installed capacity has a major share of fossil fuel power plants. Fossil fuel based system has a dependency on other countries supplies and it is not sustainable from the environmental perspective as well, it is proven by air quality indices that are not within safe limits and lower than European Union averages. Thus, renewable energy share should be increased in current installed capacity. Solar potential will be the main resource in the study of Turkey's transition and thereof the battery storage for system backups. The paper analyses 100% renewable energy (RE) systems for Turkey by an hourly resolution model for the year 2050 with 5-year steps transition. There are two scenarios in the model, the first one is power sector scenario that only includes electricity demand and the second is integration scenario that includes also seawater desalination power demand and non-energetic natural gas demand. This research showed that 100% renewable energy model is highly cost feasible, levelized cost of electricity (LCOE) is decreased to 56.7 €/MWh in power sector scenario and 50.9 €/MWh in integration scenario, total opex values in 2050 are less than 2015 values in both of the scenarios. the total capex is higher compared to power sector scenario due to other sectors are included cost calculations (desalination and non-energetic gas demand), when the desalination and non-energetic natural gas demand is included in the model. Turkey's renewable energy potential is used in a nearly full potential for all related resources except

solar. Even though the solar potential is less than 10%, total solar PV installed capacity is reached 287 GW in power sector scenario and 387 GW in the integrated scenario. Therefore, the battery usage increased in parallel and reached 561 GWh in power sector and 771.8 GWh.

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DEDICATION

I dedicate my thesis to my beloved family who always supported and encouraged me in my life.

TABLE OF CONTENT

SYMBOLS AND ABBREVIATIONS

A-CAES	Adiabatic compressed air energy storage
capex	Capital Expenditures
CCGT	Combined cycle gas turbine
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CSP	Concentrating solar thermal power
EIA	U.S. Energy Information Administration
EU	European Union
FLH	Full Load hours
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt hour
H	Hour
IEA	International Energy Agency
km	Kilometre
kWh	Kilowatt Hour
LCOC	Levelised Cost of Curtailment
LCOE	Levelised Cost of Electricity

LCOS	Levelised Cost of Storage
LCOT	Levelised Cost of Transmission
LHV	Lower Heating Value
m3	Cubic metre
MENA	Middle East and North Africa
MW	Megawatt
MWh	Megawatt hour
Mtoe	Million tonnes of oil equivalent
OCGT	Open cycle gas turbine
OECD	Organisation for Economic Co-operation and Development
opex	Operational Expenditures
PHS	Pumped hydro storage
PtG	Power-to-Gas
PtH	Power-to-Heat
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy sources
RoR	Run-of-River
RO	Reverse Osmosis
SNG	Synthetic Natural Gas
ST	Steam turbine
SWRO	Seawater Reverse Osmosis
t	Ton

TES	Thermal energy storage
TPES	Total primary energy supply
TJ	Terajoules
TWh	Terawatthours (1000 TWh = 3600 PJ = 3.6 EJ)
UN	United Nations
USD	United States dollar
UTC	Coordinated Universal Time
WACC	Weighted Average Cost of Capital
WEO	World Energy Outlook
yr	Year
η	Efficiency
€	Euro

Subscripts

el electricity

p peak

th thermal

1-Renewable and Solar Energy Markets, Investments and Turkey Case

1-1 Introduction

Energy consumptions are increasing globally since past six decades continuously (EIA, 2016). Developing countries are the major effect on this increasing rate within their economic and social changes, especially China and India are the perfect examples. When the developing countries are in a transition with their economic and social structures, their biggest requirement is energy in any case. Nearly 1.3 billion does not have access to electricity (IEA, 2016e), 3 billion people cook and supply heat demand by simplest firing techniques by biomass or coal (WHO, 2016). Energy poverty is mainly in sub-Saharan Africa and developing Asia, also mainly 80% of energy poverty belongs to rural areas. This problem might be solved by off-grid renewable energy solutions which are accessible by every community and prevents any strategical resource conflicts (Breyer, 2016).

The backbone of Turkish power system is natural gas and hydropower which has seasonality issues on energy production. On the other hand, the renewable energy potential of Turkey is huge and the market did not reach the saturation point yet comparing to the potential. Return on investment time is decreasing for renewable energy investments by learning curve effects, incentive schemes and decreased investment risk perception against renewable energy.

Current primary energy consumption 1457.24 TWh and merely 9.5% of the primary energy was supplied from renewable energy (BOTAS, 2016). Turkish government energy target is reaching 61 GW of total installed renewable energy capacity while increasing efficiency of existing power plants, transportation, industry and residential areas (EIE, 2014). One of the main targets with the policy is reducing dependency on fossil fuels and having more secured energy supply (MENR, 2016).

Environmental perspective is one of the most important aspects while meeting the demand but the trade-off between environment, social and economy should be evaluated and managed circumspectly. While meeting energy supply security, cost competitiveness and improving economic growth of the country, pollution, local jobs, and sustainability of energy mix, ecology and the future of the country should be taken care as well to sustain global life.

The objective of this thesis is proving that 100% renewable energy supply can be done for Turkey in a cost competitive and sustainable way without nuclear or fossil fuel consumption. This possibility is generally in solar PV and wind energy due to their huge potential in the country, high full load hours and highly cost competitiveness. Possible renewable technology implications are compared from different perspectives in the second part of the thesis. Regards to energy supply security and its continuously increasing demand amount, this thesis tried to be realistic, reliable, optimised and sustainable with its applications.

This thesis uses estimated data for 2015-2050 period and all the estimations are given in references or appendices if it is not mentioned in the other way. 100% renewable energy supply are applied as a transition in the model for the same time scale. Solar PV and wind power are the major drivers with battery support for the target, but the other local available renewable resources are applied in the model as well. Multi-node approach in one country by the LUT energy model is first time simulated on Turkey case, seven different geographical regions have their own renewable resource capacity, electricity consumption rates, water demand, industrial gas demand and different variable inputs. LUT energy model technical details and explanations can be found in Bogdanov and Breyer (2016).

1-1.1 Organization of the thesis

The first part of the thesis consists of energy markets analysis to understand deeply that current situation in global and local markets. The reasons for the energy demand growth such as population, industrial and economic development, urbanising and the correlation between them. The coal energy was the focus while explaining the fossil fuel energy plants due to Turkish energy strategy envisages increasing local coal-fired power plants. After this part, the thesis focuses on future costs of the energy and what are the investment risks on the market from different aspects. Due to Turkish solar energy potential is enormous, solar energy potential is examined on global and local perspective by comparing especially Europe continent. The last part explains why Turkey needs increasing renewable energy supply in its energy supply system by air quality, energy supply security and Conference of the Parties (COP 21) environment agreement.

The second part of is the empirical part of the thesis, proving that implication has a cost competitive opportunity to imply 100% renewable energy system by applying the LUT energy model. The first chapter in the second part explains Turkey’s installed capacity, electricity demand, population division, renewable energy potential by the resource. After that, the LUT energy model, input data, limit and the scope are explained by details. At last two chapters, the results are explained, analysed and discussed. Finally, the third has an overall conclusion for the thesis which gives the general findings of this research.

1-2 Global Energy Market

Technological developments reached to a point that majority of the people in the world are connected to a plug for their business, daily, social and economic lives. Since the industrial revolution, all the high efficient machines need energy resources to maintain the productions and margins of the business. When it is the case, heart of the society is becoming electronic devices which all needs electricity and it makes whole society, industries, governments and electrical devices needs electricity 24/7 Beside electricity demand, there are fundamental things for our lives such as producing materials, agriculture-husbandry, heat transportation and these necessities requires energy which is even more than electricity demand as amount.

Since industrial revolution, except from World War periods world population increased all the time, and United Nations (UN) prospect for world population 9.7 billion at 2050 (UN, 2015). Undoubtedly, increased population causes development and increased investments in industrialization, urbanizing, infrastructure, transportation which need more energy demand to produce and implement. However increasing population might not be the only reason for increased electricity demand. UN Population Outlook mentions that fertility rate is not same with 60 years ago rate and it is not exponential anymore (UN, 2015) but electricity

World population is increasing explicitly and it is going to reach the amount of 10 billion of people based on United Nation’s future population estimation at 2055, illustrated in Figure 1-1, which means 83 million newborn every year until that year. As world population increasing Turkey’s population is also increasing, current data of Turkish population of 2016 is approximately 79 million and it will 95 million at 2050 according to UN population report. The increase of population will be %20 and increasing of energy demand will be at least 150 times higher than population increasing amount for 2012 – 2050 period. These estimations are going to deeply analysed in this thesis.

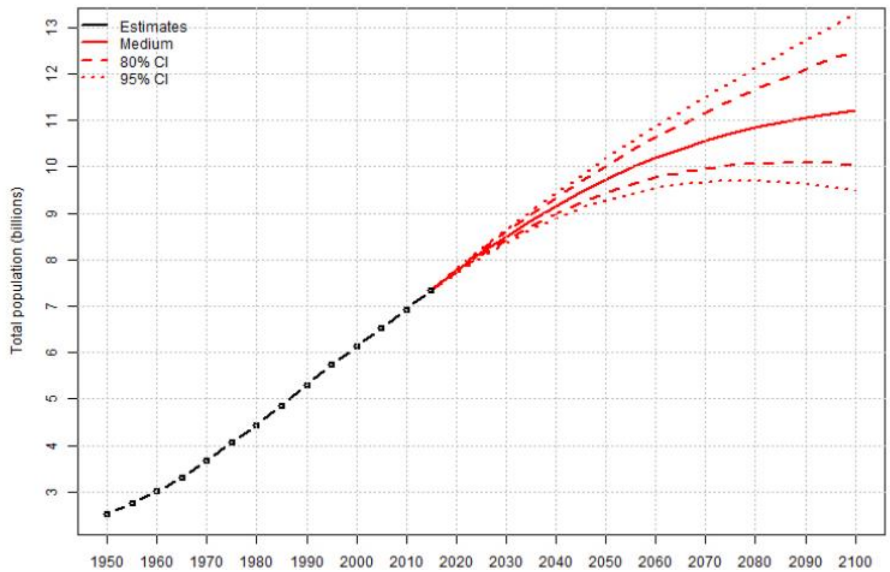


Figure 1-1: Population of the world: estimates, 1950-2015, medium-variant projection and 80 and 95 per cent confidence intervals, 2015-2100 (UN, 2015)

Electricity transmission and distribution systems need more infrastructure and investment for enhancing the supply in a required way to meet the increasing demand and to manage diversified energy systems which have higher complexity. These reasons will be main reasons of escalated electricity prices before every other reason in the market.

1-2.1 Fossil Fuels Market

Natural gas, oil and coal estimations of the UK government in every scenario (low-risk, normal and high-risk scenarios) shows that it only increases in the future (UK DECC, 2015) and results of mentioned scenarios are so similar to EIA fossil fuel scenarios (EIA, 2015). Fossil fuel resources are not sustainable and due to political reasons are not trustable energy resources from supply security perspective.

World coal production made an extremely rapid growth for the period of 2000 and 2014, the reason was production amount increased in the world, and especially in China that has 160% production increase in the same time period (IEA, 2016b). However, world coal production is decreased in

2015 by 221 million tonnes which were the biggest decline in the world history but it should be noted that international trade declined at the same time (IEA, 2016b). After Chinese economic progress started slow down, coal demand and the price declined as it can be seen from Figure 1-2. Coal-fired power plants supply approximately 29% of global electricity production currently and the responsible of 11 billion tonnes of CO_2. (IEA, 2015). Coal also has the responsibility of OECD countries 33.3% of energy –related CO_2 emissions (IEA, 2016b) and all other CO_2 emission related to energy for IEA, OECD and EU28 countries are presented in Appendix 2 (Table 1).

China is the biggest coal producer and consumer in the world, nearly half the whole countries consumption. After China, USA and India follow them with most consumption rates (IEA, 2015b). In contrast to this fact, Chinese and Indian (100 GW solar energy until 2022) governments set up their energy policies to increase renewable energy sources and decreasing fossil fuel consumptions.

On the other hand, there is fossil fuel importer can get affected easily by currency fluctuations and especially politically un-stabilized countries might suffer due to their settled agreements with foreign exchange (e.g. US Dollar, Euro). Oil price was between $35-42/barrel within May 2016 (See Figure 1-2) it was the lowest point for decades. Low oil prices give some opportunity of additional grow of gross domestic product between % 0.3-0.7 in 2015 (IMF, 2015). Oil consumer countries and producer countries both revised their expected governmental budgets due to unexpected low oil prices. Oil companies decreased their investment amount nearly %20 in 2015 and if the annual spending of the oil industry is taken into consideration, approximately 485b€ (2010-2015 annual average amounts), it is easy to understand this decrease of investment amount is huge (IEA, 2015).

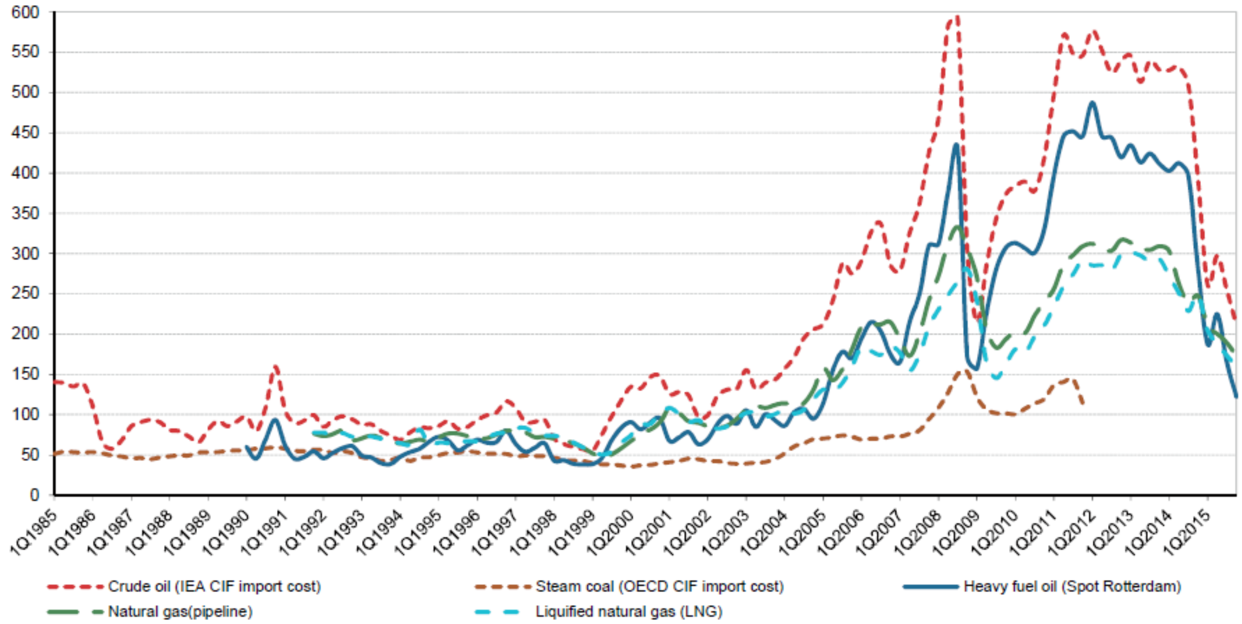


Figure 1-2: OECD international trade values for steam coal, heavy fuel and crude oil and liquefied natural gas in USD for per tonnes coal equivalent (IEA, 2016b).

In the view of such information, it should be noted that Turkey's primary energy production is highly dependent on fossil fuel resources. Turkey imports 92% of its oil, 99% of its natural gas and coal export import rate is shown in Figure 1-3 (IEA, 2016b). The consumption amounts of the same resources for last 10 years is presented in Figure 1-4. Heavy fuel oil price for power sector is decreased nearly 50%, natural gas and steam coal has slight decreases. There is an obvious correlation between consumption of these resources and price declining. However, the natural gas relation is different than the others. Even though natural gas price was increasing between 2011 and 2013 at a constant rate, consumption did not decrease at the same time. It can be said that Turkish energy system structure is strongly linked with natural gas and current installed capacity rate proves this fact (this fact can be seen in Figure 17 as historical data).

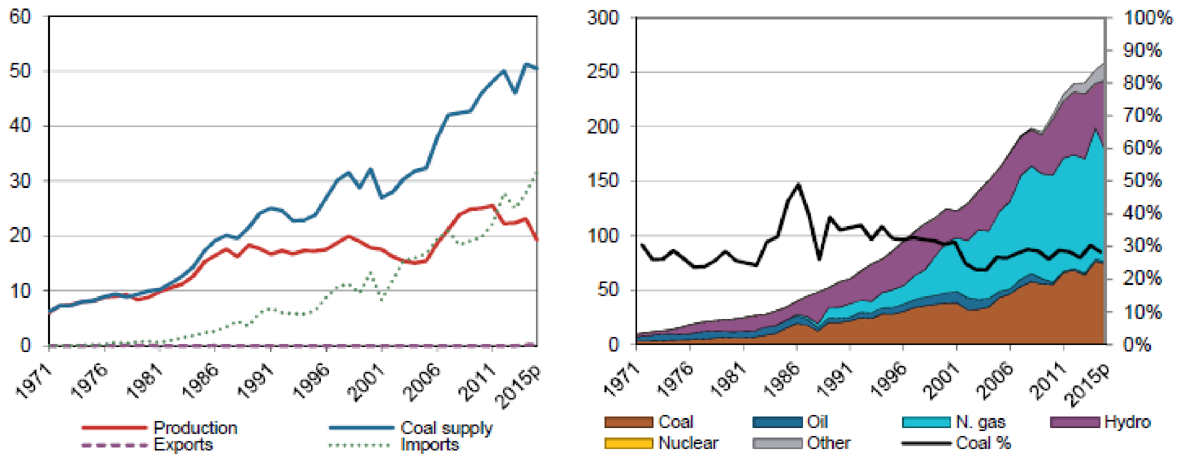


Figure 1-3: Primary coal supply (Mtoe) of Turkey (Left) and Electricity generation by fuel type (TWh) (IEA, 2016b).

While primary coal supply import starts increasing, unfortunately, generated electricity by coal is also increasing. Turkey mainly imports steam coal and Russian Federation has the biggest rate for past 25 years. For the last 5 years, Colombian steam coal has a nearly same rate (11017 thousand tonnes) with Russian Federation steam coal (11086 thousand tonnes) (IEA, 2016b). Coking coal is imported from generally Australia and USA (IEA, 2016b; IEA, 2016c).

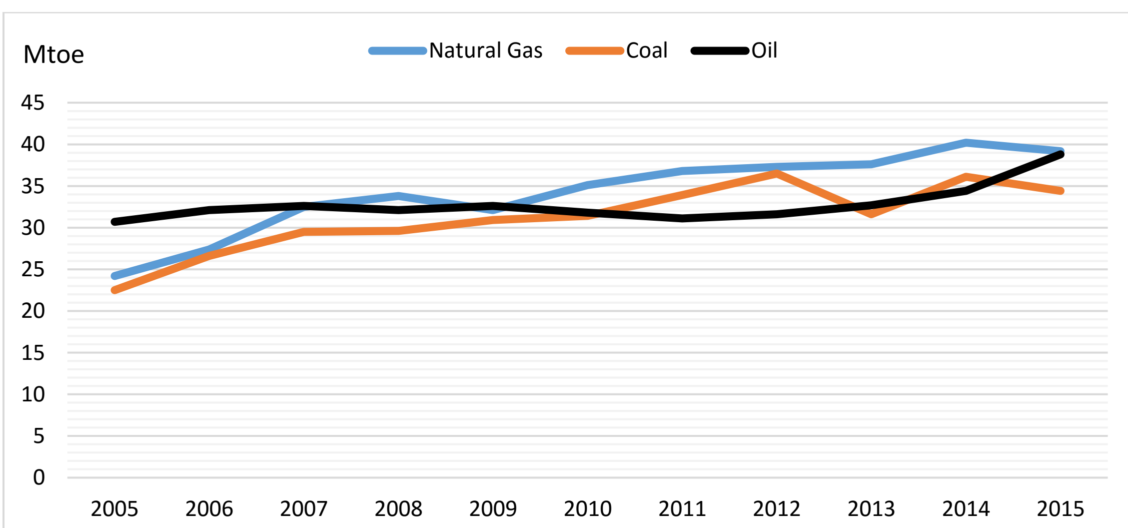


Figure 1-4: Natural gas, coal and oil consumption of Turkey for 2005-2015 (BP, 2016).

Turkey uses oil for mainly transportation, secondly for industrial usage and transformation and energy with total consumption of 11522 tonnes (IEA, 2016d). For subcategories, road transportation has 2763 tonnes of oil consumption and 2154 tonnes of oil for residential purposes are consumed for the year 2015 (IEA, 2016d). Natural gas is used for mainly electricity production which has 48.1% of total consumption, 25.4% is used by industrial purposes, 19% belongs to residential and the rest divided by other sectors (BOTAS, 2016). In addition to this, 19% of residential consumption is average, especially for the winter period the percentage is increasing and natural gas demand makes the peak demands at this period due to weather conditions. For compensating this demand, Turkey is investing gas storage under Salt Lake (Ankara) and this storage amount will be 1 billion m3 and total natural gas storage will be increased to 3.6 billion m3 (BOTAS, 2016).

1-2.2 Renewable Energy Market

Diversified energy technologies change our current world from the politic, social and economic side. None of the energy crisis will be same with 1973 oil crisis due to developed energy mix systems. Most of the developed countries are decreasing their fossil fuel based energy systems and enriching their grids with renewable energy systems. RE market has a huge financial potential which might me describes as trillions of Euros. However, it should be discussed that renewable energy transition will not be happen overnight, the system will be changed within time. Thus, it means that the market will be in a transition not in a transformation. The importance of the energy system transition is crucial due to technical management, economic sides of it and this section discusses how global renewable energy market is evaluating, how big the market is and what the risk points are and finally where Turkey is at this market.

Energy policy of the governments has a strong effect on social and economic impacts on societies. Volatile energy prices make the national economies vulnerable cost fluctuations which create a crisis in quite short time scale. Thus, the countries which have fossil fuel resources moves differently than the consumer countries. Energy policy of the consumer countries is focused on three main subjects; low supply cost, supply security and environmental issues (Linde et al. 2004). Energy security is defined by IEA as “the uninterrupted availability of energy sources at an affordable price” (IEA, 2014a) and IEA energy security definition is more comprehensive definition relatively and includes both criteria which are mentioned by Linde et al. (2004).

European Union (EU) has climate and energy targets for 2020 and these are binding regulations for the member countries (European Commission, 2011). It targets that 20% cut in GHG emissions compare to 1990 levels, 20% renewable shares in energy consumption and 20% increased energy efficiency. EU also mentions that this targets should increase EU's energy security (European Commission, 2011).

The biggest fossil fuels consumer countries, China, US, Russia and India are updating or reforming their energy policies to mainly based on the renewable energy based energy investment plans (IRENA, 2014; Ahn and Gaczyk 2012; IEA, 2014b). Targets of US federal energy policy are 50% decrease in net oil imports, 100% increase in electricity generation by the wind, solar and geothermal sources by 2020 compare to 2012. In addition to these targets of US, GHG emissions are trying to be reduced by 17% from 2005 emission levels by 2020 (IEA, 2014b).

1-2.2.1 Future Cost of Energy

IEA World Energy Investment Outlook claims that global market will demand 5.6 TW capacity addition, 3.2 million kilometres (km) transmission lines, 3 million km of transmission lines needs maintenance, 24.2 million km of additional distributional lines and 31.7 million km of distribution lines needs maintenance. With IEA's 450 scenario, global total energy supply and energy efficiency investment is approximately 41 trillion EUR until 2035. Up to IEA's definition, these investments include the cost of building new power plants, new transmission and distribution grids, replacing and maintenance of old infrastructure and power plants (IEA, 2014c).

Based on Greenpeace Energy [R]evolution scenario (Teske et al., 2015) claims that 49.9 trillion € is required until 2050 to accomplish total installed capacity of 6% fossil, 8% combined heat and power (CHP), and %86 renewable energy (Advanced Energy [R]evolution Scenario). Energy [R]evolution scenario is 7% fossil fuel, 11% CHP and %82 renewable energy capacity until 2050 and it total investment cost is 36,9 trillion €. The focus of Greenpeace Energy [R]evolution scenario is energy saving potential, RE sources potential primarily in the electricity and heat generating sector (Teske et al., 2015). The annual cost of future energy model is presented in Figure 1-5 with three different possible scenarios defined by Greenpeace Energy [R]evolution report (Teske et al., 2015).

Estimated total power sector investment for European energy transition is estimated as 5.7 trillion € until 2050 for the lean scenario which can be described as without any CO_2 or renewable energy targets. (McKinsey, 2010). OECD Europe estimation of Greenpeace Energy Revolution scenario is 2.8 trillion EUR and renewable energy investment takes the share of 70% which equals to 7.9 billion EUR. The investments also include grid updates, transmission system changes and design of power system expenditures which are in all scenario assumptions. Thus, new power plants and new demand areas which are built on different lands than the older ones increase the distances which require more investments (EU, 2011).

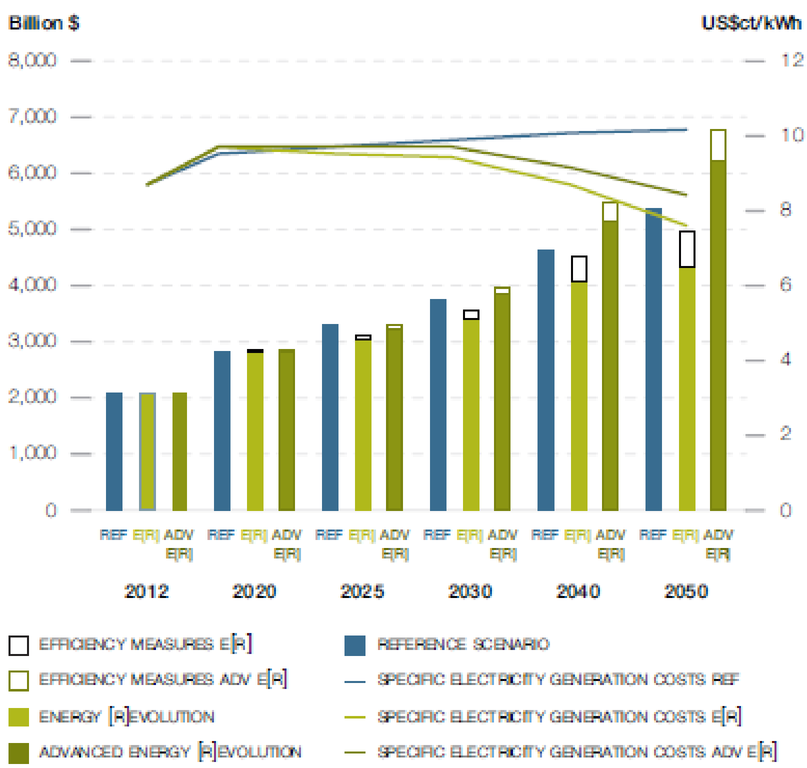


Figure 1-5: Development of total electricity supply costs and of specific electricity generation costs in Greenpeace energy scenarios (Teske et al., 2015).

Region specific power sector investments are shown in Figure 1-6 and the data is separated as The Organisation for Economic Co-operation and Development (OECD) and non-OECD. The biggest investment for total power supply investment belongs to North and South America, and 69.7 % of this belongs to the US. US will need USD 2.1 trillion of new investment in power sector which includes 579 GW of new installed capacity, 260,000 km of, 1.3 million km of new distribution lines and maintenance of these systems (IEA, 2014a). China has the major share as 53.8 % on investment estimations in Asia and Russia requires the third biggest energy supply investment and the fourth biggest efficiency-related investments for all this region (IEA, 2014c).

IRENA calculation for electricity price claims that fossil fuel based electricity production will be €0.05/kWh (in average for all fossil fuel) but if indirect cost includes to the calculation, estimation goes up to €0.15/kWh (IRENA, 2015)

	Oil	Gas	Coal	Power	Biofuels	Total supply	Efficiency
OECD	4 645	3 296	250	6 157	146	14 494	4 630
Americas	3 813	2 019	116	2 567	101	8 616	1 598
United States	2 260	1 500	102	2 052	98	6 012	1 331
Europe	666	815	22	2 434	42	3 978	2 303
Asia Oceania	167	463	111	1 157	3	1 901	729
Japan	32	43	3	664	0	741	445
Non-OECD	8 735	5 381	715	10 212	171	25 215	3 140
E. Europe/Eurasia	1 510	1 617	76	1 122	3	4 329	373
Russia	849	1 016	49	614	0	2 528	212
Asia	1 724	1 613	556	6 714	63	10 670	2 066
China	1 072	657	404	3 587	26	5 745	1 566
India	277	203	94	1 615	13	2 203	245
Southeast Asia	331	529	46	980	23	1 909	192
Middle East	1 956	699	1	573	0	3 229	169
Africa	1 395	915	46	882	0	3 238	217
Latin America	2 150	537	36	921	105	3 749	315
Brazil	1 393	157	2	565	88	2 206	183
Inter-regional transport	290	93	69	n.a.	2	455	232
World	13 671	8 771	1 034	16 370	320	40 165	8 002
European Union	394	531	19	2 227	44	3 214	2 170

Figure 1-6: Cumulative investment in energy supply and energy efficiency in the New Policies Scenario, 2014-2035 (The number unites are $ billion[1]) (IEA, 2015a).

Greenpeace Energy Revolution Turkey Report (Teske et al. 2015) has made future estimations about Turkey specific power sector investments. It shows that if Turkey wants to go on business

[1] Currency rate between Euro and US Dollar is taken as 1.3.

as usual style, the investment amount will be 240 billion EUR and energy supply mix will be 24% nuclear, 50% renewables, 23% fossil fuel and 3% CHP. However if renewable energy investment get increased by 50% and policy is changed to Greenpeace Energy [R]evolution Scenario2, total investment will be approximately 400 billion EUR which has the mix of 74% of renewables, 18% of CHP and 8% fossil fuel based power plants (Teske et al. 2015). Total supply costs are compared in Figure 1-7 with different scenario assumptions of Greenpeace Energy Revolution report. However, it should be noted that increased renewable share is going to decrease fuel cost, energy security supply risk, CO_2 emission cost and related indirect cost (i.e. health expenses).

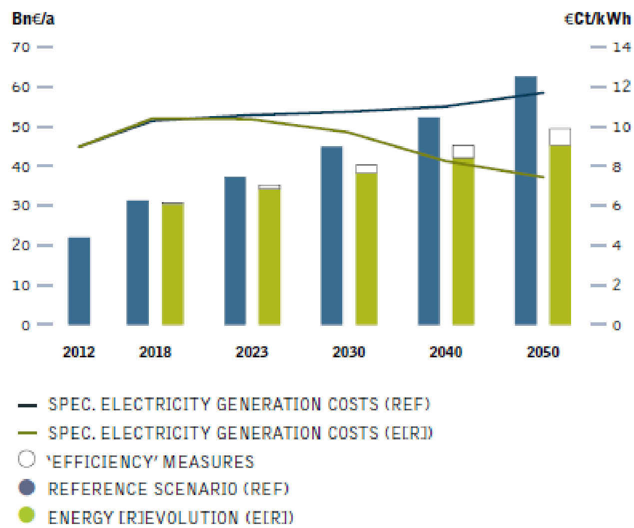


Figure 1-7: Total supply costs and specific electricity generation costs under business-as-usual scenario and Energy [R]evolution scenario (Teske et al. 2015).

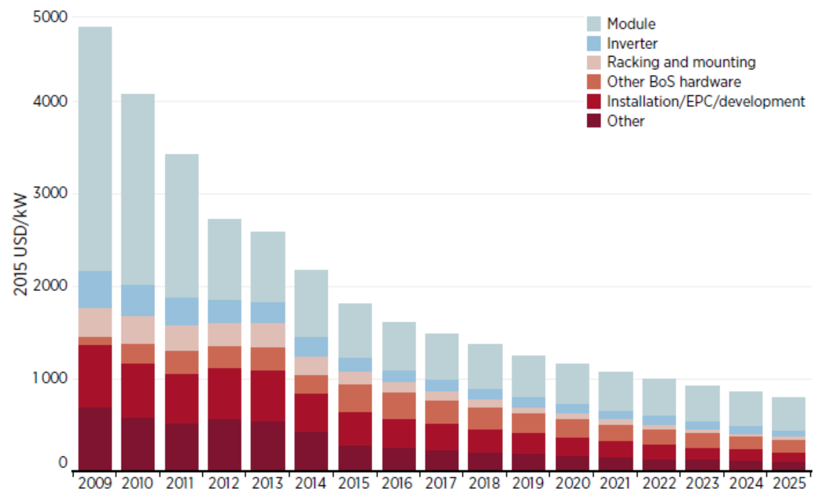
A transition from fossil fuels based energy systems to renewable based systems is already started in many countries from different continents such as Scotland, Uruguay, Costa Rica, Philippines, Maldives (Go 100 %, 2016). Unfortunately, there is a cost for it and various information resources, give varied outputs.

As in fossil fuel, costs of renewable energy depend on a lot of variables such as land cost, solar panels/wind turbines depends on technology, country, project developer and region. The costs of

[2] The Energy [R]evolution scenario is explained in detail at Greenpeace Energy Revolution Turkey Report (Teske and Atici 2009).

renewable energy projects are expected to fall down 2025; as 59% of solar PV, 43% for CSP, 26% for onshore wind and 35% for offshore wind (IRENA, 2016c). Most of the cost reduction is coming from the balance of system cost, all costs except panels such as non-module, installation and soft costs.

Practising more within the time gives more opportunity to obtain better cost amounts to RE industry. Global renewable energy installed capacity is nearly doubled since 2006 until 2015 (IRENA, 2016c). At 2009, installed capacity of global solar PV was 22.3 GW and the total value is scaled up to 222.3 GW at 2015 (IRENA, 2016a). The utility-scale PV costs are shown in Figure 1-8 by different researches and nearly 10 times more practising in all over the world made a significant effect on kW solar cost. For a fair comparison of different types of energy resources, Levelized Cost of Electricity (LCOE) is the required tool (IRENA, 2016c). Figure 1-8 present learning curve effect on solar PV projects at upper side of the figure and at below, different LCOE of solar technologies, PV, concentrator photovoltaics (CPV) and concentrated solar power (CSP) at locations with high solar irradiation (e.g. South Europe, MENA) in 2013 and Turkey can be considered as mid-high solar irradiation area due to closeness to this region.



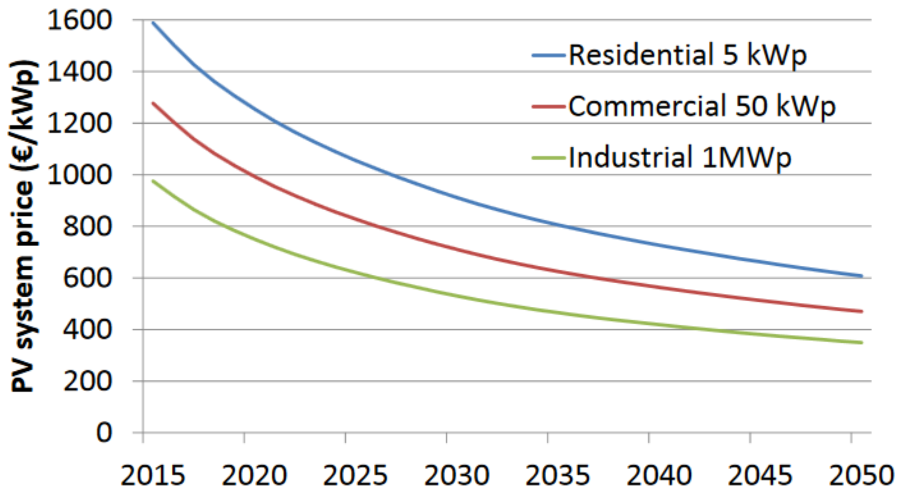


Figure 1-8 Global weighted average utility-scale solar PV installed costs 2009-2025 (IRENA, 2016c) (Top), PV System Price Future Projection (Vartiainen et al. 2015)(Bottom).

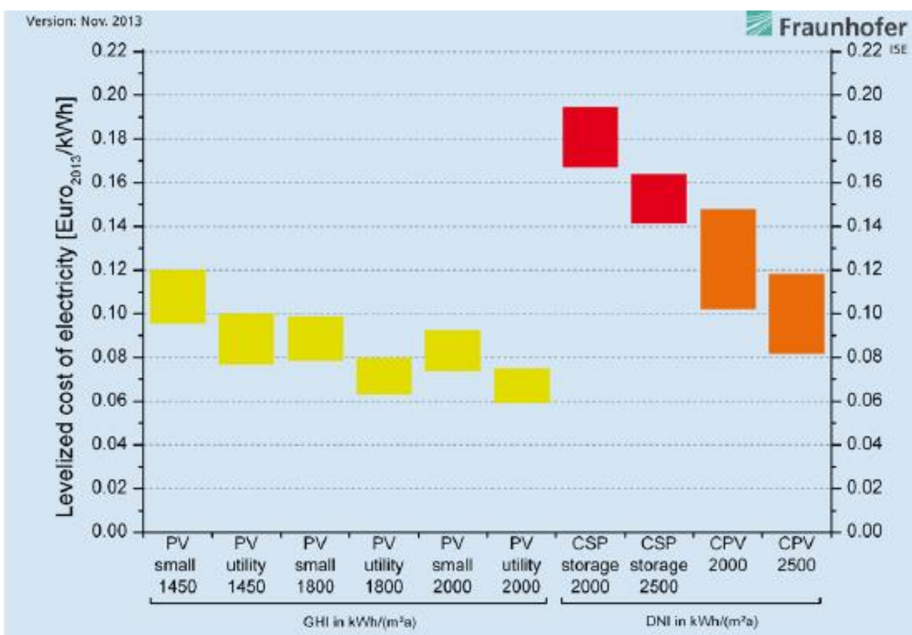


Figure 1-9: LCOE of different solar technologies at high solar irradiation regions (Fraunhofer, 2013).

The solar energy market is becoming bigger and bigger, the competition is increasing between component suppliers. As a basic economic equation, competition decreases the profit margin and if the companies cannot increase the profit share then they need to decrease the cost amount. The offshore production increases the knowledge in the host country and information transfer from home country to host country. Solar PV module production costs are decreasing by cheaper offshore production while the knowledge is increasing in the host country and causes local solar PV producer that increase the competition in the market. The estimated cost reduction of this potential technologic development is between 25% and 30% of all PV projects. PV cell efficiency has a big impact on return on investment time by the size and increased efficiency. Each year commercial c-Si PV module efficiency increases approximately 0.4% and theoretical maximum efficiency of the c-Si cell is marginally less than %30 (Vartiainen et al. 2015). However, this is the only c-Si case and some other materials might be used for higher efficiency in solar cells. In addition to this, different technology cost reduction estimations in the United Kingdom (UK) and Germany are presented in Figure 1-10.

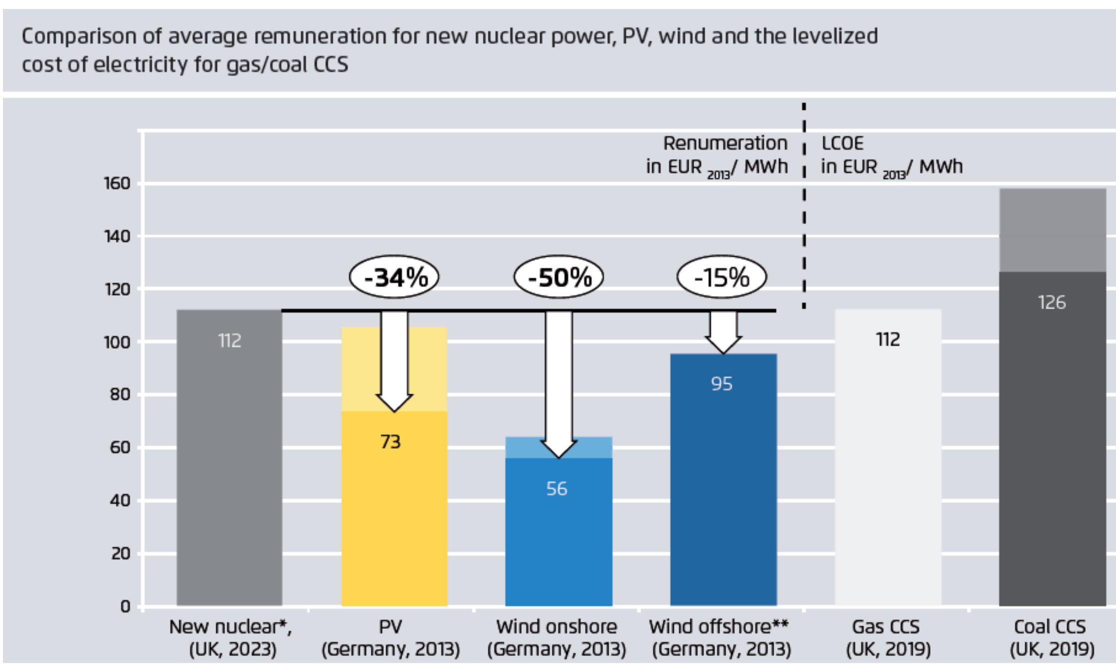


Figure 1-10: Comparison of average remuneration for new nuclear power, gas carbon capture and storage (CCS) and coal CCS in the UK, PV and wind onshore and offshore in Germany (Agora, 2014).

The assumptions of the renewable energy market are based on economies of scale, potential technological developments and certainty of profitability. Due to these reasons, there are going to be slight differences between different markets and projects but this is an overall estimation and cost forecasts might be different than the future values. However, according to intense of renewable energy policies and technological improvements, the main cost forecast assumption will remain but time scale will be changed.

1-2.2.2. Renewable Energy Investment Risks

Historical data shows that 85% of global renewable investments are made by the private sector and these are four types of institutional investors (IRENA, 2016d):

- Insurance companies which have basically three types of investments, long term (life, medical insurance), medium term (building insurance) and short term (travel, accident). Renewable investments are quite suitable for long term investment types (15-20 years).
- Pension funds manage the biggest funds in the world and majority of their investments are long term investments.
- Endowments and foundations are based on trust and donations and their stakeholders are generally having a sensitivity to environmental or social concerns.
- Sovereign wealth funds have income from government taxes or central bank reserves and these kinds of funds make long-term investments for national economy and citizens.

Renewable energy cost is not only related to material costs but also technical and managerial additional costs e.g. security, regulations and management. However, there are a lot of risk factors for renewable energy systems, this paper only focuses return-on-investment (ROI) risks.

Risk profile affects the cost of capital and LCOE and thereof it should be examined carefully. Investor behaviour is quite interesting at the energy point, if an energy portfolio owner-investor is seeking for new renewable energy technologies (higher risk than well-known renewable technologies), the portfolio will be hedged by conventional fossil fuel to decrease the risk. Highly possible that the portfolio will have less renewable energy investment than medium risk taker investor portfolio (Masini and Menichetti 2012).

The Economist prepared a report on renewable energy market risk. “Managing the Risk in Renewable Energy" consists of 280 senior executives in the renewable energy sector, these managers are working for Western Europe, North America and Australia based companies (The Economist, 2011). 51% of the companies who joined to the survey for this report has more than half billion US$ revenue according to the report. There are main risk factors for renewable energy projects which are building and testing, business/strategic, environmental, financial, market, political/regulatory, financing, construction operational and weather-related risks. Four of them are chosen by the writer which are highly correlated to energy investment risks.

Financing and currency risks are related project’s financial structure such as loan structure, credit payments, interest rates or any kind of economic related problems (The Economist, 2011) and volatility in the local currency (IRENA, 2016d). Currency risk makes investment more vulnerable and decreased the credibility options for investment. In Turkish Lira case, Figure 1-11 shows the US Dollar and Turkish Lira currency exchange rate, the exchange rate increased more than 70% within 2013-2016 (Bloomberg Market, 2016). Thus, it was a proper deal that Turkish Renewable Energy Support Mechanism (see Part 2 – Table 2-1) pays subsidies in US Dollar currency which keeps the investor risks in minimum.

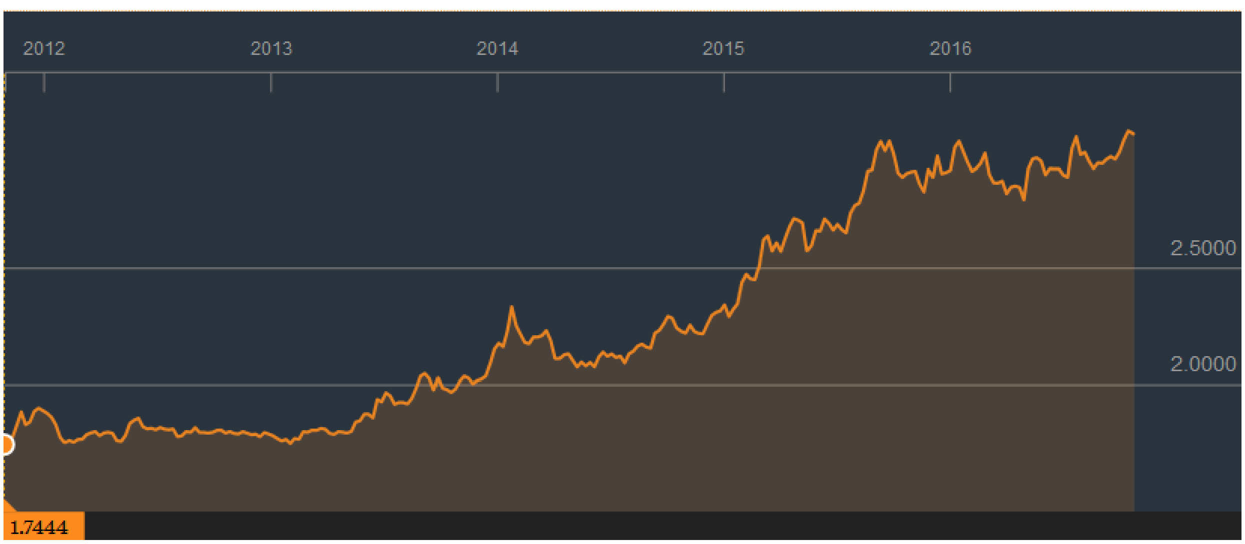


Figure 1-11: USD-TRY Spot Exchange rate for 5 year time frame (28.10.2011-24.10.2016) (Bloomberg Markets, 2016).

Regulatory risks are related to laws and regulations which affect the project in different ways. Government perspective become highly important at this risk factors and determine is it high risk or not. The reason of this is tariff system is determined by governments and tariff system is the main attraction point for the investment regards to guaranteeing payment schedule. If a project has a high regulatory risk (Spain and Italy seem like the highest risk for it due to low tariff), it should be compensated by efficient technology usage technological based on geographical needs (The Economist, 2011). Based on the survey made by Lüthi and Prässler, (2011), wind energy project developers in EU and US evaluated their risk evaluation criteria from their risk perspective and the highest score belonged to priority is legal security which includes overall legal stability, corruption levels, enforceability of contracts and reliability of business partners (Lüthi and Prässler, 2011). Another research about regulation effects on renewable investments is made by Fabrizio K., 2013. This US-based research proves that if there are fewer regulation changes in one state, renewable investments are relatively higher in this location than the other states which have more regulation changeovers.

Building and testing risks are related to supply chain risks (e.g. carrying the wind turbines to the field might bring too much cost), engineering/design failures or any contracting failure between third parties. This risk can be avoided by making agreements with experienced or reliable turnkey project business companies (The Economist, 2011). Higher reliable parts and products (the component supplied by high-tech companies or which are proven on the field after so many applications) usage can also seem that a bit more expensive at the beginning but in the long term, it will be more cost efficient.

Operational risks are unexpected output or management problems (i.e. plant might be shut down by a random plant damage) and unable to reach input resources. It affects return on investment of the project directly and shareholders might not receive any payments in these periods (The Economist, 2011). Examples can be like Northern European wind regime changed for a period and affected all the projects in these regions. Weather-related risks might be counted as operational risks due to the uncertainty of energy output (The Economist, 2011).

IEA World Energy Investment Outlook has similar but more detailed renewable energy investment risks which are categorised under three main categories; political, economic and project specific

(IEA, 2015b). Political risk category consists of country-specific risks like the legal system, security, international issues and the other subcategory is policy and regulatory which consists of support schemes, environmental policies, the stability of investment, business environment and easiness of money transfer. Economic risk category has market, macroeconomic and financial risk and this category focuses on subsidies, competition, inflation, exchange rate and interest rates. Project-specific risk has construction, partner, human resources, environmental and social, operation, technological, measurement risks (IEA, 2015b). International Renewable Energy Agency (IRENA) uses similar but different categorization and it is presented in Figure 1-12.

Despite these investment risks analysis, global renewable investment in the world in 2015 is 219.9 b€ excluding large hydro-electric projects. It is important that the amount was nearly 100% times bigger than new coal or gas technologies. China itself committed a total of 79.2 b€ just by itself which is equal to 36% of total global investment (FS-UNEP, 2016) and solar-specific installation/investment by geographical regions are illustrated in Figure 1-13.

Phase	Pre-construction	Constuction	Operation	Country risk
Risks	• Technology risk • Project design • Debt and equity financing	• Constuction delays • Cost overruns • Environmental mitigation plans • Social mitigation plans	• Operation and maintenance plans • Output quality/ volume • Resource fluctuations • Electricity sales payments (PPA contracts, etc.)	• Currency devaluation • Currency convertibility/ transfer • Political force majeure • Environmental force majeure • Regulatory risk

Figure 1-12: IRENA categorization of energy sector project risk factors.

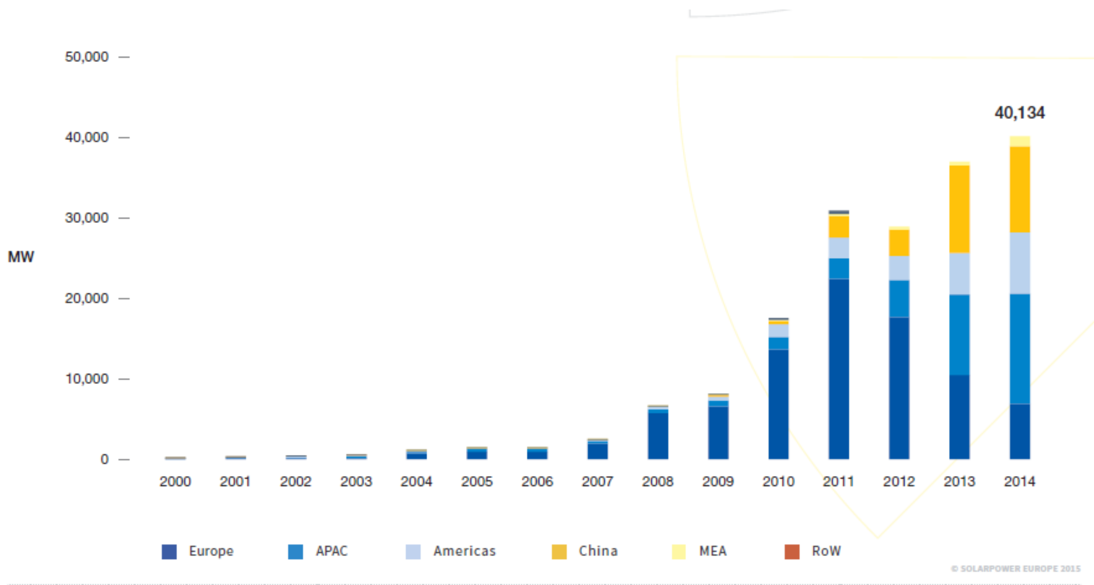


Figure 1-13: Solar installation capacities by regions since 2000 until 2014 (SolarPower, 2015).

1-3 Solar Energy

Sun is a huge energy resource which is formed of hydrogen and helium mostly and the world is in the field of sun's irradiance capability. When sunlight reaches the atmosphere reflects and absorb some of the irradiance and heat. Average total amount of energy from the sun is %57 after atmosphere effect and this equals to 93.8 PWh (IEA, 2011).

Photovoltaics (PV) are the systems which convert sunlight into electricity. The history of the converting light into electricity goes back to 1839 and even Albert Einstein put his mark to science about the subject and he won his Nobel award about defining photoelectric effect. However even prior patents are taken at the 1920s, first feasible products and commercialization of this technology started with Bell Laboratories which figured out that silicon materials have the ability to make this conversion. First panels had %6 of efficiency and one of the milestone usages was at US Vanguard I space satellite (1 kW PV array). Japan started investing in this field and Sharp made 242-watt PV array at a lighthouse which was the biggest amount of installation until that time. NASA and other corporations increased their investments in this field and until the mid-1970s, solar cells' prices went down nearly %80. (IEA, 2011) After this point, solar industry generally improved itself with government subsidies and some companies who made innovative solutions which affected the material usage or mixing with other products (e.g. calculators with solar cells). At 1999, Germany launched a huge budget program (1 Billion Mark) which is called "100000 Solar Roofs" and Renewable Energy act came into the force with EUR 0.5/kWh feed-in tariff for 20 years (IEA, 2011). After that, US Government started a program and made big investments in the solar projects.

Since 2003 to 2009, average annual growth rate (AAGR) of PV systems had a spectacular amount of %40. Until nearly 2005, the market was dominated by US, Japan and German Companies but China made a big step on the market and became dominant and currently it continues in the same way. The quality became a problem in the beginning but it is solved within the time. Second biggest reason is China itself decided to be a self-consumer (43 GW capacity was operational at the end of 2015) and they made huge investments in the solar projects and they used their own companies to invest on. A parallel fact with these investments is China is the biggest solar PV related employer and the approximate number is quite big both in installation and manufacturing as 1.7 million jobs in 2015. After this big boom in Chinese solar sector, Chinese companies moved their new facilities to other countries but generally, investment stayed in Asia (e.g. Thailand, Malaysia, and India) (IRENA, 2016b).

The current situation is Chinese and Taiwan producers have the major shares in the market but we cannot say the same thing for innovation and improvement of the technology which is still generally produced by Japan, US and German companies. It might be more understandable if it is checked that biggest solar projects made by which company and country. It can be easily seen that majority is the countries which are mentioned above. In spite of this, Europe Union (EU) PV related employment rates decreased by %13 in 2014 (IRENA, 2016b).

Global electricity production has just 1% share of solar power but solar installation trends show that the share is increasing slightly. At the year 2000, there was 100,000 residential building and facility (Deutsche Bank, 2015) which was approximately 1,000 MW and within 15 years this amount is increased to 6 million residential and facility based installation is made, which equals to 200 GW and with a value of 692 billion € (Morgan Stanley Research, 2014).

Future estimations of Deutsche Bank show that next two decade will have 100 million new users and it will create approximately $4 trillion value to the market. 1% share of solar in global electricity production will be 10 % if everything goes as expected (Deutsche Bank, 2015).

Economic performance of photovoltaic systems can be determined by solar irradiation, the cost per unit or installed peak power (€/kWp), the lifespan of the product and operational cost with capital cost. (Šúri et al. 2007) Solar irradiation does not change within time and cost of solar panels are decreasing within time regards to technological developments. The lifespan of the products are guaranteed by producers at least 30 years currently in the market and operational cost of solar panels stated in other words as operational expenditures (OPEX) are explicitly much less than the other renewables. Turkey has good irradiation values compared to Europe and a comparable geographical map is illustrated in Figure 1-14. The same map has the data for energy payback time, and Turkey's values are good for making investments.

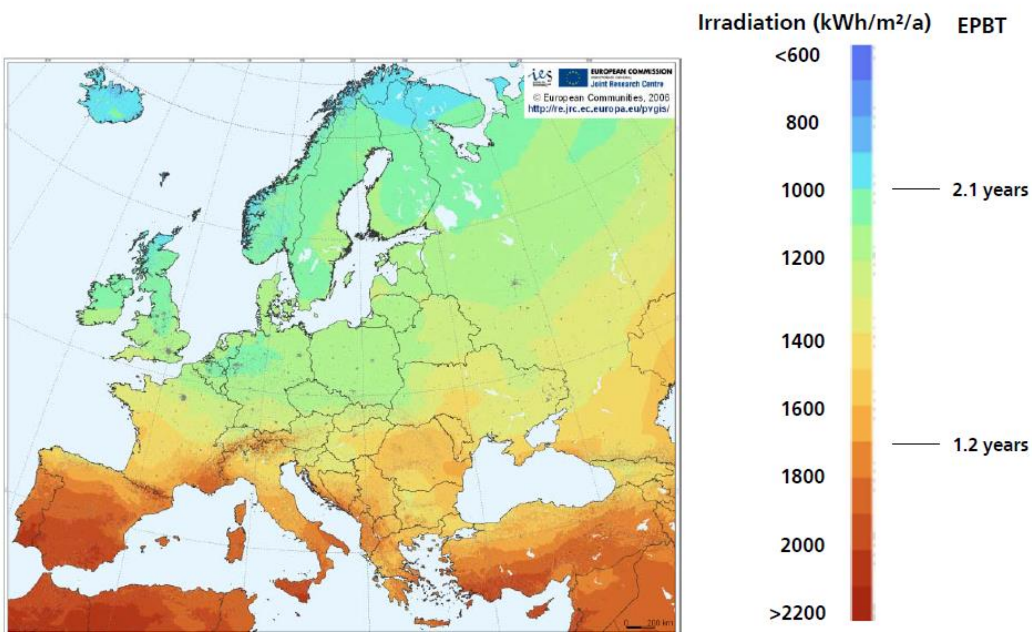


Figure 1-14: Solar irradiation data on Eurasia and energy payback time of multicrystalline silicon PV rooftop systems (Fraunhofer, 2016).

Potential of solar electricity generation in the EU (Šúri et al. 2007) research shows the generated electricity by 1 kWp PV system and Turkey's average is pretty high compare to other EU and candidate countries. The most efficient countries in Europe are Portugal, Spain, Southern Italy, Malta and Turkey which are presented in Figure 1-15. When the countries are starting to be part of central Europe and Nordic countries solar irradiation is declining and the generated electricity as well (Šúri, 2007). The same research provides Figure 1-16 to show that how many percentages of the country's area is needed to meet the same country's electricity demand. It proves the same fact that Turkey's solar potential is relatively higher than other European countries. Similar solar potential countries Spain needs 0.32% and Italy needs 0.80%. This data compares the 2007 electricity consumption and PV potential but it should be noted that Turkey's electricity consumption is converging Italy and Spain's consumption amounts in current years (BP, 2016). Therefore for the future electricity demand, even with increasing technology, the area needed for meeting electricity by PV will be bigger than this research's claim.

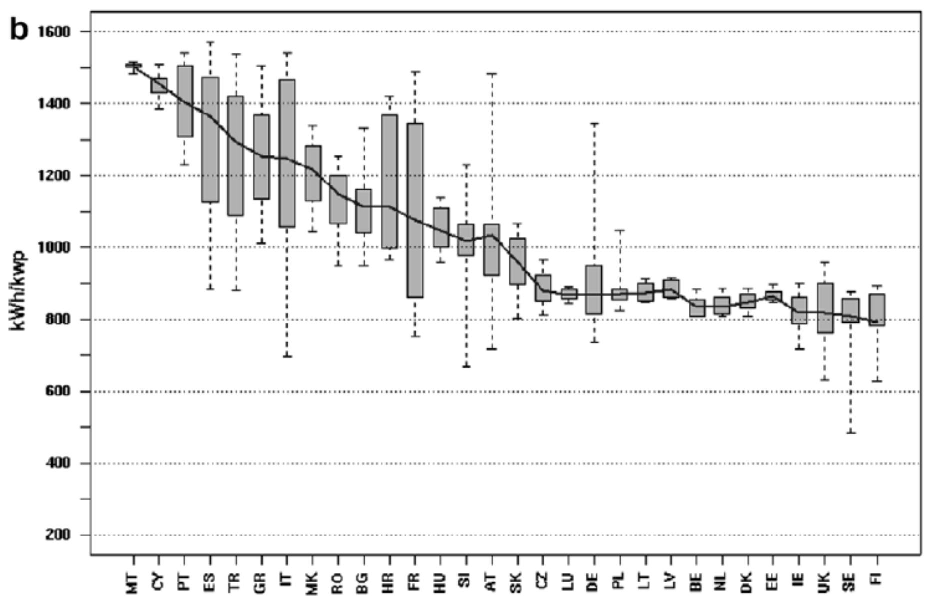


Figure 1-15: Yearly sum of electricity generated by a typical 1 kWp PV system in the EU 25 Member States and 5 Candidate Countries (kWh/kWp) with modules mounted: at the optimum angle. The box plot depicts the 90% of occurrence of values in urban residential areas (Šúri et al. 2007).

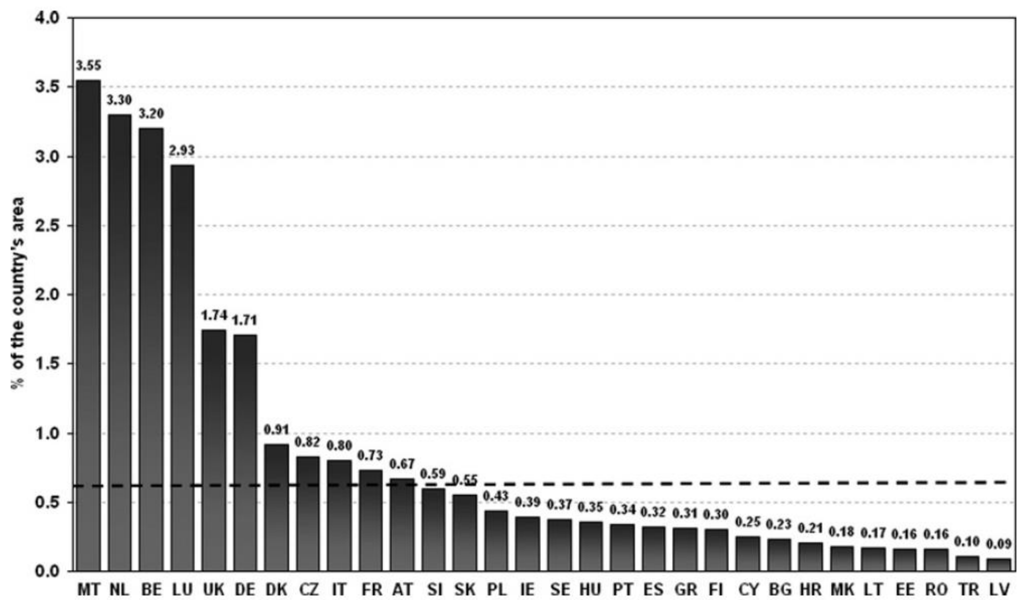


Figure 1-16: Theoretical PV potential: surface of PV modules mounted at the optimum angle that would be needed to completely satisfy country's electricity consumption (expressed as % of the country's area). The dashed line represents the EU25+5 average 0.6% (Šúri et al., 2007).

1-4 Overview of Turkey and Constraints

The Turkish economy is the 23rd largest economy in the world with GDP of nearly $798 Billion at the end of 2015. If expected growth rates will be seen, Turkey is going to be the biggest fifteen economies in the world (Deloitte, 2013). The population is urbanising, young, growing and will keep growing until 2050 (UN, 2015). In contrast to the population growth, total primary energy supply per capita and power generation per capita much lower than EU average (IEA, 2016).

Production industry is one of the biggest income of Turkey and this industry requires to consume a huge amount of energy, it was equal to 34.4% of the all energy consumption at 2014. While the industry is growing, it might not create the expected positive income on national macro level income due to dependency on imported fossil fuel. The more demands mean, more fossil import with current policies and installed generation capacities. Fossil fuel imports for the power sector, heat, transportation and industrial usage is the biggest share of Turkey's current account deficit and it equals more than 20% and 33.9 billion € (TUIK, 2016a). The same database shows that this amount was less than previous years despite the fact that energy consumption did not decrease.

There might be varied options to affect decreasing on the cost but it is a high probability that the reason was declining of fossil fuel prices. Transportation sector is the second biggest consumption under industrial consumption statistics with a share of 19.3% at 2014 (TUIK, 2016b). Automobile amount per capita (TUIK, 2016c) is far below than EU average which might be estimated as Turkey's car amount will converge to EU values. Diesel and oil engine cars are the vast majority in the market which contributes to GHG emissions and oil import.

Turkish political targets show that %30 of all energy demand will be supplied from renewable energy sources in 2023 (MENR, 2015). The target for the installed capacity of solar power is 5 GW, the wind is 20 GW, hydropower is 34 GW, geothermal and biomass is 1 GW each based on Turkish on the same renewable energy strategic plan (MENR, 2015). Historical installed capacity is illustrated in Figure 1-17, it includes the data since 1970 until 2015. The detailed installed capacity shares, renewable energy potentials and the official subsidy programme are explained in the next part of the thesis; "Energy Transition towards 100% Renewable Energy at 2050 for Turkey for the sectors electricity, desalination and non-energetic industrial gas demand".

The historical data shows that Turkey made a huge investment in natural gas and energy production is highly dependent on this. The second biggest share is hydropower and nearly equal shared resource is the imported coal. Turkey is in one of the water stressed countries and highly vulnerable to water shortage and drought (IEA, 2016f).

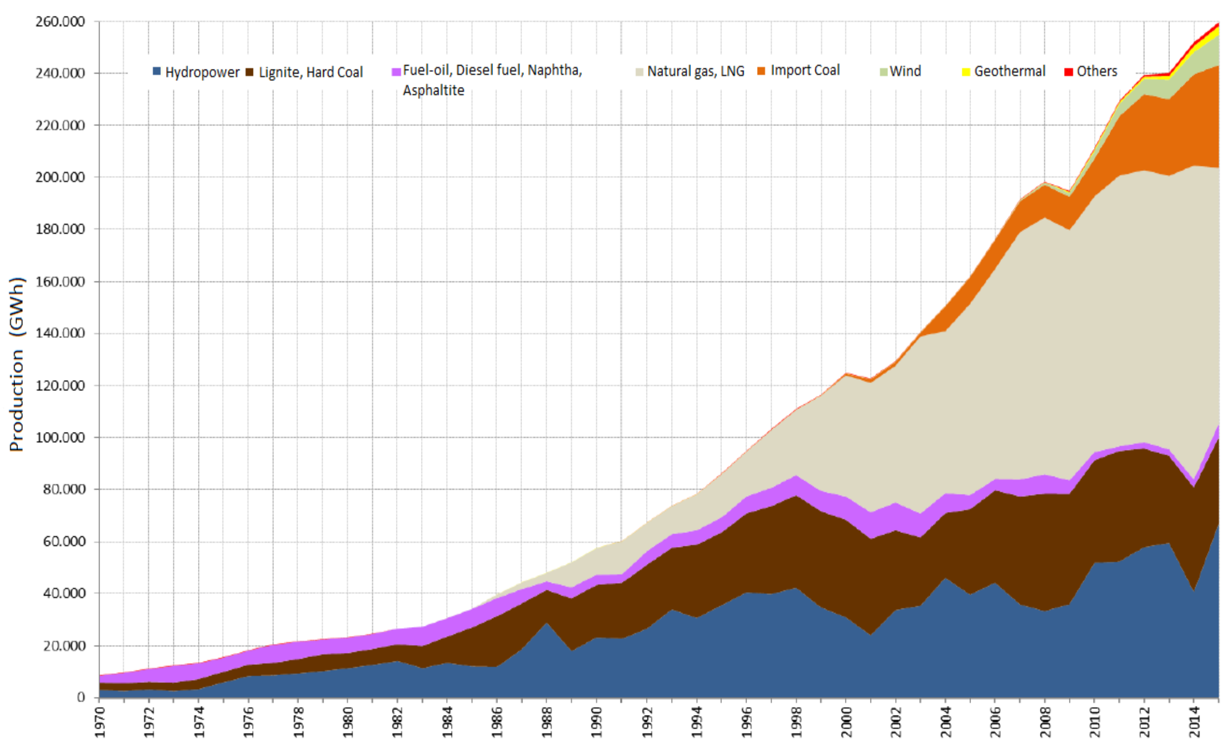


Figure 1-17: Turkish energy production by resource for 1970-2015 period, (EMO, 2016)

Especially the coal has air pollution issues and this problem can be seen from air pollution index in Figure 1-19 at Air Pollution in Turkey section. The government enacted a new subsidy for local coal and the feed-in tariff will be 185 Turkish Lira which is equal to 56.6 €/MWh[3] (The Official Gazette, 2016). The main reason for the decision is utilising rich local lignite resources of Turkey and reaching 60 TWh of generated electricity from coal plants (IEA, 2016f). However, the supply chain of local coal reserves needs to be revised and improve for occupational safety. In 2014, Turkey faced with a dramatic occasion when 301 miners were trapped in coal mine at Soma. This tragic case revealed a fact that the real price of the coal might not be the same as calculated (BBC, 2015).

Turkey is going to be one of the most affected countries in the future by climate change. The Turkish State Meteorological Service (TSMS) prepared a report for possible climate change effects on Turkey (TSMS, 2015). According to this report, Turkey's annual temperature will rise between

[3] In this research conversion rate of Turkish Lira to Euro is taken as 1 € = 3.3 TRY

1.0°C and 2°C in 2016-2040 period. For further future, the forecast is 1.5°C and 4.0°C in 2041-2070, and 1.5°C and 5°C for 2071-2099 (TSMS, 2015).

The energy supply system of Turkey highly dependent on hydropower which is going to be affected dramatically by climate change in high probability. Available water per capita is 1519 m^3/year in Turkey and this water availability (under 1700 m^3/year) is considered as water stress for a country by UN (UN, 2006). If the population increase is taken into consideration with future water drought, it can be easily said that water availability is going to be a critical issue in the future and even the point of water scarcity which is defined as under 1000 m^3/year (Teske et al. 2015). Also, Turkey drew 4.29 billion m3 water and 99% of it used for cooling purposes (Teske et al. 2015).

1-4.2 Paris Agreement and Turkey

2015 was an important year for all countries and energy players in the world because of Paris Agreement, 2015. 188 countries have signed the Conference of the Parties (COP 21) 2015 in Paris and all the signed countries are going to pledge their plan which is called nationally determined contributions (NDCs) for how to reduce their carbon emissions. (UNFCC, 2016).

It is a keystone agreement about environmental impacts of national energy policies and the agreement is accepted by 195 countries. Some bullet points of the agreements are;

- “As nationally determined contributions to the global response to climate change, all Parties are to undertake and communicate ambitious efforts.”
- “Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.”
- “This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty.”

- “Agreement shall set a new collective quantified goal from a floor of USD 100 billion per year, taking into account the needs and priorities of developing countries.” (Paris Agreement, 2015)

The most important decision for renewable energy strategies was launching International Solar Energy Alliance with the leadership of France and India and totally 120 countries. The target with this alliance is building 100 TW/h solar installed capacity.

Turkey pledged its nationally determined contribution to The United Nations Framework Convention on Climate Change (UNFCC) in 2015 (UNFCC, 2015). The vision is GHG emission will be 21% less compare to 1990 level during 2021 to 2030. Also, increasing renewable energy share in the energy and reaching 10 GW for solar capacity, 16 GW of wind capacity and utilising all hydropower potential capacity by 2030 (IEA, 2016a).

Turkey was in a complex position in environmental acts since 1992 Rio Agreement. Turkey was in Annex-1 (Developed and economies-in-transition) countries and Turkish government were complaining about financial credit demands since then. This problem decelerated of creating environmental solutions and still, there are some problems about positioning of the country. However, Turkey made a pressure on the Paris Agreement negotiations about this issue and took a financial support promises (Cerhozi, H., 2015).

1-4.3 Air Pollution in Turkey

Air pollution changes the natural features of the atmosphere by physical, chemical or biological effects which are divided to two as outdoor air pollution and indoor air pollution. Outdoor air pollution consists of fines particles due to fossil fuel consumption, noxious gases, ground level ozone and tobacco smoke (NIH, 2016).

CO_2 emissions from varied sectors are shown in Figure 1-19 and power generation sector is the leader by far and after that transportation is following. The main reason power generation sector pollution is coal usage (43%) and natural gas (30.5%). The reason of transportation sector pollution is oil and it causes 26.5% of all air pollution in Turkey (IEA, 2016a).

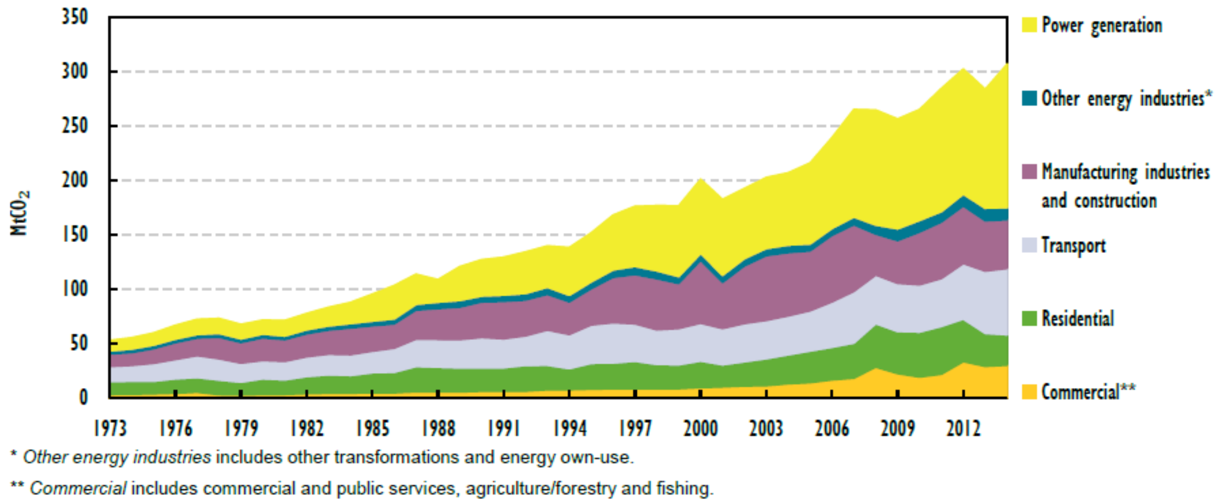


Figure 1-18: CO_2 emissions by sector in Turkey for 1973-2015 (IEA, 2016).

Turkish energy system policies air pollution results indicate that quality is mostly under EU standard limits (HEAL, 2015). The cleanest air is the point S14 - Bornova, Izmir and the worst air quality point is the point S19 - Soma, Manisa where is in the middle of 6 coal-fired energy plant (Buke and Köne, 2016). This data consists of SO_2, NO_2, and PM_{10} averages by 20 different monitoring stations in Turkey and these emissions shows that current energy facilities are not sustainable at all with these emission rates. Current and previous energy policies clearly unsuccessful with air pollution emissions. (Buke and Kone, 2016). Air pollutions in the cities are in critical levels and IEA Turkey Energy Outlook (2016) drew attention to this point at Climate Change topic. Approximately 97% of the city population has to breathe particulate matter (PM_{10}, $PM_{2.5}$), Ankara has PM annual average concentrations of 58 ug/m^3, and Istanbul 48 ug/m^3 (IEA, 2016a).

OECD claims that 28,924 of people who died prematurely in Turkey from ambient PM and ozone exposure and this amount is 3.5 million in a global scale (OECD, 2014). The global cost estimation for air pollution related deaths is US$ 1.2 trillion and in Turkey case, it is 45 b € (OECD, 2014).

Index Value	Air Quality
>1	The EU standards are exceeded by one pollutant or more
1	The EU standards are fulfilled on average
<1	The situation is better than the norms on average

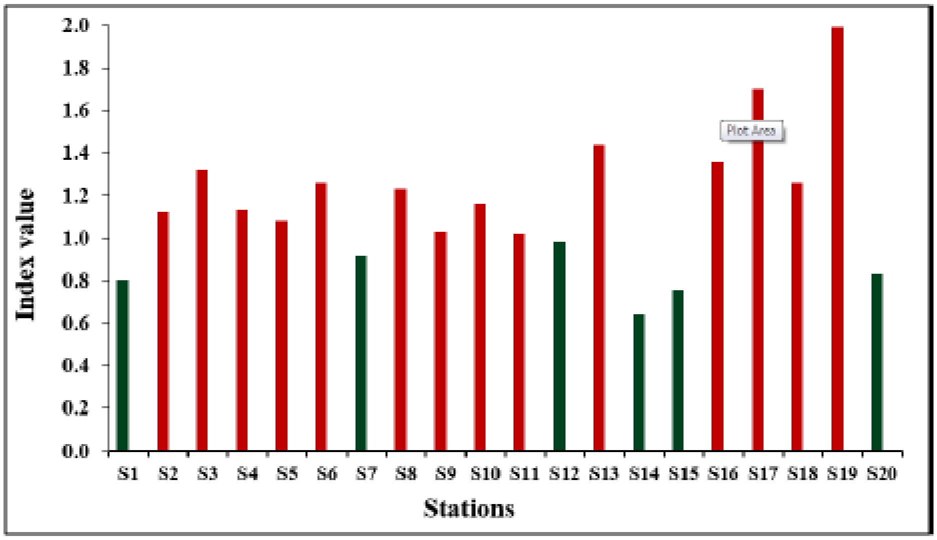


Figure 1-19 Air quality index for 20 air quality monitoring stations in Turkey. X axis values are based on index values explained on top (Buke and Köne, 2016).

Unsustainable air pollution emissions should push the power plant management reconsider and act about emission and the governmental supervisor should monitor, control and pushes to decrease the emissions to healthy limits. The cost of this renovation, restructuring or rebuilding of existed plants might be more expensive. However, indirect costs of current emissions would compensate the cost difference, and it should be noted that the air pollution is a direct threat to the most basic human right of "right to life". Indirect costs at this stage mean healthcare payments for the public (mentioned air pollutants increase cancer risk substantially) and environmental protection (such as water resource pollutions, global warming effects. Besides these recommendations, there is a positive regulation which obliges that all new power plants shall be subjected to EU Large Combustion Plant Directive Industrial Emission Directive and existing ones by 2019 (IEA, 2016a).

1-5 Conclusions

The risks mentioned above are reviewed by renewable energy field specific but renewable energy is not only energy type has the risks. Fossil fuel fired conventional power plant investments have own specific risks which are not the focus of this paper but unfortunately it can be seen that governments still has subsidy programmes for this type of power plants. The Group of Twenty (G20) countries' total average annual subsidies were nearly 54 b€ for the 2013-2014 period (Bast et al., 2015). This statistic has different kinds of fossil fuel investment but the common investment for all members is upstream oil and gas investments. Turkey's national subsidy is 482 M€ for coal mining, upstream oil and gas, coal-fired power and unspecified multiple fossil fuels. The total fossil fuel power plant investments' amount which is backed up by government banks is 0.77 b€ for the same time period which mentioned in the same report, Empty Promises – G20 Subsidies to Oil, Gas and Coal Production by Bast et al. (2015)

Renewable energy investment risks can be solved by strong financial and governance management (IRENA, 2016). Greenpeace 2015 Turkey (Teske, 2015) report suggests some policy' finance and development for all countries and these suggestions are most realistic ones for making renewable energy production major in energy production sector. These suggestions are;

- Developed and improved policy and financial mechanisms needed in every country to make investments more reliable for an investor, clearing uncertainties and supporting/guarantying the revenues more.
- Research and development budget for renewable energy may support whole industry and the budget for it should be created or increased.
- Legal and operative issues should be handled easily and grid connection priority should be given to the investor. Time for permits should be decreased and clear schedules should be published.

There are two signed nuclear plant agreements with Russia (The Official Gazette, 2010) and Japan (The Official Gazette, 2015). The official reasons to build nuclear plants are explained by Turkish Energy Ministry as increasing energy supply security, creating new job opportunities by the facility itself and sub-industry investments, and "creating dynamism" to the other sectors which are not explained by the details. Based on these explanations, creating jobs and sustain those opportunities should be analysed and compare with the renewable energy job creations. It should be noted that renewable energy employment was 8.1 million in 2015 and it is increasing by the estimated trends (IRENA, 2016b). The solar photovoltaic job employment has the leadership and solar potential of Turkey is huge and enough to create job opportunity for every level of education. The second thing to discuss for Turkish nuclear agreements is the environmental factors and about this issue, Turkey and Germany would be a perfect example to compare. Germany's primary energy consumption is 3847.2 TWh and Turkey's is value is less than half of Germany, 1575.6 TWh (BP, 2016). Germany is supplying 6.5% of their primary energy consumption by nuclear energy, equals to 250 TWh (BP, 2016). In the view of such information, German Federal Court made a decision about nuclear energy plants in Germany and declared that after Fukushima nuclear accident phasing out of nuclear plants should be accelerated for the common welfare, to protect life and health of the population, to protect the environment and future generations (The Federal Constitutional Court of Germany, 2016). Turkey can implement 100% renewable energy system to meet the required energy demand in the future and nuclear energy plants might create more problems than it is supposed to do.

Highly dependency on imported fossil fuels and the huge potential of renewable energy is on the contrast as two concepts. The learning curve of the renewable energy technologies encourage local and international investors and especially stabled countries with strong subsidy systems can easily be a charming point as discussed in Renewable Energy Investment Risk section. Due to water scarcity, seawater desalination will be integrated into the energy system sooner or later. Starting as soon as possible might decrease the future cost

2. Energy Transition towards 100% Renewable Energy at 2050 for Turkey for the sectors electricity, desalination and non-energetic industrial gas demand

In the thesis work and the paper, Anil Kilickaplan is the main author and Professor Christian Breyer is the main examiner and has a lot of valuable contributions. Mr Onur Peker contributed for the installed capacities data and wrote a parallel thesis; The Opportunities and Limits of Bioenergy for a Sustainable Energy System in Turkey. Ms Upeksha Caldera modelled and contributed water demand, storage and all water related input data, Mr Dmitrii Bogdanov made coding of the hourly resolution, sub-region divided energy modelling and visualisation of the results, the last but not the least Mr Arman Aghahosseini made the visualisation of the results. The benchmark for the paper structure is Ms Upeksha Caldera's "Integration of reverse osmosis seawater desalination in the power sector, based on PV and wind energy, for the Kingdom of Saudi Arabia" paper (Caldera et al., 2016).

This paper is the core of the thesis and is submitted to an journal.[4]

ABSTRACT:

In this research, Turkey's energy transition towards 100% renewable energy (RE) until 2050 is analysed by using an hourly resolved model. Turkey is structured into seven geographical regions and all assumptions and data are applied and collected separately for the regions. The energy transition is simulated for two scenarios: a power sector and power sector plus desalination and non-energetic industrial gas demand. Turkey has an enormous solar energy potential, which leads to an installed solar PV capacity of 287 GW (71% of total installed capacity) in the power scenario and 387 GW (73% of total installed capacity) in the integrated scenario in 2050. Solar PV and other installed RE systems are balanced by storage systems to increase the flexibility of the system. Fossil fuel usage is decreased from 268 TWh_{el} to zero in both scenarios and likewise the carbon emissions. Levelised cost of electricity dropped from 62.9 €/MWh_{el} to 56.7 €/MWh_{el} for the power scenario and from 73.1 €/MWh_{el} to 50.9 €/MWh_{el} for the integrated scenario in 2050. It is shown that 100% renewable energy is financially and technical feasible. Growing affluence, increasing population and industrialisation pushes Turkey's electricity consumption to a higher level.

[4] The paper is authored by Anil Kilickaplan, Dmitrii Bogdanov, Onur Peker, Upeksha Caldera, Christian Breyer. The first author did the main part of the paper.

Turkey's current energy system is highly dependent on imported fossil resources. A 100% renewable energy system reduces the energy import dependency and the carbon emissions, while reducing the cost of energy supply. Flexibility through sector integration of seawater desalination in industrial gas demand increases the overall energy system efficiency.

2-1 Introduction

Turkey is the second largest country after Russia in Europe-Asia region that occupies an area of 769,604 km^2. It is a hub point between Central Asia, Middle East and Europe geographically and as for the energy sector. The total population of Turkey of 78.6 million is the third biggest in the same region. Future population prospects show that the population amount will be 87.7 million at 2030 and 95.8 million at 2050 (UN, 2015). The population is rather concentrated on generally industrialised cities and regions. Nearly 60% of all industry is located on Marmara region and the followers are Aegean and Central Anatolia regions.

Turkey's annual electricity consumption was 209.2 TWh in the year 2013 and it was the 5th highest electricity consumption in Europe (IEA, 2015b). Since the year 2000 until 2015, annual electricity consumption in Turkey increased more than 170%, from 98.3 TWh to 268.8 TWh, and per capita consumption increased 90% from 1449 kWh to 2749 kWh, (TEIAS, 2016). This electricity boom had been a main driver in increasing the expenditures for the annual total imported fuel from 10.4 b€[5] (year 2000) to 41.2 b€ (year 2014), and 33.9 b€ (year 2015), respectively, which is equivalent to approximately 20% of all imported goods for the mentioned years (TUIK, 2016b). Several reasons are pushing Turkey's electricity demand to upper levels: the ongoing economic development is increasing the Gross Domestic Product (GDP) which has been increased by 230% between 1990 and 2012, increasing population and urbanisation, industrialisation, global warming, and an increasing demand for transportation (Wilbanks et al., 2008). GDP and electricity demand are highly correlated with each other based on the historical data (Breyer, 2012). GDP raise causes raise of electricity demand in terms of construction, manufacturing and transportation requirements (Chen, 2016). European Union's electricity consumption per capita is 6036 kWh, and is far ahead compared to 2745 kWh for Turkey (World Bank, 2016). Hence, Turkey will reach

[5] The data is provided by Turkish Statistical Institute database and the currency is automatically converted by base year currency rate.

the matching point to European Union's per capita electricity consumption according to future developments and optimised policies.

The Turkish government energy policy is based on energy supply security, energy efficiency and an optimum energy resource mix for changing the current unsustainable and unbalanced situation (MENR, 2015). The pursued energy policy is based on overcoming supply security issues, increasing local resource usage percentage in the whole energy system and further connection to the European transmission network and renewable energy support. On the contrary, this policy addresses only the period of 2015-2019 and it is in the 10th National Development Plan (The Official Gazette, 2013). For the national energy efficiency policy, there is the Energy Efficiency Strategy Paper (The Official Gazette, 2012) for the years 2012-2023, which pursues the report of 9th National Development Plan targets (The Official Gazette, 2006). The Energy Efficiency Strategy Paper points out that Turkey needs to increase energy supply security, making the energy costs sustainable and making the energy related development more sustainable (EIE, 2012). The RE targets are made by MENR based on mentioned reports above and the targets are until 2023 (EIE, 2014). The latest year which shows official energy targets for Turkey is 2030 and this functions also as the climate pledge submitted for the Paris Agreement (COP21) in 2015 (UNFCC, 2015).

Official energy action plans and strategies of Turkey have no further target after 2030 and the IEA (2016) report on Turkey also drew attention to this gap. One of the requirements mentioned by IEA is that Turkey is one of the parties of COP21 and emission reduction targets has to be integrated into the long-term action plan in a cost effective way. While reducing the emissions, it should be traced, monitored and evaluated whether it is successful or not. Also, co-operations with all stakeholders and securing finance resources to implement carbon emission reductions is crucial. The other point is policy should be clarified about RE subsector targets for building trustable long-term investor relations with visibility. Any regulatory barrier will block the renewable investment and will affect the return on investment, thereof the policy should take the decisions without any delay for the investors. In addition to these, policymakers need to be more insistent on developing and investing in the grid system to prepare it for distributing more RE (IEA, 2016g).

Hydropower represents the major share of the installed power capacity in Turkey with 35.4% in 2015 (Fig. 1). However, the major electricity production share is represented by natural gas with 29%, due to higher full load hours than hydropower. All renewable energy generation contributes to 49.2% to the installed capacity by the end of 2015 (TEIAS, 2016b).

Turkey is a natural gas importer country and 99.2% of all consumption is imported, thereof 55.3% from Russia and 16.2% from Iran (EPDK, 2016). This consumption ranks Turkey as a major natural gas consumer in Europe after the United Kingdom, Germany and Italy (BP, 2016). In contrary to the Turkish energy policy, two countries are keeping more than 71% of all natural gas supply.

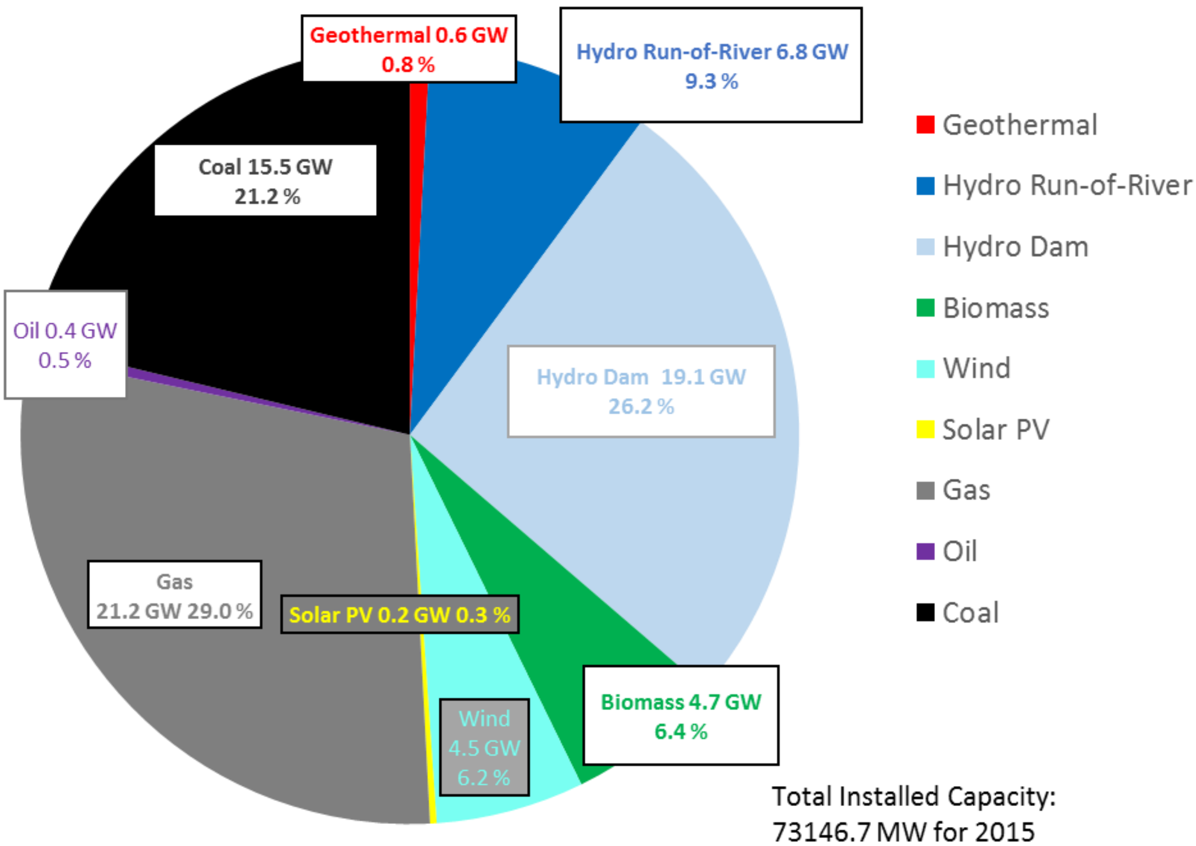


Figure 2-1: Total installed electricity capacity of Turkey by the end of 2015 (TEIAS, 2016b).

The renewable energy (RE) targets of Turkey are set to: 34 GW for hydropower, 20 GW for wind energy, 5 GW solar energy and 600 MW for geothermal energy until 2023 (EIE, 2014). These policies are tools to reach 120 GW of total installed power generation capacity in the year 2023. Accordingly, renewable energy investments are subsidized by the *Renewable Energy Support Mechanism* which is shown in Table 2-1. In addition to this support programme, there are additional support schemes such as discounted energy production license fees or no license permission requirement at all and subcategories about the mentioned technologies that investor can take more subsidy with locally produced goods usage such as wind turbines, solar invertors (TPMISPA, 2014).

Table 2-1: Subsidy rates for renewable energy investments in Turkey 2016 (TPMISPA, 2014). Official renewable energy subsidies are based on USD and payments are done with equal amount of TRL at the end of every reconciliation period.

Renewable Energy Guarantee of Purchase			
Type of Energy	**Feed in Tariff (USD¢/kWh)**	**Max. local production incentive (USD¢/kWh)**	**Maximum possible tariff all included (USD¢/kWh)**
Solar PV	13.3	6.7	20
Concentrating Solar Power	13.3	9.2	22.5
Bioenergy	13.3	5.6	18.9
Geothermal energy	10.5	2.7	13.2
Wind energy	7.3	3.7	11
Hydropower	7.3	2.3	9.6

There is no legislative restriction about the maximum capacity of hydropower which makes the investments charming by a guaranteed purchase. Total feasible hydropower potential of Turkey is 42 GW (Baris et al., 2012; Demirbaş, 2002) and the current installed capacity is 25.8 GW at the end of 2015 (TEIAS, 2016b). Nonetheless, Turkey's water stress will increase and future estimations of the hydropower generation might be affected in a negative way (Sur et al., 2010).

The installed wind energy capacity is approximately 5 GW by the end of 2015 and the future projection of the government is 20 GW. Turkish Wind Energy Potential Atlas (REPA) shows the wind energy potential for all Turkish cities and the potential calculations are based on minimum 6.8 m/s at 50 m height (EIE, 2016). The total wind energy technical potential mentioned in REPA is 114 GW. In addition to this, the REPA shows the economically feasible wind investment amount based on the wind energy potential and economically feasible investment condition for the ministry is a minimum capacity factor of 35% (EIE, 2016). Especially Aegean coast and North West part of Turkey are most feasible locations for wind energy investments as it can be seen from Figure 2-2 and major parts of installed wind plants are in these areas located.

Solar energy has a very large potential in Turkey as shown in Figure 2-2, which ranks Turkey in the top five countries in Europe (Šúri et al., 2007). The average of annual global horizontal irradiation for seven regions is 1311 kWh/ (m2·a) equal to 3.6 kWh/ (m2·day). The best irradiations are in the Southeastern, Mediterranean and East Anatolian regions (EIE, 2012). Solar photovoltaic installed capacity reached 248.8 MW (TEIAS, 2016b) by end of 2015, which is a negligible fraction of the potential in Turkey. In contrast to the deployment of solar PV, the third largest capacity in the world of solar flat panel collectors is installed in Turkey (IEA SHC, 2016). Concentrating solar thermal power is at demonstration level with the Greenway CSP Mersin Tower Plant with 5 MW power (NREL, 2016).

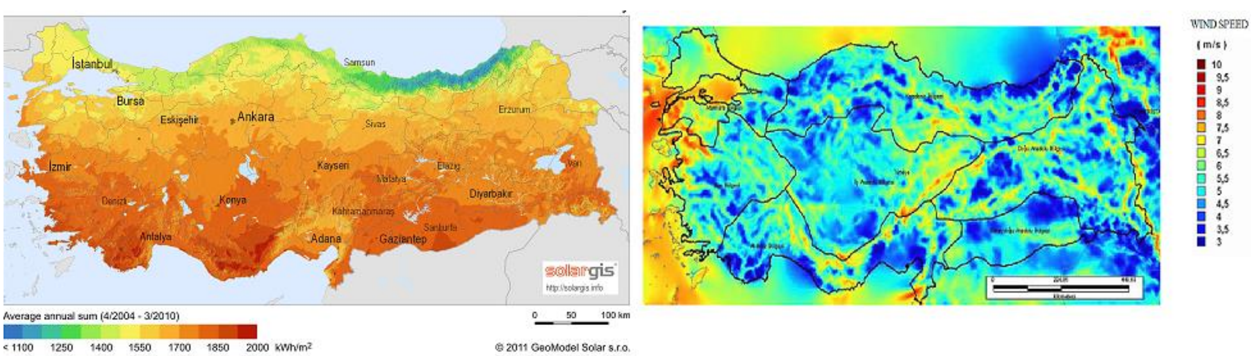


Figure 2-2: Solar horizontal irradiation (left) (Solar GIS, 2016) and average wind speed at 50 m height in Turkey (right) (Caliskan, 2016)

The geothermal energy potential of Turkey is approximately 2.7 GW and the current installed capacity is 623.9 MW that equals to 0.9% of all installed capacity (TEIAS, 2016b). Turkey is one of the few countries with large installed capacities and in near future the capacity is expected to reach 1000 MW (EIE, 2016).

Ideal climatic conditions and high farming yields enable a substantial bioenergy potential. Waste-to-energy has begun in Turkey in the year 1996 and reached an aggregated capacity of about 260

MW by end of 2014 (Farfan and Breyer, 2017). The Energy Ministry of Turkey claims that the total biomass energy potential is 236.2 TWh (MENR, 2016a) and the German Biomass Research Center, DBFZ, claims that it is 61.7 $TWh_{th,a}$, (DBFZ, 2010). The same report, which is very strict in sustainability criteria shows that biomass for solid waste potential is 13.9 $TWh_{th,a}$, for solid biomass 41.6 $TWh_{th,a}$ and for biogas 6.2 $TWh_{th,a}$.

The average consumable water amount is 112 billion m^3 with the ratio of 98 billion m^3 of surface water and 14 billion m^3 underground water (DSI, 2016). According to the World Resources Institute, Turkey is going to become one of the top 30 water stressed countries by 2040 based on surface water projections and climate models (WRI, 2016). United Nations describe the water stress for water supplies below 1700 m^3 of fresh water per person and water scarcity is below 1000 m^3 of fresh water per person (UN, 2006). Turkey has approximately 1500 m^3 usable water resource per person and projections shows that at 2030 Turkey will be between water scarcity and a highly stressed position (DSI, 2016). Private investments are focusing on desalination to supply the demand, especially for industry which needs fresh water for their processes and the government provides supports to implement water efficient technologies in industry, agriculture and household usage (MEU, 2016). Turkey is well suited to use seawater desalination due to its surrounding Black Sea, Mediterranean and Aegean Sea. Accordingly, hydro reservoir investments are increased and subsidized by the government to better utilize the available water resources to a maximum efficiency.

There are two cooperation agreements on nuclear power plants signed by the Turkish government. One is with the Russian Federation for the Mersin-Akkuyu nuclear plant from 2010 (The Official Gazette, 2010) and the other is with the Japanese government from 2015 (The Official Gazette, 2015). These plants are designed for a capacity of 4480 MWe for the Sinop project and 4800 MWe for the Mersin-Akkuyu project. The estimated total capital expenditures are 16.9 b€ for the Sinop plant and 19.2 b€ for the Mersin-Akkuyu plant (IEA, 2016g; WNA, 2016). Power purchasing agreement for Akkuyu nuclear plant is 12.35 USD¢/kWh for 15 years (The Official Gazette, 2010) and for Sinop is not certain but it may be 10.8 USD¢/kWh (The Official Gazzette, 2015). The Russian nuclear energy technology costs about the same as European technology, as documented on several construction sites (OECD, 2010). The levelised cost of electricity (LCOE) for the Turkish nuclear plants have been estimated on 2008 values to be at least 53.8 €/MWh

(Kumbaroglu, 2011). However, nuclear power shows a negative learning curve hence new projects are typically more expensive than the older ones (Grubler, 2010). Furthermore, past experiences showed that nuclear power plant projects have more than 100% overruns of budget and time (Sovacool et al., 2014). Furthermore, German Federal Constitutional Court decision about the accelerated nuclear power phase-out in Germany is quite important for future nuclear investments. The court emphasised in its decision that phasing out of nuclear plants could be even accelerated for the common welfare, to protect life and health of the population, to protect the environment and future generations (The Federal Constitutional Court of Germany, 2016). A more detailed discussion on the sustainability shortcomings and associated risks of nuclear energy can be found in Child and Breyer (2016).

Grid parity value is highly related with solar irradiation and electricity prices. If solar irradiation and electricity price are high in a region, reaching grid-parity is faster compare to others (Breyer and Gerlach, 2013). Turkey is in a high solar irradiation and average electricity price range, and therefore Turkey is one of the first grid parity market segments with Germany, Japan, Mexico and the United Kingdom. Turkey reached residential grid-parity at 2016, commercial grid-parity at 2015 and industrial grid-parity at 2014 (Gerlach et al., 2014). The purpose of this study is to design a 100% renewable energy transition scenario for Turkey in the time period of 2015 to 2050 and to put a special emphasis on the respective economics. It is investigated whether this would be beneficial for the Turkish energy policy, an increased energy supply security and less negative environmental impact. In addition, seawater desalination demand and the industrial gas demand is integrated into the energy scenario for an improved understanding how it will affect the cost structure of the energy system and water sector. The study aims to show how an optimum transition pathway can meet Turkey's electricity, water and gas demand in the mid- to long-term by a 100% renewable energy system.

2-2. Methodology

Typically, market or regulatory models are used for energy scenarios. The regulatory model is used for this study, which does not take short-term market considerations into account, but long-term cost optimization (Bogdanov and Breyer, 2016).

The used LUT energy system model is designed for analysing the energy transition. Time resolution of the model is hourly for most data, such as wind speed and solar irradiation and load demand and daily for precipitation. The model is based on linear optimization method with interior point optimization and a spatial resolution of 0.45^0 x 0.45^0. The energy model can be used for describing local, national or global energy systems. The LUT energy system model is composed of all relevant power generation and storage technologies and respective installed capacities and different operation modes of these technologies which are used to supply the electricity demand of the whole system as described in more detail in Bogdanov and Breyer (2016). For this study it is also used the additional development of the model to simulate an energy transition for a given period, as described in Caldera et al. (2016). New in this study for Turkey is the energy transition modelling for a multi-node regional energy system, in the case of Turkey seven different geographical regions, and the inclusion of the non-energetic industrial gas demand.

Main methodological improvements are listed below.

- Energy transition for a 100% renewable energy system is applied for the period 2015 to 2050 in 5 year steps, whereas the single years are simulated in full hourly resolution for an entire year. The power plant capacity at end of 2014 are used for the year 2015 and used till they reach their individual year of decommissioning at the end of their technical lifetime according to Farfan and Breyer (2017). New investments in coal are not allowed for avoiding stranded assets according to the COP21 targets.
- Desalination demand for the period 2015 to 2050 is integrated into the energy system. The demand is determined for the regions applied in the model. Seawater reverse osmosis (SWRO) desalination plants are used due to their attractive economics. Currently used multi stage flash (MSF) desalination and multi effect distillation (MED) capacities are phased out according to their individual lifetime.
- No power line interconnection is taken into account for Turkey and neighbouring countries. All electricity demand is supplied by domestic capacities, however electricity transmission among the Turkish regions is possible without limitation.

2-2.1 Model Overview

The aim of the study is the analysis of the energy transition pathway towards 100% renewable energy for Turkey and how the integration of large SWRO desalination capacities and industrial gas demand affects the energy system. The aim of this system optimization is to minimise the total annualized energy system cost. The energy system also contains distributed self-consumption of residential, commercial and industrial end-users (prosumers) by installing of rooftop PV and battery systems, in case it is financially beneficial. The model is described in much detail in Bogdanov and Breyer (2016).

The three main technology classes of the energy model are as follows:

- Technologies for the conversion of renewable energy resources into electricity
- Energy storage technologies
- Energy sector bridging technologies to provide more flexibility to the complete energy system

In this study, Turkey is structured into seven geographical regions: Marmara, Aegean, Black Sea, East, Southeast, Central Anatolia and Mediterranean. All the regions' electricity demand for the period 2015 to 2050 were used on future projections while distributing the values on different geographical regions as presented in Table 2-2.

Table 2-2: Future estimation of electricity consumption of Turkey by regions

	Electricity demand of Turkey by regions (TWh)							
Region	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Mediterranean	38	53	59	65	72	79	84	90
Marmara	112	157	175	193	215	237	252	268
Aegean	42	58	65	71	79	87	93	99
Black Sea	20	27	31	34	38	41	44	47
Central Anatolia	33	46	52	57	63	70	74	79
Southeast Anatolia	15	22	24	26	29	32	35	37
East Anatolia	9	13	14	15	17	19	20	21
Total	**269**	**376**	**419**	**462**	**514**	**565**	**603**	**641**

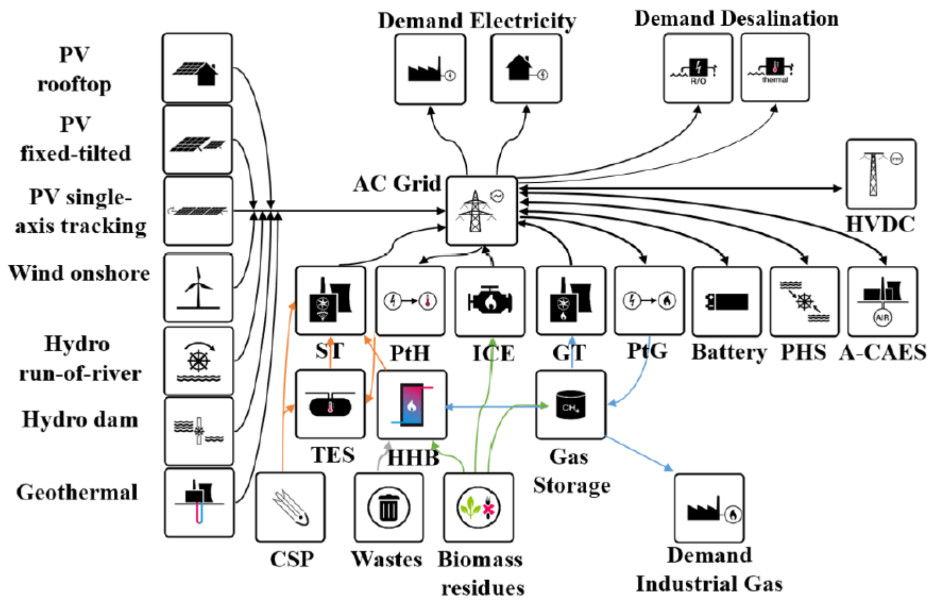


Figure 2-3: LUT Energy System model block diagram for Turkey

One of the key feature of the model is the inclusion of different kinds of flexibility for the optimised solution. The hourly load demand in the power scenario has to be met by the model, however the matching of the non-energetic industrial gas demand, desalination demand and excess generation optimisation is done within the model autonomously, in addition to the utilisation and operation of the storage options. This feature gives the model flexibility to use excess capacity as well as several storage options, which different characteristics (Böttger et al., 2014). In addition to these features, generation losses and electricity curtailment can be foreseen to be converted into heat for residential and industrial needs by bridging technologies, such as power-to-heat and heat storage (Bogdanov and Breyer, 2016).

2-2.2 Power Plant Capacities - Technical and Financial Assumptions

Total electricity consumption of Turkey is 268.9 TWh in the year 2015 and it is assumed that the average consumption of the European Union per capita of 6036 kWh (World Bank, 2016) is achieved before 2050 as presented in Table 2-3.

The model is initialised for the energy transition with the power plant structure of the year 2015 in regard to capacities, age, technical lifetimes according to Farfan and Breyer (2017). Cost assumptions of all used technologies are part of the energy transition pathway to achieve a 100%

renewable energy system by 2050. It replaces the old energy plants according to lifetime expiring by sustainable renewable energy plants.

Table 2-3: Population, total electricity demand and electricity consumption per capita of Turkey. Data for population is taken from UN (2015).

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Population (Million)	78.7	81.7	84.7	87.7	89.7	91.8	93.8	95.8
Total Electricity Demand (TWh)	269	376	419	462	514	565	603	641
Electricity consumption per capita (kWh)	3418	4604	4947	5267	5724	6161	6433	6693

The capital expenditures (capex) and operational expenditures (opex), lifetime and efficiency variations of all the energy system components for integrated scenario are provided in the Appendix (Table 1). The RE technologies have different learning curve assumptions and all the capex assumptions for the RE technologies applied in this research are shown in Caldera et al. (2016) and they are presented in the Appendix-1 (Figure 1). The capex and opex mainly refers to a kW of electrical power. On water electrolysis term, capex and opex refer to kW of hydrogen thermal combustion energy, and for CO_2 scrubbing, methanation and gas storage to a kW of methane thermal combustion energy. The financial assumptions for storage systems refer to a kWh of stored electricity, and gas storage refers to a thermal kWh of methane at the lower heating value. Weighted average cost of capital (WACC) is set to 7% for all the years in the model. The technical assumptions concerning power to energy ratios for storage technologies, and efficiency numbers for generation and storage technologies are provided in the Appendix (Table 2-2).

The non-energetic industrial gas demand is calculated based on Energy [R]evolution scenario of Greenpeace (Teske et al., 2015). Non-energetic industrial gas demand is calculated by using the data of Energy [R]evolution Greenpeace scenario (Teske et al., 2015). The energetic consumption of natural gas is excluded, i.e. demand for heat, electricity and transportation, to reach the non-energetic use of natural gas. The regional division is based on Turkish Statistical Institute’s values of the years 2004-2011 Regional Gross Value shows the total values of all goods and services produced by local units less the total inputs used for these goods or services in domestic production activities in a specific time and period (TUIK, 2014) and presented in Appendix (Table 2-3) for Turkey.

Biomass potential data are taken from MENR Biomass Energy Potential Atlas (BEPA) that divides the data into four main waste categories: animal, agricultural, municipal and forestry waste (MENR, 2016) and the annual energy potential of each category is shown in Table 2-4. However, BEPA does not explain how the data was collected and calculated. Thus, technical and economical feasible bioenergy capacity is taken from German Biomass Research Center, DBFZ, database which explains the data collection in the report with details and it's bioenergy potential of Turkey is taken as 61.9 TWh (DBFZ, 2009).

Table 2-4: Biomass potential of Turkey, (MENR, 2016)

Animal Waste [TWh_{th}/a]	**Agricultural [TWh_{th}/a]**	**Municipal [TWh_{th}/a]**	**Forestry and Wood [TWh_{th}/a]**
15.4	185.4	25.4	9.95

Feed-in full load hours (FLH) for solar PV, solar thermal power plants (CSP) and wind energy for Turkey are computed based on 0.45° × 0.45° spatially resolved data as described in Bogdanov and Breyer (2016). FLH averages for CSP, PV fixed tilted, PV single-axis tracking and wind power plants in Turkey are presented in Table 2-5, whereas the regional breakdown can be found in Appendix (Table 2-4).

Table 2-5: Average full load hours (FLH) for PV fixed tilted, PV single-axis tracking, CSP and wind onshore power plants in Turkey

PV fixed tilted FLH	**PV single-axis FLH**	**CSP (Solar Field) FLH**	**Wind onshore FLH**
1580	2030	1791	2722

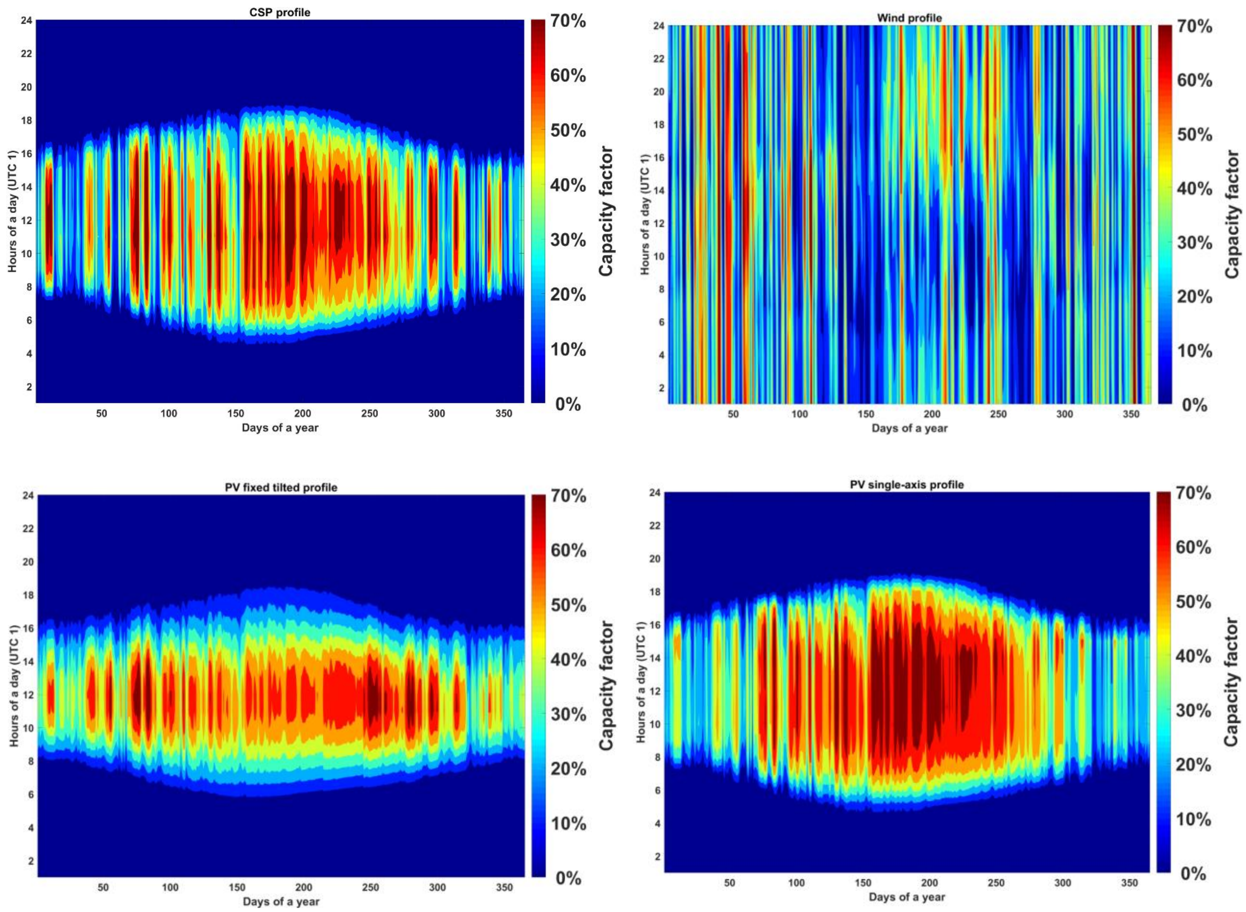


Figure 2-4: Top Left: Aggregated feed in profile for CSP solar field in Turkey
Top Right: Aggregated feed in profile for wind power plant in Turkey
Bottom Left: Aggregated feed in profile for PV single-axis tracking in Turkey
Bottom Right: Aggregated feed in profile for PV fixed tilted PV in Turkey

The model uses a range for installable capacities within upper and lower limits. Lower limits of RE capacities are the values of the installed capacity values in the year 2015. All the lower limit values are shown in Table 2-6.

Table 2-6: Installation RE capacities by end of 2015 and sub-divided to the seven regions in Turkey, applied as lower limits in the model. Abbreviation: Run-of-River (RoR)

	MW			
Regions	**PV fixed tilted**	**Wind energy**	**Hydro RoR**	**Hydro Dams**
Mediterranean	70.7	541	1477.5	5088
Marmara	4.4	1731.6	126.5	326.2
Aegean	34.4	1303.5	117.2	264.2

Black Sea	2.1	60	2175.1	3466.2
Central Anatolia	115.3	518.9	1448.3	5467.1
Southeast Anatolia	21.8	27.5	967.3	4290.8
East Anatolia	0.0	0	1316.2	2069.9
Total	248.7	4182.5	7628.1	20972.4

Upper limits levels are calculated based on different assumptions which can be found in Bogdanov and Breyer (2016). The results for upper limit are shown in Table 2-7. All other energy technologies are not limited to any value but bioenergy and geothermal have their own specific assumptions based on the country's natural potential. Geothermal capacity calculations and assumptions are discussed by Aghahosseini et al. (2016) and the capacity is taken as 1438 GW for Turkey with the same approach.

Table 2-7: Upper limits for installation capacity in Turkey by regions (solar CSP unit is GW_{th} and for others GW_{el})

Regions	**Area [1000 km^2]**	**Solar PV**	**Solar CSP**	**Wind energy**	**Hydro RoR**	**Hydro Dams**
Mediterranean	116.1	406.6	813.1	30.4	2.2	7.6
Marmara	63.6	327.8	655.6	24.5	0.2	0.5
Aegean	88.0	406.1	812.3	30.3	0.2	0.4
Black Sea	135.6	522.8	1045.5	39	3.3	5.2
Central Anatolia	154.1	848.6	1697.3	63.4	2.2	8.2
Southeast Anatolia	55.9	338.4	676.7	25.3	1.5	6.4
East Anatolia	156.3	675.9	1351.9	50.5	2	3.1
Total	769.6	3526.2	7052.4	263.4	11.6	31.4

2.3 Seawater Desalination Capacities - Technical and Financial Assumptions

Three kinds of desalination technologies are currently online in Turkey and these are Multi-Stage Flash Distillation (MSF) and Multi-effect distillation (MED) as thermal technologies and seawater reverse osmosis (SWRO) as membrane technology. The current desalination capacity is characterised by a SWRO dominance and just 10% of it is MED. SWRO desalination technology is the only allowed technology in the model after 2015 due to its energy efficiency advantages and lower cost (Caldera et al., 2016b). Table 2-8 shows all online seawater desalination facility capacities in Turkish in the regional breakdown.

Table 2-8: Active capacities of seawater desalination in Turkey by 2015

	Active Total Capacity (m^3/day)			Active Total Capacity (m^3/day)
Regions	**MSF**	**SWRO**	**MED**	**Total Capacity by Region**
Mediterranean	0	43,000	5250	48,250
Marmara	1000	116,782	3606	121,388
Aegean	0	22706	0	22,706
Black Sea	0	92,072	0	92,072
Central Anatolia	0	28,190	0	28,190
Southeast Anatolia	0	0	0	0
East Anatolia	0	0	0	0
Total	**1000**	**302,750**	**8856**	**312,606**

Required desalination capacity for the time period from 2015 to 2050 is calculated by using the methodology described in Caldera et al. (2016b). 2015 and future water demand for Turkey in the regional breakdown is shown in Table 2-9. The approach is based on an optimistic future scenario for water stress and water demand in Turkey.

Technical and financial parameters of seawater desalination technologies are shown in the Appendix (Table 12). Estimates for the required desalination capacity, water demand, desalination technologies and their energy consumptions and related financial assumptions for 2015 to 2050 can be found in Caldera et al. (2016b).

Table 2-9: Estimated water desalination demand for Turkey.

	Million m^3/day							
Regions	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Mediterranean	1.75	2.48	3.38	4.37	5.37	6.36	7.4	8.42
Marmara	4.16	5.9	8.06	10.42	12.79	15.15	17.62	20.07
Aegean	1.77	2.51	3.42	4.42	5.43	6.43	7.48	8.52
Black Sea	1.34	1.9	2.6	3.35	4.11	4.88	5.67	6.46
Central Anatolia	2.14	3.04	4.15	5.36	6.58	7.79	9.06	10.32
Southeast Anatolia	1.45	2.06	2.82	3.64	4.47	5.3	6.16	7.01
East Anatolia	1.04	1.48	2.02	2.62	3.21	3.8	4.43	5.04
Total Desalination Demand	**13.65**	**19.37**	**26.46**	**34.19**	**41.95**	**49.72**	**57.82**	**65.85**
Total Water Demand	**129.6**	**146.4**	**158.4**	**175.2**	**184.8**	**199.2**	**216.0**	**230.4**

2-2.4 Definition of Scenarios

Two scenarios are applied by the model to simulate the energy transition in Turkey from the today's fossil fuel dominated system to a 100% renewable energy system in the year 2050:

1. Power sector scenario
   This scenario shows the optimized pathway for Turkey's power sector transition, assuming no exchange with other energy sectors. The seven regions of Turkey are modelled separately, however, exchange of electricity by power lines is allowed.
2. Sector integrated scenario
   The seawater desalination demand and non-energetic industrial gas demand is added to the energy system and the energy transition is modelled in an integrated way for Turkey. The desalination plants and the non-energetic industrial gas demand, integrated into the power system, will allow for an optimal use of the hourly energy produced by the RE power plants. The energy produced by the RE power plants can be stored as desalinated water and in form of methane in times of more supply than power demand and at times of low energy production, the stored water and methane can be used instead of base load generation. Thus, the desalination plants and power-to-gas (PtG) plants offer additional flexibility to the energy system.

The model determines the power capacities required for the scenarios and the two scenarios are compared to understand the impacts of the integrated desalination and PtG plants on the power scenario.

Technical and financial results of the model for the scenarios are presented in the following results section.

2-3 Results

2-3.1. Power Sector Scenario

All relevant renewable energy resources are used to reach a 100% renewable energy target for Turkey. Figure 2-5 shows the installed capacities for the period of 2015 – 2050 in 5 years steps.

As shown in Figure 2-1, coal contributed with a capacity share of 20% to the electricity demand of Turkey in 2015. The model started to substitute coal power plants from the system, in the beginning due to reaching the end of plants' lifetime. The coal plants are completely phased out of the system by 2050 and the energy system achieves 100% renewable energy supply in that year. Existing open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT) are using synthetic natural gas (SNG) as fuel for electricity generation in times of power shortage. The SNG is produced in times of excess solar and wind electricity by using PtG technology, in form of electrolyser and methanation plants.

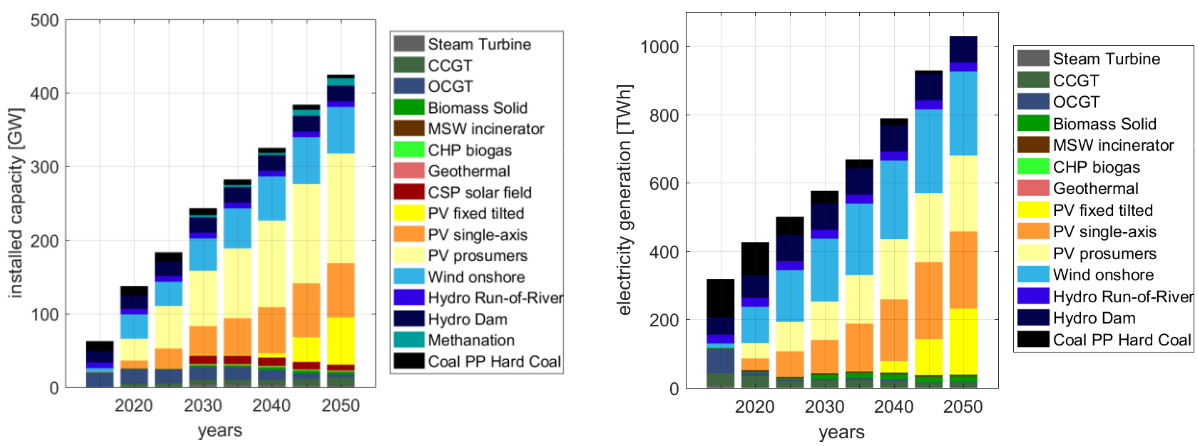


Figure 2-5: Power sector scenario installed capacities (left) and generated energy (right) by technology from 2015 to 2050

In the year 2050, total installed capacity of all plants is about 405 GW and the majority of the capacity are solar and wind plants of 350 GW. The solar PV capacity is comprised by PV prosumer systems (149 GW), fixed-titled power plants (64 GW) and single-axis tracking power plants (74 GW), leading to a total solar PV installed capacity of 287 GW. The highest total PV installed capacities by descending order are at Marmara region (97.3 GW) and Aegean region (61 GW). Most of the PV prosumer capacity is installed in the Marmara region (approximately 67 GW), and the second highest capacity is in the Aegean region with 21.6 GW. PV prosumers are categorised as residential, commercial and industrial. Industrial prosumers have 54%, residential ones have 29.7 % and commercial prosumers have 16.3% of all prosumer installed capacity in 2050. The second solar technology, CSP, has 7.75 GW of installed capacity. The wind energy follows with a capacity of 63 GW as the second largest contributor in power capacities. Marmara and Aegean regions are home to 72% of total installed wind capacity in Turkey which matches the wind energy potential map shown in Figure 2-2. For hydropower, the model shows that Turkey's capacity will be 28.8 GW which reaches about 60% of the hydropower potential. The reason that Turkey is not using all its hydropower potential is a consequence of a LCOE being higher than other RE technologies which makes it less competitive. The total capacity of geothermal energy is slightly decreasing within time and the capacity is reaching 648 MW in 2050 from 682 MW in 2015. Biomass, waste and biogas power plant capacity is increasing slightly within the same period. Biomass capacity reaches 2.8 GW, waste-to-energy plant capacity reaches 0.6 GW and biogas power plant capacity reaches 1.29 GW. Based on the power scenario, bioenergy installed capacity in 2050 is about 10 times higher than in 2015.

The model determines the optimum full load hours and power plant capacities. FLH of the different power plants are presented in Figure 2-6. Solar PV single-axis tracking, PV fixed tilted, concentrated solar power (CSP) and the wind onshore full load hours are assumed to be nearly constant throughout the transition period, and have values of about 2070, 1580, 1870 (solar field) and 2730, respectively. The Mediterranean region has the highest FLH of PV, Aegean has the highest FLH of CSP, Marmara and Aegean regions have highest FLH for wind power plants. Hydro dams and hydro river-of-river power plants have similar FLH of about 3345 and 3410, respectively. Coal power plants show a steep decline in FLH from about 7000-8000 in the early years of the transition to a level of 2000-3000 from 2025 to 2040 and finally a phase-out in the year 2050. New coal-fired power plants are not allowed to be built due to CO_2emission constraints and to avoid stranded assets. However, solar PV and wind power plants become very fast competitive to coal-fired power plants.

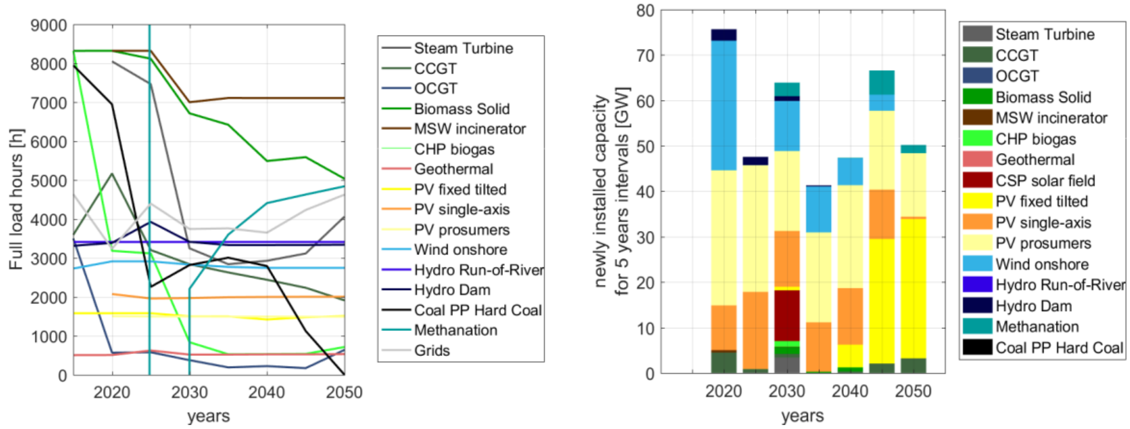


Figure 2-6: FLH variation of the different power plants (left) and new capacity installations of the different technologies (right) in the years 2015 to 2050.

The new installed capacities are shown in Figure 2-6 in a resolution of 5-years steps. RE capacities are needed to cover the increased energy demand and to substitute phased-out fossil fuel plants. The energy system gets increasingly dominated by RE capacities, since wind power, PV prosumers and PV power plants start to contribute together with hydropower from the 2020s onwards the majority in electricity supply. The energy mix is diversified among the different technologies. Between 2020 and 2050 PV prosumers lead the RE installations, whereas the wind onshore installations grow substantially in the early 2020s and start to decline in the following 5-years periods. Hydro dams increase their installed capacity, but at a rather low rate. PV power plants start to grow from the very beginning and show an accelerated growth in the 2040s.

Figure 2-7 shows the required storage capacity for the period 2015-2050. The seasonal gas storage dominates in capacity (Figure 2-7). A-CAES and TES storage have substantial installations around 2030. Batteries show a constant growth, whereas prosumer batteries contribute more in 2020-2035 to the growth and utility-scale batteries contribute more from 2040 onwards to the total growth of battery capacities. The increasing cost competitiveness of solar PV and batteries is the driver for that growth. By 2050, the total output of the batteries is 147 TWh_{el} that is equivalent to 23% of the electricity demand.

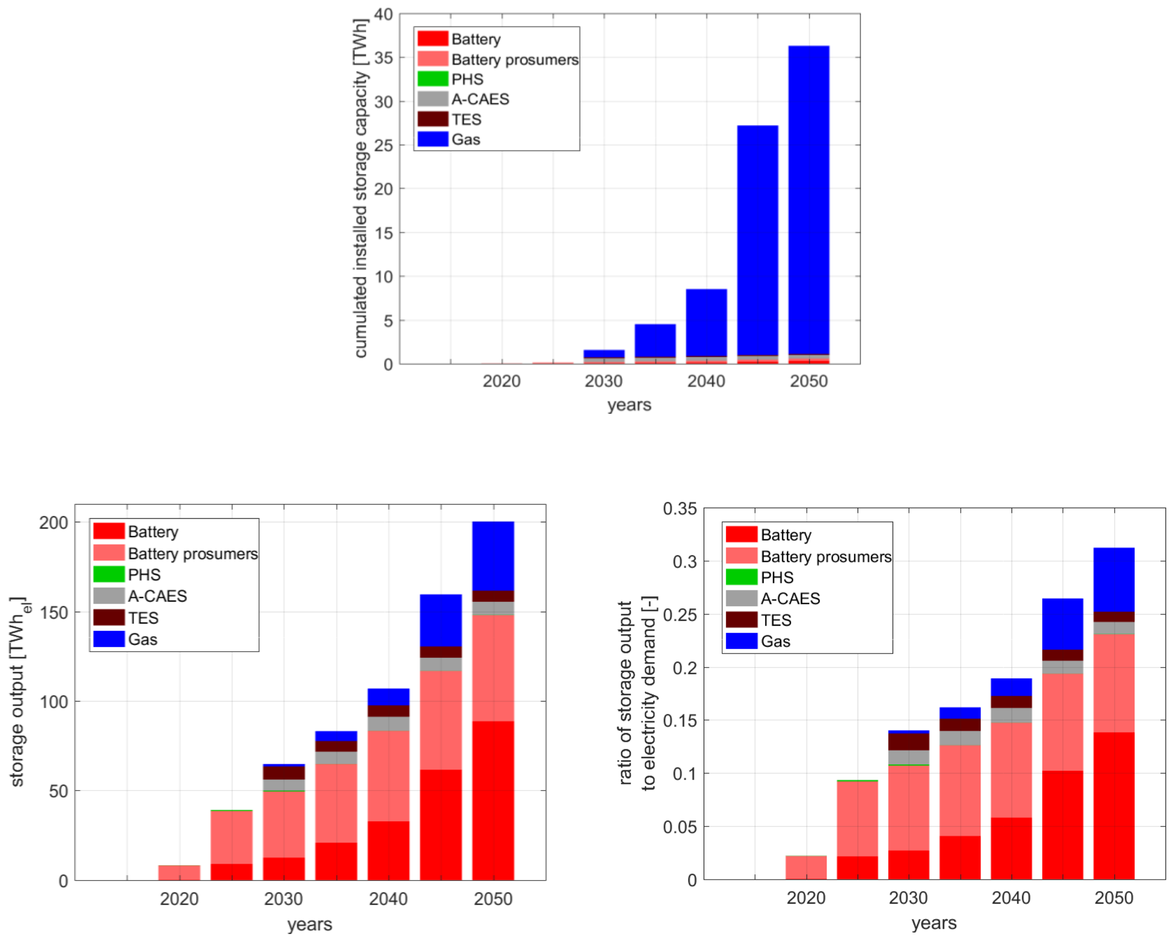


Figure 2-7: Additional storage capacity required from 2015 to 2050 (top), storage output to balance generation and demand absolute (bottom left) and relative (bottom right) from 2015 to 2050.

Figure 2-8 (top, left) shows the contribution of different fundamental components to the total energy system LCOE from 2015 to 2050. In the beginning the total system cost are mainly based on the cost of the power plants plus the respective fuel cost. The fuel cost start to become negligible from 2025 onwards, which marks also the beginning of a higher allocated cost fraction of the entire system to storage. Cost for curtailed electricity starts in the early 2030s. At the end of the energy transition period the total energy system cost are more than 30% for energy storage, 60% for the power generation technologies and the remaining smaller parts equally for power transmission among the 7 modelled regions in Turkey and cost of curtailment (Figure 2-8 bottom, left). The total power system cost remain rather stable throughout the entire energy transition period (Figure

2-8 top, left), despite of the substantial investments, with a slight trend of cost decline at the end of the transition period. The largest share in the total system cost is contributed by all types of solar PV and wind energy, followed by batteries and hydropower, as shown in Figure 2-8 (top, right). Fossil fuel cost and therefore CO_2 emission cost decreases in the transition and disappear at the end. The change of the cost structure is illustrated in Figure 2-8 (bottom, right). The fuel cost share of 30% from the beginning is reduced to a rather low fraction of less than 5% within 10 years. The capex share represents always the largest cost fraction, growing from a 40% contribution in 2015 to about 70% within about 10 years and then growing very slowly until 2050

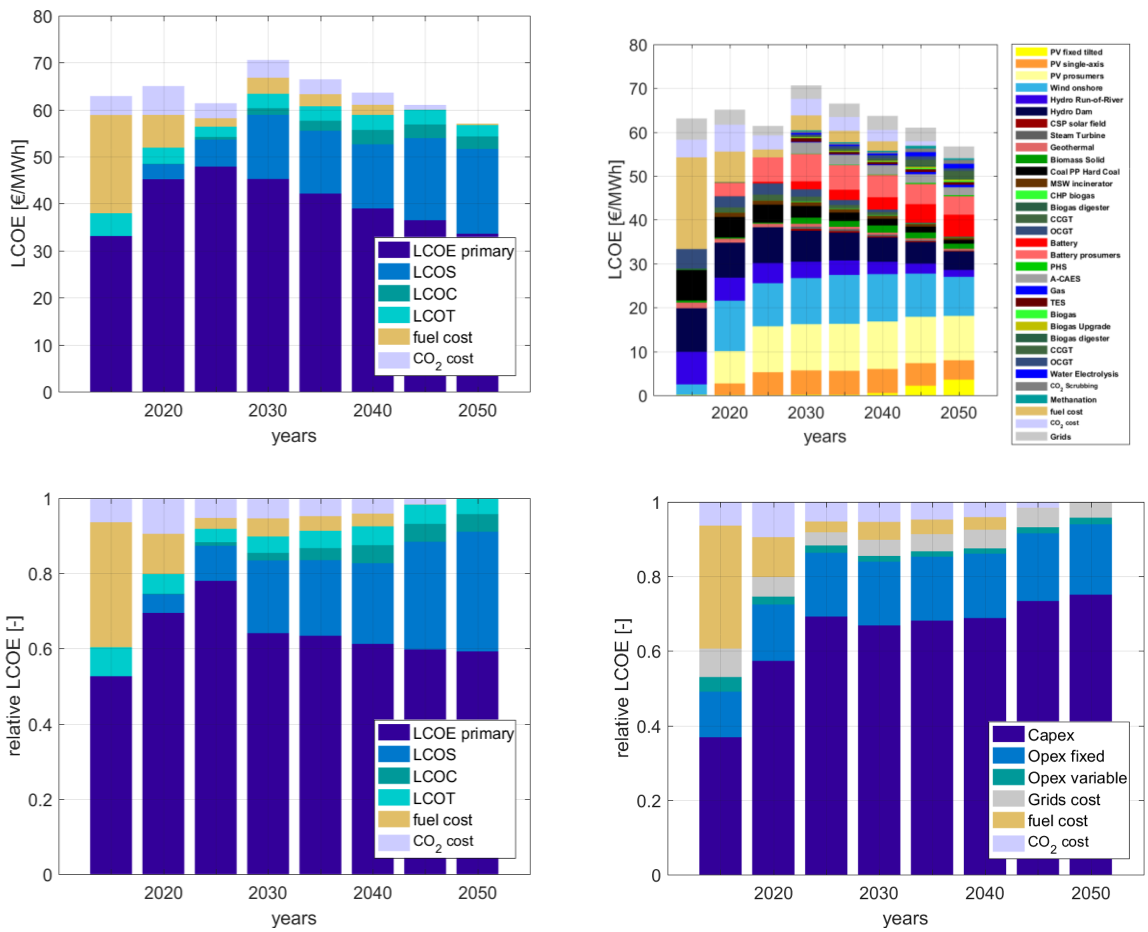


Figure 2-8: Contribution of different components to the total LCOE from 2015 to 2050 (top left), detailed contribution of components to the total LCOE from 2015 to 2050 (top right), Relative contribution of different system (bottom left) and financial (bottom right) components to the total LCOE from 2015 to 2050

CO_2 emissions are illustrated in Figure 2-9 in absolute numbers and relative to the electricity generation. The emissions decrease substantially within 10 years from about 120 Mt_{CO2}/a to about 25 Mt_{CO2}/a and then in the late 2040s to zero. CO_2 emissions of the coal power plants are substituted first by RE generation and in a second step the natural gas related emissions are also substituted by RE generation, mainly solar PV and wind energy.

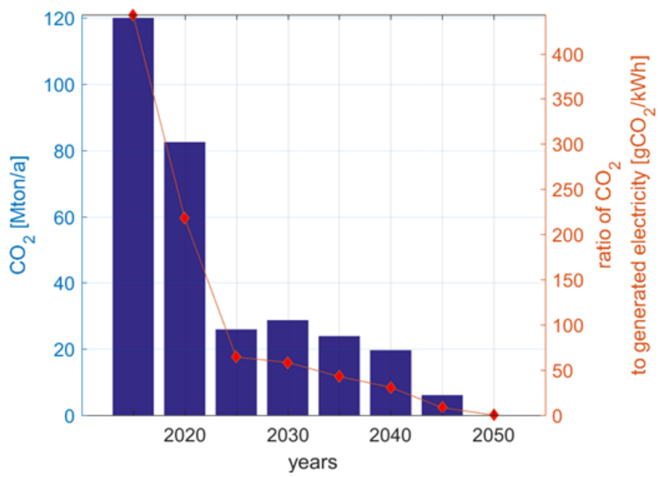


Figure 2-9: Annual CO_2 emissions in Mton (bars) and specific emissions (line) throughout the energy transition.

Capex of different technologies contributions is presented in Figure 2-10 until 2050 by 5-year steps. Major contributors are PV and wind onshore capex, with varying amounts for wind. PV technologies show more stable capex compared to other technologies and grid costs are relatively low, showing a stable capex requirement, since a growing energy transmission need requires more respective infrastructure. The total capex show a decreasing trend, however different technologies may require more capex in time. During the transition period, capex shares are mainly for solar PV, wind power, battery and grid investments.

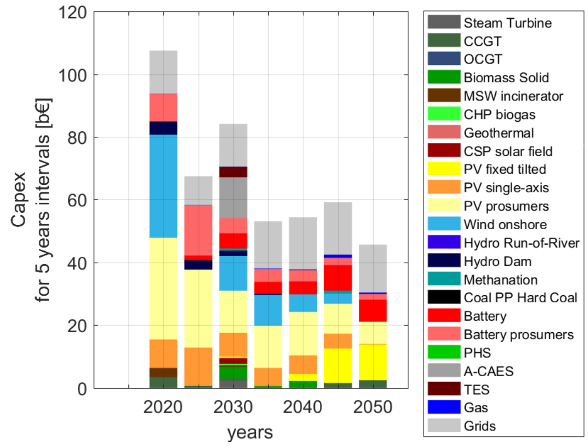


Figure 2-10: Total capital expenditures for all energy technologies required in the integrated scenario

Electricity transmission in the grid system makes the highest utilisation rates between 7:00 and 17:00 in the winter season as it is presented in Figure 2-11. While the weather conditions are changing, grid utilization starts dropping during the day but the peak points are now nearly same. Evening and night (17:00-05:00) demand has smooth changes while the weather changes. Highest evening and night demands are in cold months, winter months and after the second half of autumn. During spring and summer time, transmission rate drops nearly zero, especially in summer months and August reaches nearly zero during the day.

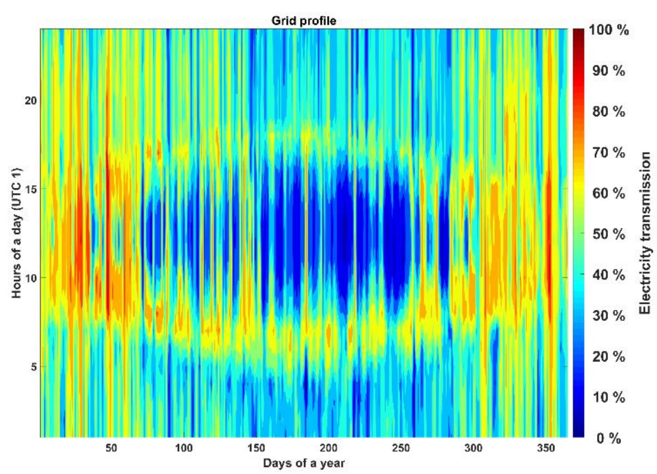


Figure 2-11: Grid utilization of the power sector scenario for 2050

Figure 2-12 present the hourly data for an exemplarily week for Mediterranean region that has the highest potential of solar power. It had been assigned 63.9 GW of solar PV (optimally tilted, single-axis and all prosumers included) and 0.57 GW of wind energy to the Mediterranean region. Solar PV charges the prosumer and system batteries during the daytime when it is the most effective time for it. After the sun loses its power, batteries discharge the surplus energy from the daytime. For this specific region, it can be seen that solar PV single-axis tracking, optimally fixed titled and prosumers represent the majority of the energy flow followed by hydropower, which is mainly dispatched during hours of no or little sun shine when it can provide the highest value to the system. In hours of very low sun shine some gas turbine capacities are used or neighbouring regions support with electricity which is imported. The desalination demand is covered independently of the resource availability, which is the least cost solution for the entire energy system due to the high relative capex of desalination plants (Caldera et al., 2017).

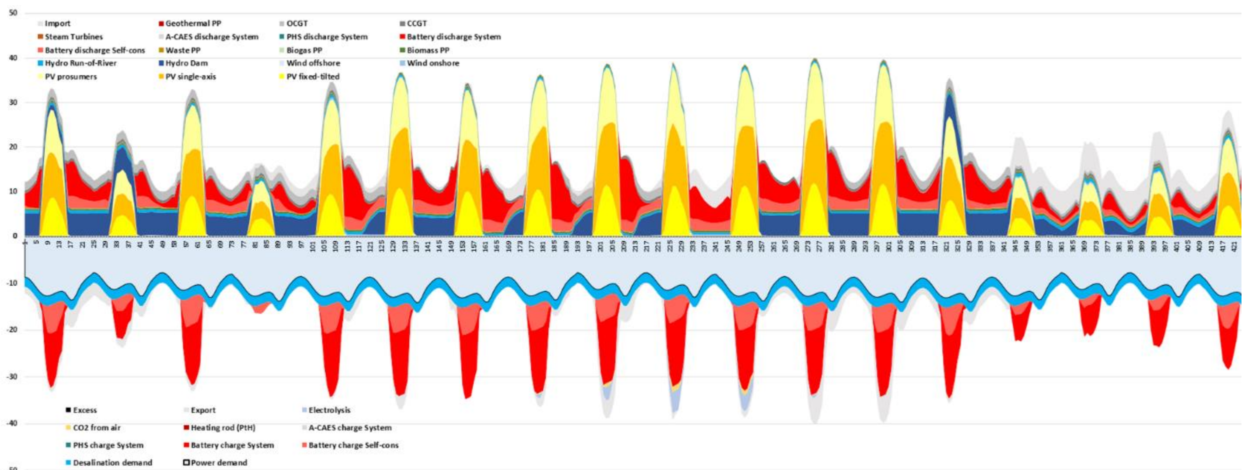


Figure 2-12: Electricity generation and demand profile in full hourly resolution for Mediterranean region in 2050

The energy flow diagram for Turkey for the integrated scenario is shown in Figure 2-13. It represents the RE sources, the storage technologies, transmission grids, total electricity demand by the power scenario, desalination and industrial gas. The difference between primary electricity generation and final electricity demand gives the result of generated usable heat and system losses. The losses occur in curtailed electricity, treatment during biomass processes, biogas and waste-to-energy power plants, charge and discharge losses of storage facilities, electrolysers and methanation processes.

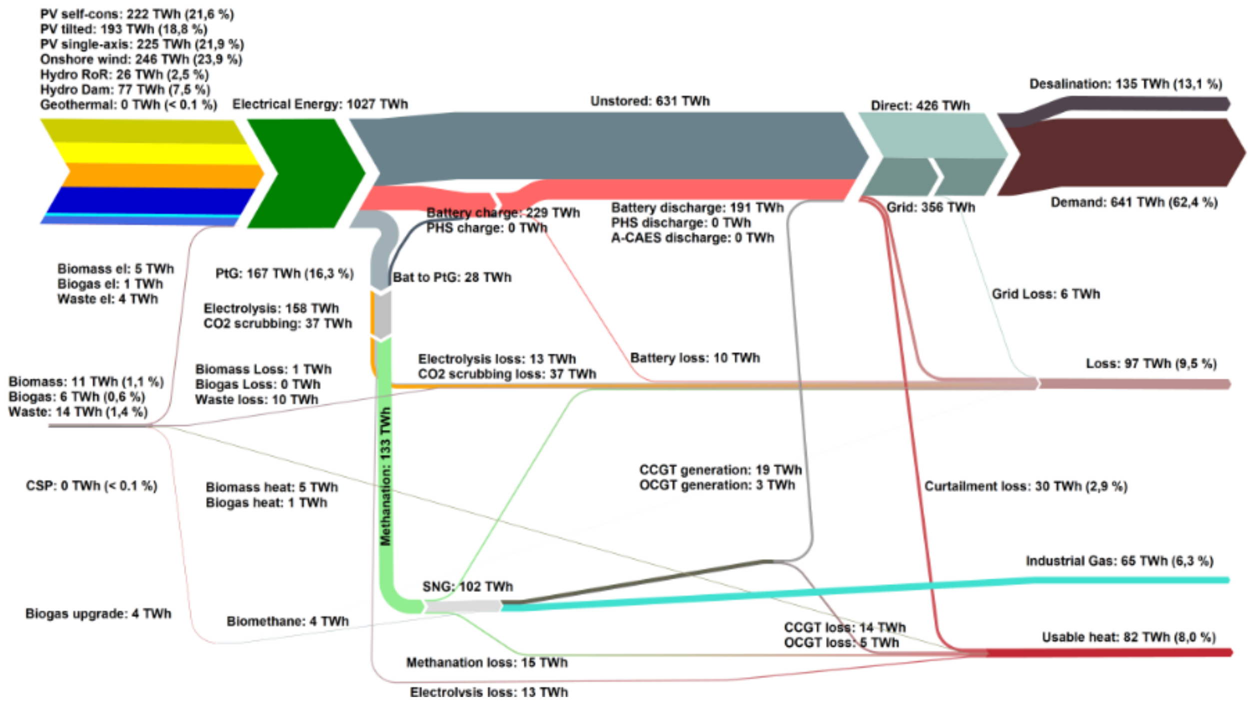


Figure 2-13: System energy flow diagram for the integrated scenario for Turkey in 2050.

3.2. Integrated Scenario – Industrial Gas Demand and Desalination Sector

The total water demand in Turkey is met by renewable water sources and in the beginning non-renewable groundwater sources, which makes it necessary that an increasing share of the water demand has to be covered by seawater desalination (Caldera et al., 2016). Seawater reverse osmosis (SWRO) plants are energy and cost efficient and therefore applied for the seawater desalination demand in Turkey. In 2015, the water demand is 47.6 billion m^3 as presented in Figure 2-14 and the installed desalination capacity meets 10.4% of this demand. The initial desalination rate is increased to 28% in 2050. The Black Sea region requires the highest relative desalination share. The highest absolute demand for desalination arises in the Marmara region due to its higher population, more widespread industry and commercial areas. It should be mentioned that the Marmara region has the lowest water cost for the whole scenario. In contrast to the water cost, the demand volume of Marmara and Middle Anatolia region shows the highest total requires capex compare to other regions. The total electricity demand of the SWRO plants and the respective water pumping equals to 3.8% of all electricity generation in the year 2015 and 14% in 2050.

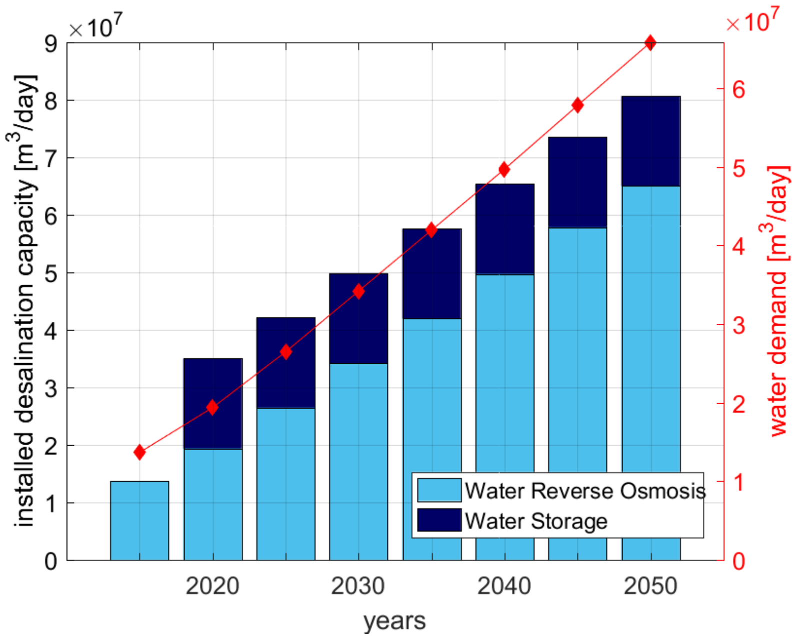


Figure 2-14: Water desalination capacities for covering Turkey's total water demand from 2015 to 2050

Within the years from 2015 to 2050, SWRO efficiency increases from 4.1 kWh/m^3 to 2.6 kWh/m^3, whereas the LCOE in the integrated scenario decreases from 73 €/MWh to 51 €/MWh. Levelised cost of water (LCOW) is strongly dependent on both the LCOE and the efficiency (Caldera et al., 2016) and it decreases from 0.73 €/m^3 to 0.29 €/m^3 in the transition period. Water storage is also increasing proportionally while SWRO desalination capacity is increased. The regions with the furthest distances from the sea and the highest difference in altitude have the highest the water costs, such as Middle Anatolia (0.56 €/m^3, South East Anatolia (0.59 €/m^3 and East Anatolia (0.69 €/m^3). However, the average LCOW in 2050 is about half compared to 2015. The reason of the reduction in the cost is related to the LCOE reduction, SWRO desalination efficiency increase and capex decrease.

Figure 2-15 shows the variation in capex and annual fixed and variable opex of desalination capacities. The fixed opex value increases while the desalination capacities are growing. The fixed opex exclude the electricity consumption of the desalination plants and water transportation system

(Caldera et al., 2016). The variable cost of desalination consists of electricity cost and shown in Figure 2-15 (bottom left) and the value increases also with the desalination capacity growth.

The LCOW of the final system decreases from 0.92 €/m^3 to 0.46 €/m^3. The main reason for the decline in the cost is phasing out of fossil fuel power plants and therefore decreased electricity cost and in addition to these, increased efficiency of SWRO desalination plants in the future (Caldera et al., 2016)

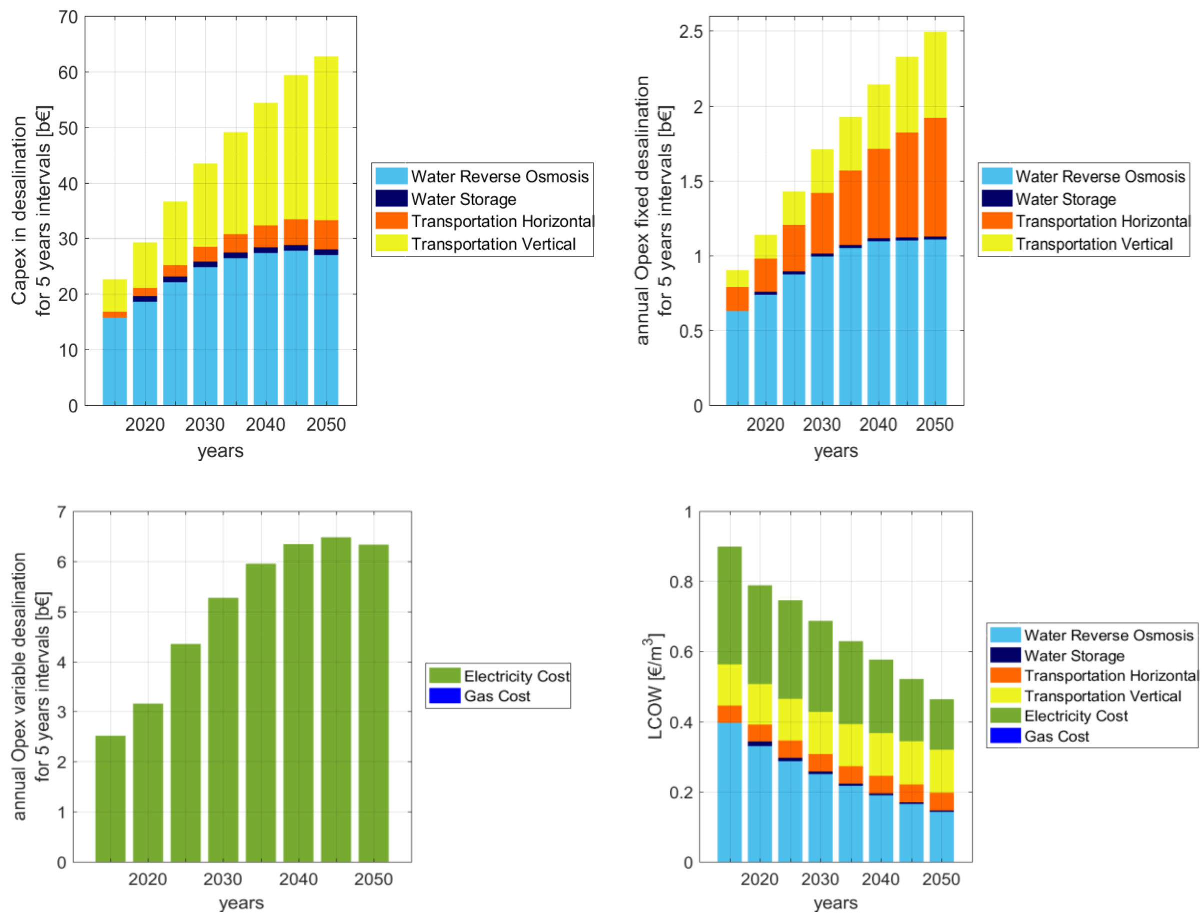


Figure 2-15: Capex (top left), annual fixed opex (top right) and annual variable opex (bottom left) for all desalination sector components and LCOW development (bottom right) from 2015 to 2050

Bogdanov and Breyer (2016) describe the industrial gas demand based on the total gas demand excluding demand for electricity generation and residential demand. Fossil natural gas represents 43% of electricity generation in 2015 it declines to zero in 2050. The energy system starts using biomethane with a slight share in 2020 and synthetic natural gas (SNG) production starts in 2035. The share of biomethane and SNG rise steadily to fully substitute the fossil gas by 2050. The produced gas is needed by the industry (64.8 TWh_{th}) and for balancing the power sector (29.3 TWh_{th}) representing 68.8% and 31.2%, respectively, of the sustainable gas supply in 2050.

Gas for the power sector is reduced drastically after strong growth of RE in the first periods of the transition, however from 2035 onwards the gas demand in the power sector is growing again, driven by the need to balance out the remaining demand after using all other lower cost storage and flexibility options. From 2025, the power sector demand share is increasingly growing from about 25% to about 65% till 2050. Industrial gas capex rises gradually from 0.1 b€ in 2020 to 12.6 b€ in 2050 while the opex increases from 8 m€ to 720 m€. Gas related capex, opex and demand numbers are provided in Table 2-10.

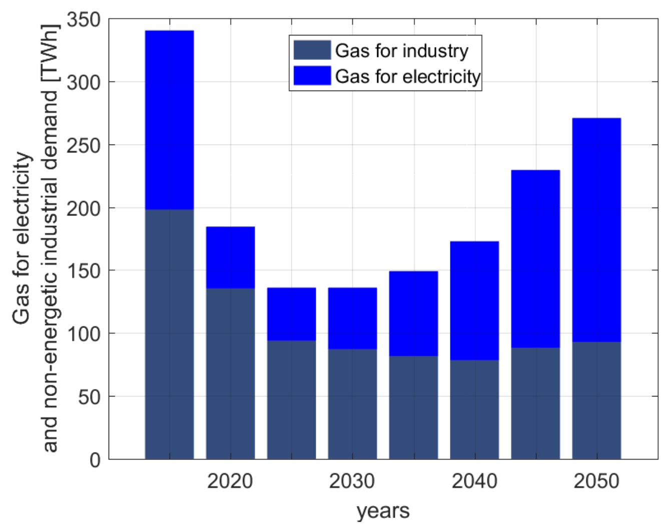


Figure 2-16: Gas demand from industry and power sector for 2015-2050 in the integrated scenario.

Table 2-10: Integrated scenario results for capex, opex, demand, storage and levelized cost of gas for industrial consumption for the year 2015 - 2050.

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Industrial gas Capex	b€	0	0.1	0.1	0.1	2.5	6.8	12.3	12.6
Industrial gas Opex	b€	0	0	0	0	0.1	0.4	0.7	0.7
Gas demand industry	TWh_{th}	85.1	98.5	95.3	88.6	82.7	77	70.9	64.8
Gas demand power	TWh_{th}	229.2	82.8	38.4	45.1	48.3	38.1	23.4	29.3
Gas storage	TWh	0.1	0.1	0.1	0.1	0.12	4.7	22.1	45.2
LCOG	€/MWh_{th}	55	38.7	40.3	44.6	58.8	82.2	117.0	120.2

The SNG production and SNG storage in hourly resolution for the year 2050 is depicted in Figure 2-17 The SNG production happens mainly during the daytime hours from March to October and during days of excellent wind conditions, so that the wind excess energy needs not to be curtailed but can be used for methanation. The full load hours of the PtG plants are about 2900. The gas storage reaches the highest state of charge at the end of the SNG production season, which is around October and continuously decreases till the next begin of the SNG production in March. SNG functions as a seasonal balance of the energy system, since it is produced mainly from March to October, whereas the industrial demand is more or less constant over the year and the SNG demand for the gas turbines balancing the power sector is mainly in the period from November to February.

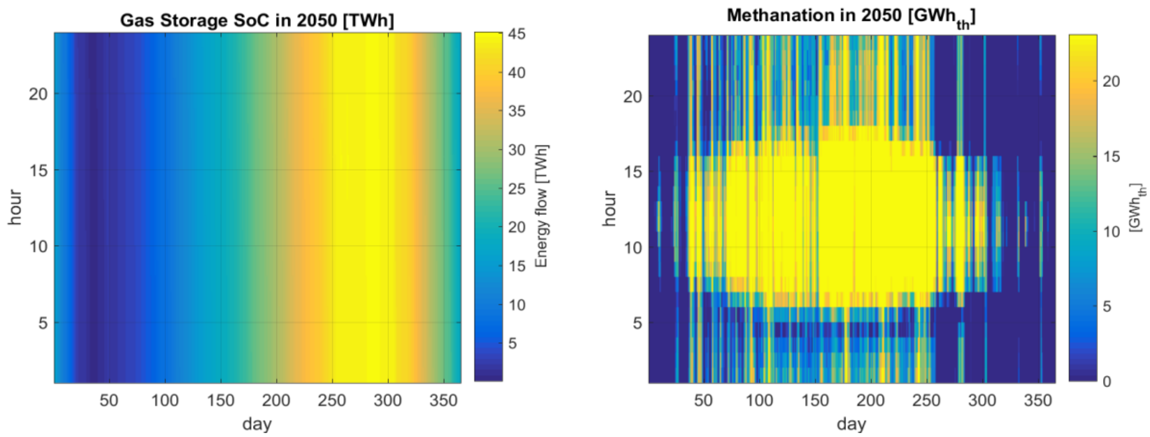


Figure 2-17: State of charge of gas storage and methanation hourly resolution for a whole year of 2050

2-3.3 Comparison of the Power and Integrated Scenarios

For the power scenario, the electricity demand of the power sector needs to be covered, whereas for the integrated scenario additional electricity demand from the sectors desalination and industrial gas has to be covered. Annual levelised costs are used to compare both scenarios from 2015 to 2050 and the data are presented in Table 2-11. The annual levelised cost for the integrated scenario is 22% higher than for the power scenario. Highly related to this are the generated electricity and total installed capacity, which are 24.4% higher in the integrated than in the power scenario in 2050. The total losses in the system consists of curtailed electricity, heat produced by biomass, biogas and waste-to-energy power plants, heat generated from electrolysers for transforming power-to-hydrogen, in methanation process transforming hydrogen-to methane and methane-to-power in gas turbines.

In both scenarios, the installation capacities are dominated by PV and wind capacities, due to their low cost and resource availability. PV single-axis and fixed tilted power plants and wind energy is added to the system to meet the growth in energy demand in the integrated compared to the power scenario. However, there may arise a slight advantage for fixed tilted PV systems, since their growth is substantially higher than that of single-axis tracking systems, especially after the year 2040.

The curtailment losses in the integrated scenario are higher in absolute numbers in the integrated scenario due to higher installed capacities, however the relative curtailment losses decline from 6.5% to 5.7% in the power and integrated scenario, respectively. The flexibility of the system in the integrated scenario is increased mainly due to the industrial gas demand and as a consequence the generated electricity is utilised more efficiently in this scenario.

Table 2-11: Total electricity demand generation, curtailment losses, annualized system cost, installed capacities by different technologies for the power and integrated scenario in 2050

	Units	Power Scenario	Integrated Scenario
Total electricity demand	TWh_{el}	641.3	894.5
Total electricity generation	TWh_{el}	766.4	1014.6
Curtailment losses total	TWh_{el}	49.8	58.1
LCOE	€/MWh_{el}	56.7	50.9
System total OPEX	b€	6.3	9.4
Installed Capacities			
Hard coal PP	GW	4.7	4.7
CCGT	GW	11.6	11.7
OCGT	GW	4.1	4.8
Steam turbine	GW	1.6	0.3
PV prosumers	GW	149.0	149.0
PV fixed tilted systems	GW	64.1	126.6
PV single-axis systems	GW	73.9	111.4
Wind onshore	GW	63.3	92.2
Hydro Run-of-River	GW	7.6	7.6
Hydro dams	GW	21.2	23.4
Biogas PP	GW	2.8	2.7
Geothermal power	GW	0.6	0.6
Waste PP	GW	0.6	0.5
Total	GW	405.3	535.7

Different storage technologies by their capacity, output and full cycles are shown in Table 2-12 for the year 2050. For both scenario, gas storage has the major share but the biggest difference is in A-CAES and TES storage. Integrated scenario increases the flexibility of the system and instead of storing the excess capacity, the model tries to control it from the demand side and store less. More installed batteries are installed due to more electricity demand in the scenario and it requires more solar and wind energy to be stored. A-CAES storage capacity is highest in the Marmara, Mediterranean and East Anatolia regions and the minimum capacity is in the Aegean region (no installed A-CAES) at 2050. TES storage capacity is nearly same in the same region but the maximum is in the Aegean region within the time scale all-region TES capacities converges to each other. Gas storage output is shown in Table 2-12 and it justifies that most produced SNG is used by the system immediately and only 45.6 TWhth are stored in the power scenario and 30.2 TWhth are stored in the integrated scenario in 2050

Table 2-12: Integrated and power scenario storage capacities, output and full load cycles per year at 2050.

	Storage Technology	Unit	Scenario	
			Power	**Integrated**
Storage capacities	Battery	GWh_{el}	561.9	771.7
	PHS	GWh_{el}	0.2	0.2
	Gas	GWh_{th}	41545.0	45225.0
	A-CAES	GWh_{el}	421.2	59.9
	TES	GWh_{el}	111.4	3.0
Throughput of storage	Battery	TWh_{el}	147.9	211.7
	PHS	TWh_{el}	0.1	0.0
	Gas	TWh_{th}	45.6	30.2
	A-CAES	TWh_{el}	7.4	0.6
	TES	TWh_{el}	6.2	0.2
Full load cycles per year	Battery		263.3	274.3
	PHS		688.44	195.86
	Gas		1.10	0.67
	A-CAES		17.51	10.53
	TES		55.55	57.59

2-4. Discussion

One of the most exhaustive reports for the Turkish future energy system is published by Greenpeace (Teske et al., 2015). The report consists of two scenarios, a business as usual and the Energy [R]evolution scenario. The Turkish energy system model is considered for all energy sectors (power, heating, transportation), but also CO_2 emissions, energy sector investments and employment opportunities for both scenarios. The Energy [R]evolution scenario is a comprehensive one from different perspectives but there are some major differences from the input and by the virtue of the fact that outputs were quite different. The total installed capacity in the energy system is 177 GW (Teske et al., 2015) in the year 2050 compared to 535.7 GW obtained in this research. This deviation can be explained by the quite different assumptions on the future electricity demand, which is 894.5TWhel and 413 TWhel for the Energy [R]evolution and this research, respectively. The generation mix differs, in particular in the mix of solar PV and wind energy, since 0.25 kWh of PV per 1 kWh of wind electricity in the Energy [R]evolution scenario shows less PV impact compared to the ratio of 2.16 kWh of PV per 1 kWh of wind electricity in this research. The major reasons for the relative difference are the lower assumed solar PV capex, the broad set of flexible storage options and the full hourly modelling for an entire year in this research, compared to the Greenpeace scenario design and methodology setup.

The most critical years for Turkey's 100% renewable energy transition are 2020 and 2025. In these years, electricity generation from RE technologies is increased more than 331% and the generation from fossil fuel is 58% lower in the power scenario in comparison to 2015. After the year 2025 the change in the system would be slower.

In both scenarios, electricity cost is decreased. The RE supply is growing substantially for covering the increasing energy demand in Turkey. Comparable cost reduction results are shown previously for the MENA region for 2030 assumptions (Aghahosseini et al., 2016), Saudi Arabia (Caldera et al., 2016) and Ukraine (Child et al., 2017). The highest solar PV share found so far had been for Saudi Arabia of about 80% in 2050 and for Ukraine a solar PV share of about 44% has been found. Turkey is not only geographically between these two countries, but also with the solar PV share of about 70% to 72%, depending on the scenario.

The second largest contribution to the energy supply is provided by wind onshore plants. The total amount of the wind onshore installed capacity reaches 92 GW in 2045. The total available wind energy potential in Turkey is used to 34%, so that more demand could be easily covered by more wind power installations. Total energy supplied by installed onshore wind power plants is 245.7 TWh which meets 24.2% of all electricity demand. The Marmara and Aegean regions have the highest share in installed wind capacities.

The last coal power plant is phased out in 2045, as well as the last used fossil natural gas. While the fossil fuels are phased out, RE generation capacities are increased, as well as battery capacities.

Total battery output is 211.7 TWhel for the integrated scenario and 147.9 TWhel for power scenario, respectively. Batteries provide 0.73 full load cycles per day in average for both scenarios.

PtG plants start in the scenarios around 2035 with an initial capacity of 5.3 GWel (power scenario) and 6.1 GWel (integrated scenario) and it increases until 2050 to 26.5 GWel (power scenario) and 60 GWel (integrated scenario). The reason for the rather late installations of PtG capacities is due to its starting cost competitiveness around 2035. The total PtG capex for meeting the non–energetic gas demand is 8.2 b€ (power scenario) and 18.7 b€ (integrated scenario). The opex for PtG reaches 0.38 b€ (power scenario) and 0.85 b€ (integrated scenario) in 2050.

The LCOE primary dominates the total LCOE but due to an increasing share of intermittent solar PV and wind energy, the share of LCOS increases continuously. In 2015, total LCOE is 73.1 €/MWhel (and 62.9 €/MWhel for the integrated and power scenario, respectively, and they decline to 50.9 €/MWhel and 56.7 €/MWhel in 2050, respectively. In the transition period the LCOE primary decreases from 61.4 €/MWhel to 32.4 €/MWhel in the integrated scenario, which represents the major part of the total energy system LCOE for Turkey.

The increasing water demand in Turkey cannot be covered anymore by renewable water sources which leads to an increased desalination demand. After increasing not only the capacities but also the efficiency the LCOW reaches 0.46 €/m3, which is about a quarter less than the LCOW in the Kingdom of Saudi Arabia (Caldera et al., 2016), which can be mainly explained by different cost for water pumping. This cost includes the cost for water desalination, water transportation to the demand site and water storage. The total annualised cost for water supply including all cost are in 2050 11.1 b€ and 4.8 b€ only for the desalination and pumping infrastructure without cost for electricity.

The development of the total LCOE shows an interesting difference in the two scenarios, since the total LCOE is lower until 2035 in the power scenario compare to the integrated scenario and leads to an 10% lower LCOE in the integrated scenario in the year 2050. The main difference of the two scenarios is the LCOS. Desalination and industrial gas demand makes the energy model flexible and decrease the storage requirement which leads to a more efficient use of the storage facilities in the entire energy system.

The electricity transmission grid in Turkey provides a very valuable flexibility and cost optimal allocation of RE capacities. Most electricity is imported by the Marmara region with 134 TWh, followed by the Black Sea region with 26.4 TWh. The main electricity exporting regions are the Aegean region and Middle Anatolia. The Aegean region has a huge potential of wind, solar and geothermal capacity and Middle Anatolia has an excellent solar, wind and bioenergy potential but rather low local demand.

2-5. Conclusions

Developing economy and growing population of Turkey increases the electricity demand, but the current energy supply is highly dependent on fossil fuels. Energy supply security is supposed to be the most crucial factor to examine Turkey's energy system, since the government of Turkey clearly stated to substantially reduce the energy import dependency.

The energy transition for Turkey can be separated in two major phases. In phase one from 2015 to 2030 the electricity generation base for the power sector will be mainly switched from fossil coal and gas-based electricity to solar PV and wind power supply. The highly competitive cost of PV and wind enable a transition pathway which keeps the total system LCOE almost stable. The PV systems comprise both distributed prosumer systems and larger PV power plants. The second phase from 2030 onwards is more related to an increased ramp up of storage capacities for a better balancing of a still raising RE supply share. In addition more impact on the power system can be observed due to a more intensive sector coupling. The role of SWRO desalination and PtG-based SNG supply for the gas sector is focused in this research. Since both sectors are almost fully based on electricity one can observe to main impacts, first an increase of electricity demand of about 39.5% and second a higher flexibility in the energy system leading to a partly substitution of the flexibility requirements provided by storage.

Natural gas is the biggest import item of Turkey and in this research it is shown that all gas demand can be supplied by power-based SNG with a smooth transition from 2035 – 2050. Industrial gas demand is important for Turkey due to growth of the chemical industry. In addition to the gas demand, Turkey will become a water-stressed country in mid-term and SWRO desalination demand is a cost competitive way to cover this demand.

100% renewable energy supply is possible for Turkey with competitive costs in the remaining time till 2050, which fully matched the COP21 Paris agreement. Different geographical regions within Turkey provide a wide span of valuable RE resources, which can be harvested by respective RE technology capacities, such as hydropower in East and South East Anatolia, wind and geothermal energy in Aegean region and solar PV in all regions of Turkey. Integration of energy sectors can decrease total system LCOE by about 10.1% compared to regarding only the power sector. Solar PV electricity emerges to the largest contributor for covering the growing energy demand of Turkey and supplying about 43.2% of total demand by 2050. The second largest source of electricity is wind contributing 10.3% of total demand by 2050. The higher supply share of solar PV is driven by the cost decline of PV, but also of batteries enabling a 24/7 demand coverage by solar energy.

More research will be needed for a comprehensive understanding of the energy transition options for Turkey. Key aspects should be the integration of the heat and transportation sector in the integrated energy system modelling and further scenario variations, such as the planned nuclear energy capacities in Turkey.

The vast untapped RE resource potential of Turkey allows to cover all the energy demand by RE resources for a growing population demanding for more energy and enabling higher standards of living in Turkey.

3 – Overall Conclusion for the Thesis

The Paris Agreement is crucially important for respective macro-level energy policies and Turkey is part of it which is explained in Part 1, Overview of Turkey and Constraints. In the same chapter, air pollution in Turkey is showed briefly which is highly correlated with industrialisation and fossil fuel plant locations. It explains that emissions are not in safe limits while it is comparing air quality in EU countries and Turkey. Turkey needs to (and suppose to) reduce and CO_2 emissions in the long term to sustain and increase its air quality (the indicators are SO_2, NO_2, and PM_{10} averages in this study). Updating current installed conventional fossil fuel power plants might be a short-term solution and the exact solution is phasing out these power plant when they fulfil their lifetimes. sustainable energy supply and low carbon emission,

Turkey's pathway to 100% renewable energy at 2050 is modelled, presented and analysed in the second part of the thesis in "Energy Transition towards 100% Renewable Energy at 2050 for Turkey for the sectors electricity, desalination and non-energetic industrial gas demand. Due to Turkey's current water capacities and future estimations of water stress is highly possible and therefore, desalination demand is included in the paper. Estimated water desalination demand is presented in Part 2, Seawater Desalination Capacities - Technical and Financial Assumptions, it shows that the demand will increase five times in 2050, and total water demand will be doubled in 2050. The paper includes two scenarios Power Sector and Integrated which consists desalination and SNG demand which is important due to Turkey's natural gas demand is supplied by importing the resource.

Turkey has varied natural energy resources and all of them are included in the model. When the resources are utilised in maximum levels (even though used solar potential in the model is less than 10%), Turkey can be a self-sufficient country in energy production. Installed RE capacities are balanced by different types of storage to sustain energy consumption and supply 24 hours a day. The solar potential of Turkey is showed in Part-1 and Part-2, this huge amount of potential should be managed smartly. There are obvious examples of countries manage solar energy and integrating into energy systems beneficially even though, these countries solar potentials are way less than Turkey has. Germany's "100000 Solar Roofs" campaign would be a perfect example for this comparison and the results are obviously beneficial. Especially, the financial perspective of solar technologies and battery technologies are rapidly going down. Integrating battery technologies into energy systems will be a game changer especially for increasing grid stability. The model shows the parallel fact that while the wind and solar installations are increasing, the battery storage capacities increases too. At 2050, battery storages reach 561.9 GWh in power sector scenario (self-consumption share is 46.7%) and 771.7 GWh (self-consumption share is 34%).

Solar PV prices are examined in Part 1- Future Cost of Energy, it shows that it will be cheaper in the future, even though Turkey has already reached grid parity with current costs. In the model, solar PV is the major energy system with wind energy. Turkey's solar irradiation level has an enormous advantage on solar PV efficiency and return on investment times.

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Appendix -1

Table 1: Technical and financial assumptions of all energy system components used in this research. Further assumptions are taken from Pleßmann et al. (2014) and European Commission (2014) and other references are shown in reference column.

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
PV fixed tilted	Capex	€/kWp	1000	800	650	550	490	440	400	370	Vartiainen et al., 2015
	Opex fix	€/(kWp a)	15	12.0	10	8	7	7	6	6	Fraunhofer ISE, 2015
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kWp	1150	920	720	620	535	480	435	400	Vartiainen et al., 2015
	Opex fix	€/(kWp a)	17.3	13.8	10.8	9.3	8.025	7.2	6.525	6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	Fraunhofer ISE, 2015
	Lifetime	years	30	30	35	35	35	40	40	40	
PV prosumers rooftop	Capex	€/kWp	1360	1090	890	760	680	610	550	500	
	Opex fix	€/(kWp a)	20.4	16.35	13.35	11.4	10.2	9.15	8.25	7.5	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW	1250	1150	1060	1000	965	940	915	900	Neij et al., 2008
	Opex fix	€/(kW a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/m^2	270	240	220	200	180	170	150	140	
	Opex fix	%	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	
	Opex var	-	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal	Capex	€/kW	5250	4970	4720	4470	4245	4020	3815	3610	
	Opex fix	€/(kW a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW	800	685	500	380	340	310	280	260	Agora, 2014
	Opex fix	€/(kW a)	32	27	20	15	14	12	11	10	Breyer et al. 2015

	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW	492	421	310	234	208	190	172	160	Agora, 2014
	Opex fix	€/(kW a)	10	8	6	5	4	4	3	3	Breyer et al. 2015
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/kW	749	641	470	356	314	286	258	240	
	Opex fix	€/(kW a)	29.9	25.6	18.8	14.2	12.6	11.4	10.3	9.6	
	Opex var	€/(kWh)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	Lifetime	years	30	30	30	30	30	30	30	30	
CCGT	Capex	€/(kW_{el})	775	775	775	775	775	775	775	775	IEA, 2003
	Opex fix	€/(kW_{el} a)	19.375	19.375	19.375	19.375	19.375	19.375	19.375	19.375	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency		58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW_{el})	475	475	475	475	475	475	475	475	IEA, 2003
	Opex fix	€/(kW_{el} a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency		43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW_{el})	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW_{el} a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30	30	30	30	
Steam turbine (coal-fired PP)	Capex	€/(kW_{el})	1500	1500	1500	1500	1500	1500	1500	1500	IEA, 2003
	Opex fix	€/(kW_{el} a)	20	20	20	20	20	20	20	20	
	Opex var		0	0	0	0	0	0	0	0	
	Efficiency	%	45	45	45	45	46	46	47	47	
	Lifetime	years	40	40	40	40	40	40	40	40	
Biomass CHP	Capex	€/kW	3400	2900	2700	2500	2300	2200	2100	2000	

	Opex fix	€/(kW a)	238	203	189	175	161	154	147	140	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	36	37	40	43	45	47	47.5	48	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas CHP	Capex	€/kW	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	35	36	39	42	44	46	46	47	
	Lifetime	years	30	30	30	30	30	30	30	30	
MSW incinerator	Capex	€/kW	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
-	Opex var	€/(kWh)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	29.5	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW	340	290	270	250	230	220	210	200	Urban et al., 2009
	Opex fix	€/(kW a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWh_{el})	600	300	200	150	120	100	85	75	
	Opex fix	€/(kWh_{el} a)	24	12	8	6	4.8	4	3.4	3	
	Opex var	€/($kWh_{throughput}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
A-CAES	Capex	€/kWh	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	

	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh$_{th}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table 2: Energy to power ratio of the storage technologies

Technology	**Energy /Power Ratio (hours)**	**Self-Discharge**
Battery	6	0
A-CAES	100	0.001
Gas Storage	80*24	0

Table 3: TUIK Regional Gross Value Added (GVA) at Current Basic Prices (TUIK, 2014) ratios applied on non-energetic industrial gas demand by regions

Regions	**GVA of Region**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Mediterranean	0.11	9.65	11.17	10.81	10.04	9.39	8.73	8.04	7.35
Marmara	0.41	35.23	40.75	39.45	36.64	34.25	31.86	29.33	26.81
Aegean	0.15	12.55	14.51	14.05	13.05	12.20	11.35	10.45	9.55
Black Sea	0.07	5.88	6.80	6.58	6.11	5.71	5.31	4.89	4.47
Central Anatolia	0.17	14.24	16.47	15.94	14.81	13.84	12.88	11.86	10.84
Southeast Anatolia	0.06	4.74	5.48	5.31	4.93	4.61	4.29	3.95	3.61
East Anatolia	0.03	2.85	3.30	3.19	2.96	2.77	2.58	2.37	2.17
Total	**1**	**85.14**	**98.48**	**95.34**	**88.55**	**82.77**	**76.98**	**70.89**	**64.79**

Table 4: Full Load Hours for CSP, PV fixed tilted, PV single-axis tracking and wind power plants in regions of Turkey

		FLH PV 0-axis	**FLH PV 1-axis**	**FLH CSP**	**FLH Wind onshore**	**FLH Wind offshore**	**FLH Wind Total**			**FLH PV 0-axis**	**FLH PV 1-axis**	**FLH CSP**	**FLH Wind onshore**	**FLH Wind offshore**	**FLH Wind Total**
Region	Year	[h]	[h]	[h]	[h]	[h]	[h]	**Region**	Year	[h]	[h]	[h]	[h]	[h]	[h]
Medi terranean	2015	1644.0	0.0	0.0	2108.0	0.0	2108.0	Marmara	2015	1399.4	0.0	0.0	2997.0	0.0	2997.0
	2020	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2020	1399.4	0.0	1520.6	2997.0	0.0	2997.0
	2025	1644.0	2098.2	4469.0	2108.0	0.0	2108.0		2025	1399.4	1739.4	4374.0	2997.0	0.0	2997.0
	2030	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2030	1399.4	1739.4	1520.6	2997.0	0.0	2997.0
	2035	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2035	1399.4	1739.4	1520.6	2997.0	0.0	2997.0
	2040	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2040	1399.4	1739.4	1520.6	2997.0	0.0	2997.0
	2045	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2045	1399.4	1739.4	1520.6	2997.0	0.0	2997.0
	2050	1644.0	2098.2	2003.2	2108.0	0.0	2108.0		2050	1399.4	1739.4	1520.6	2997.0	0.0	2997.0
Aegean	2015	1591.2	0.0	0.0	2797.1	0.0	2797.1	Black Sea	2015	1407.9	0.0	0.0	1747.6	0.0	1747.6
	2020	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2020	1407.9	0.0	1512.3	1747.6	0.0	1747.6
	2025	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2025	1407.9	0.0	4427.0	1747.6	0.0	1747.6
	2030	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2030	1407.9	1721.9	1512.3	1747.6	0.0	1747.6

	2035	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2035	1407.9	1721.9	1512.3	1747.6	0.0	1747.6
	2040	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2040	1407.9	1721.9	1512.3	1747.6	0.0	1747.6
	2045	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2045	1407.9	1721.9	1512.3	1747.6	0.0	1747.6
	2050	1591.2	2057.8	2010.9	2797.1	0.0	2797.1		2050	1407.9	1721.9	1512.3	1747.6	0.0	1747.6
Central Anatolia	2015	1540.4	0.0	0.0	2387.7	0.0	2387.7	South East Anatolia	2015	1613.7	0.0	0.0	2351.6	0.0	2351.6
	2020	1540.4	0.0	1711.2	2387.7	0.0	2387.7		2020	1613.7	2057.9	2008.2	2351.6	0.0	2351.6
	2025	1540.4	1937.2	4418.0	2387.7	0.0	2387.7		2025	1613.7	2057.9	4391.0	2351.6	0.0	2351.6
	2030	1540.4	1937.2	1711.2	2387.7	0.0	2387.7		2030	1613.7	2057.9	2008.2	2351.6	0.0	2351.6
	2035	1540.4	1937.2	1711.2	2387.7	0.0	2387.7		2035	1613.7	2057.9	2008.2	2351.6	0.0	2351.6
	2040	1540.4	1937.2	1711.2	2387.7	0.0	2387.7		2040	1613.7	2057.9	2008.2	2351.6	0.0	2351.6
	2045	1540.4	1937.2	1711.2	2387.7	0.0	2387.7		2045	1613.7	2057.9	2008.2	2351.6	0.0	2351.6
	2050	1540.4	1937.2	1711.2	2387.7	0.0	2387.7		2050	1613.7	2057.9	2008.2	2351.6	0.0	2351.6

Table 5: Full Load Hours (h)

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV optimally tilted	**[h]**	1580	1580	1580	1580	1580	1532	1519	1526
PV single-axis	**[h]**	0	2070	2031	2013	2024	2023	2023	2023
CSP	**[h]**	0	1844	1804	1797	1796	1796	1796	1702
Wind total	**[h]**	2728	2901	2758	2701	2688	2673	2663	2663
Hydro total	**[h]**	3346	3372	3338	3338	3338	3338	3338	3338
Geothermal	**[h]**	504	507	507	519	519	524	524	531
Bat total	**[h]**	153	1594	1627	1586	1576	1596	1630	1646
PHS	**[h]**	347	1187	1820	1727	1762	1735	1707	1567
TES	**[h]**	3261	1293	2023	2291	2424	2404	2689	2421
CAES	**[h]**	1518	289	898	1142	1285	1198	1072	1053
PtSNG	**[h]**	0	801	1318	2014	2443	2700	2734	2897
CCGT	**[h]**	6954	4560	2406	2721	2755	2081	1410	1315
OCGT	**[h]**	3562	532	180	260	350	242	90	324
GT	**[h]**	4266	1619	812	1000	1081	976	831	1028
ST	**[h]**	3910	5707	4287	3966	3997	3899	2171	2420
Biomass PP	**[h]**	7254	8322	7561	6499	5883	5527	5854	5871
Waste PP	**[h]**	0	8322	8322	8322	8322	8322	8322	8322
Biogas PP	**[h]**	7008	6147	3428	3111	2703	1555	1687	1388
Biogas Upgr	**[h]**	0	8322	8322	8322	8322	8318	8322	8221
Biogas Dig	**[h]**	8322	8322	8322	8322	8322	8322	8322	8322
Hard coal PP	**[h]**	8260	7622	4243	3851	3320	2848	1522	0
Internal combustion generator	**[h]**	0	0	0	0	0	0	0	0
Nuclear PP	**[h]**	0	0	0	0	0	0	0	0

Table 6: Key power capacities required for the power scenario energy transition pathway for Turkey from 2015 to 2050

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
PV prosumers	(GW)	0.0	29.7	57.6	75.2	95.0	117.7	135.0	149.0
PV single-axis	(GW)	0.2	0.2	0.2	1.0	1.0	6.0	33.5	64.1
PV optimally tilted	(GW)	0.0	9.8	26.8	39.1	50.0	62.5	73.3	73.9
Wind total	(GW)	4.5	33.1	33.1	44.1	54.2	60.2	63.7	63.3
Hydro power	(GW)	23.2	25.7	27.6	28.6	28.9	28.9	28.9	28.9
Geothermal	(GW)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6
CSP	(GW)	0.0	0.0	0.0	11.2	11.2	11.2	10.0	7.8
Biomass PP	(GW)	0.2	0.2	0.2	1.7	2.0	2.9	2.8	2.8
Biogas PP	(GW)	0.2	0.2	0.3	1.5	1.5	1.5	1.5	1.3
Biogas digester	(GW)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Biogas upgrade	(GW)	0.0	0.5	0.5	0.8	0.8	0.8	0.8	0.7
Waste PP	(GW)	0.0	0.5	0.5	0.6	0.6	0.6	0.6	0.6
Battery self consumption	(GWh)	0.0	29.3	109.6	141.7	175.7	210.9	237.8	262.7
Battery total	(GWh)	0.0	29.4	116.9	181.5	247.0	323.6	446.3	561.9
Gas storage	(GWh)	22.6	1256.2	2288.1	4262.8	7016.7	11933.8	32865.8	41545.3
PHS Storage	(GWh)	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TES Storage	(GWh)	0.0	0.0	0.1	110.6	110.8	111.4	111.4	111.4
PtG electrolyser input	(GW_{el})	0.0	0.0	0.0	5.3	5.3	7.4	21.6	26.5
A-CAES storage	(GWh)	0.1	0.1	0.6	419.6	420.0	421.2	421.2	421.2
Hard coal PP	(GW)	13.5	12.6	12.4	9.4	7.6	6.8	6.8	4.7
CCGT	(GW)	0.0	4.5	5.3	6.0	6.0	6.4	8.4	11.6
OCGT	(GW)	19.8	19.7	18.3	17.4	17.2	13.5	7.5	4.1
ST	(GW)	0.0	0.0	0.1	3.5	3.4	3.3	2.6	1.6

Table 7: Key power capacities required for the integrated sector scenario energy transition pathway for Turkey from 2015 to 2050

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
PV prosumers	(GW)	0.0	29.7	57.6	75.2	95.0	117.7	135.0	149.0
PV single-axis	(GW)	0.0	15.9	36.2	47.7	68.4	89.3	111.4	111.4
PV optimally tilted	(GW)	0.2	0.2	0.2	0.2	0.2	21.8	69.0	126.6
Wind total	(GW)	4.5	36.7	54.9	68.2	77.9	86.3	92.2	92.2
Hydro power	(GW)	23.2	27.4	31.0	31.0	31.0	31.0	31.0	31.0
Geothermal	(GW)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6
CSP	(GW)	0.0	1.6	2.1	2.4	2.4	2.4	2.4	0.8
Biomass PP	(GW)	0.2	0.2	0.6	1.8	2.7	2.9	2.8	2.7
Biogas PP	(GW)	0.0	0.1	0.2	0.2	0.3	0.5	0.5	0.6
Biogas digester	(GW)	0.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Biogas upgrade	(GW)	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Waste PP	(GW)	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Battery self consumption	(GWh)	0.0	29.3	109.6	141.7	175.7	210.9	237.8	262.7
Battery total	(GWh)	4.9	34.2	114.6	180.4	279.2	418.9	602.6	771.7
Gas storage	(GWh)	109.7	109.7	109.7	109.7	121.5	4652.7	22101.9	45225.5
PHS Storage	(GWh)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
TES Storage	(GWh)	47.0	47.0	47.0	47.0	47.0	47.0	3.0	3.0
PtG electrolyser input	(GW_{el})	0.0	0.0	0.0	0.0	6.1	20.2	48.4	60.0
A-CAES storage	(GWh)	59.9	59.9	59.9	59.9	59.9	59.9	59.9	59.9
Hard coal PP	(GW)	13.5	12.6	12.4	9.4	7.6	6.8	6.8	4.7
CCGT	(GW)	5.3	7.4	7.4	7.4	7.4	8.8	9.3	11.7
OCGT	(GW)	20.1	20.0	18.6	17.2	16.9	13.3	7.3	4.8
ST	(GW)	1.7	0.2	0.4	0.5	0.5	0.5	1.0	0.3

Table 8: Power scenario (a), Desalination and Industrial Gas Demand integrated scenario (b) results for PV installed capacities for the year 2050.

a,

2050	PV prosumers Residential	PV prosumers Commercial	PV prosumers Industrial	PV prosumers total	PV fixed tilted systems	PV single-axis systems	PV systems	PV total
	GW	GW	GW	GW	GW	GW	GW	GW
TR-S	5.23	3.03	10.07	18.33	17.47	27.77	45.24	63.57
TR-NW	20.20	10.88	35.89	66.97	45.50	5.01	50.50	117.48
TR-W	6.61	3.48	11.51	21.59	32.48	29.01	61.50	83.09
TR-N	3.57	1.99	6.61	12.17	3.28	0.00	3.28	15.45
TR-Mid	5.14	2.97	9.86	17.97	22.51	26.04	48.55	66.52
TR-SE	2.21	1.22	4.06	7.49	3.52	5.38	8.90	16.40
TR-E	1.28	0.74	2.47	4.50	7.83	16.46	24.29	28.79
TOTAL	**44.25**	**24.31**	**80.46**	**149.02**	**132.58**	**109.68**	**242.27**	**391.29**

b,

2050	PV prosumers Residential	PV prosumers Commercial	PV prosumers Industrial	PV prosumers total	PV 0-axis system	PV 1-axis system	PV System	PV Total
	GW	GW	GW	GW	GW	GW	GW	GW
TR-S	5.23	3.03	10.07	18.33	17.47	27.77	45.24	63.57
TR-NW	20.20	10.88	35.89	66.97	45.50	5.01	50.50	117.48
TR-W	6.61	3.48	11.51	21.59	32.48	29.01	61.50	83.09
TR-N	3.57	1.99	6.61	12.17	3.28	0.00	3.28	15.45
TR-Mid	5.14	2.97	9.86	17.97	22.51	26.04	48.55	66.52
TR-SE	2.21	1.22	4.06	7.49	3.52	5.38	8.90	16.40
TR-E	1.28	0.74	2.47	4.50	7.83	16.46	24.29	28.79
TOTAL	**44.25**	**24.31**	**80.46**	**149.02**	**132.58**	**109.68**	**242.27**	**391.29**

Table 9: Different levelised cost of electricity, levelised cost of storage, levelised cost of curtailment, levelised cost of water, total annual cost of system, capital expenditure between 2015 and 2050 in integration scenario.

	Total LCOE	LCOE primary	LCOC	LCOS	LCOT	Total ann. Cost	LCOW	Total CAPEX of Power Sector	Desalination Capex	Gas for Industry Capex
	€/ MWh_{el}	€/MWh	€/MWh	€/MWh	€/MWh	€/MWh	€/m^3	b€	b€	b€
2015	69.1	60.5	0.3	3.9	4.4	25.4	0.9	123.8	182.5	0.0
2020	69.9	60.8	0.1	5.3	3.7	33.3	0.8	229.8	251.2	0.1
2025	74.7	61.0	1.4	8.4	3.8	40.6	0.7	296.6	347.4	0.1
2030	71.1	56.0	2.5	8.8	3.7	43.5	0.7	321.6	449.8	0.1
2035	66.6	50.8	2.7	9.4	3.7	46.7	0.6	354.7	547.1	2.5
2040	61.1	44.7	2.6	10.2	3.5	49.2	0.6	397.6	652.9	6.8
2045	55.2	37.5	2.2	12.1	3.3	49.5	0.5	439.2	763.5	12.3
2050	50.8	32.4	2.1	13.2	3.1	48.1	0.5	464.3	858.7	12.6

Table 10: Lower and Upper capacity limits for renewables

PV optimally tilted	PV single-axis tracking	Wind onshore	Wind offshore	Hydro Run-of-River	Hydro Dam	CSP
GW	GW	GW	GW	GW	GW	GW
0.25-3645	0-3645	4.5-272.1	0-NL*	7.6-11.5	21.2-23.4	0-7290
NL- No upper limit specified *Not utilized for Turkey						

Table 11: Lower and Upper capacity limits for fossil fuels

Coal	**Natural Gas**
GW	GW
13.5-NL	19.8-NL
NL - No upper limit specified *Not utilized for Turkey	

Table 12: Technical and financial parameters of the seawater desalination technologies from 2015 – 2050 (Caldera et al., 2016)

			2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Sea Water Reverse Osmosis	**Capex**	€/(m^3·day)	1150	960	835	725	630	550	480	415
	Opex fix	€/(m^3·day)	46	38	33	29	25	22	19	17
	Energy consumption	kWh/m^3	4.1	3.6	3.35	3.15	3	2.85	2.7	2.6
	Lifetime	years	25	25	30	30	30	30	30	30
Water Transportation										
Piping	**Capex**	€/(m^3·a·km)	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053
	Fixed Opex	€/(m^3·a·100 km)	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
	Lifetime	years	30	30	30	30	30	30	30	30
Vertical Pumping	**Capex**	€/(m^3·h·m)	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	Fixed Opex	€/(m^3·h·m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Energy consumption	kWh/(m^3·h·100 m)	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	Lifetime	years	30	30	30	30	30	30	30	30
Horizontal Pumping	**Capex**	€/(m^3·h·km)	19.26	19.26	19.26	19.26	19.26	19.26	19.26	19.26
	Fixed Opex	€/(m^3·h·km)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Energy consumption	kWh/(m^3·h·100km)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Lifetime	years	30	30	30	30	30	30	30	30
Water Storage	**Capex**	€/m^3	65	65	65	65	65	65	65	65
	Fixed Opex	€/m^3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	Lifetime	years	30	30	30	30	30	30	30	30

Table 13: Regional water demand for 2015 – 2050

Million m^3/day								
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
TR-S	16.8	18.7	20.5	20.5	23.7	25.7	27.7	29.5
TR-NW	39.9	44.6	48.9	48.9	56.5	61.3	65.9	70.4
TR-W	17.0	18.9	20.7	20.7	24.0	26.0	28.0	29.9
TR-N	11.9	13.2	14.5	14.5	16.8	18.2	19.6	20.9
TR-Mid	21.0	23.4	25.6	25.6	29.6	32.1	34.6	36.9
TR-SE	14.0	15.6	17.1	17.1	19.7	21.4	23.1	24.6
TR-E	10.0	11.2	12.3	12.3	14.2	15.4	16.5	17.7
Total	**130.4**	**145.5**	**159.5**	**174.6**	**184.3**	**200.0**	**215.3**	**229.9**

Table 14: Regional water desalination demand for 2015 - 2050

Million m^3/day								
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
TR-S	1.8	2.5	3.4	4.4	5.4	6.4	7.4	8.4
TR-NW	4.2	5.9	8.1	10.4	12.8	15.2	17.6	20.1
TR-W	1.8	2.5	3.4	4.4	5.4	6.4	7.5	8.5
TR-N	1.3	1.9	2.6	3.4	4.1	4.9	5.7	6.5
TR-Mid	2.1	3.0	4.2	5.4	6.6	7.8	9.1	10.3
TR-SE	1.5	2.1	2.8	3.6	4.5	5.3	6.2	7.0
TR-E	1.0	1.5	2.0	2.6	3.2	3.8	4.4	5.0
Total	**13.7**	**19.4**	**26.5**	**34.2**	**42.0**	**49.7**	**57.8**	**65.9**

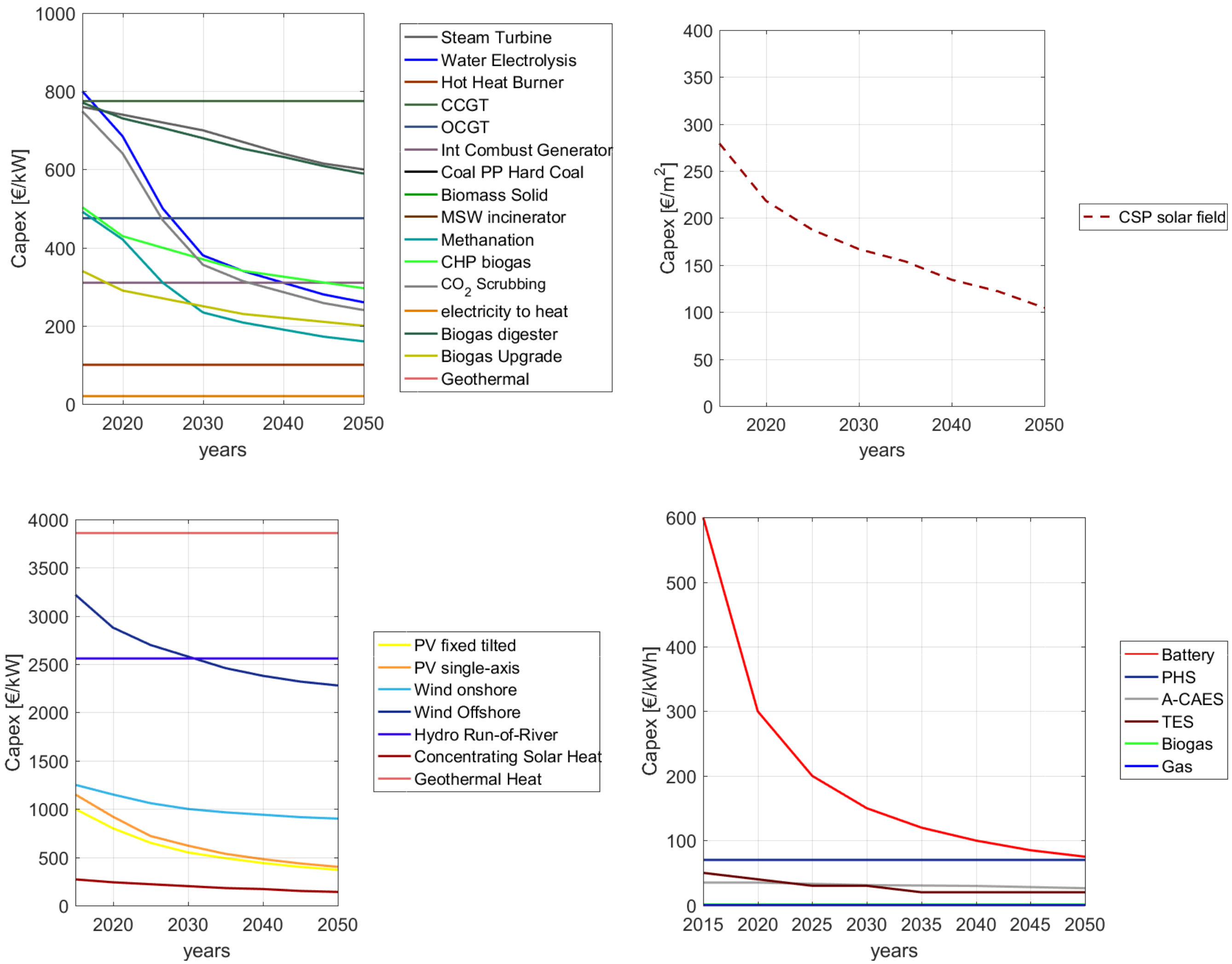

Figure 1: Top Left: Variation in capex of power system components assumed in the model
Top Right: Variation in capex of the CSP solar field assumed in the model
Bottom Left: Variation in the capex of the RE components assumed in the model
Bottom Right: Variation in the capex of the storage components assumed in the model

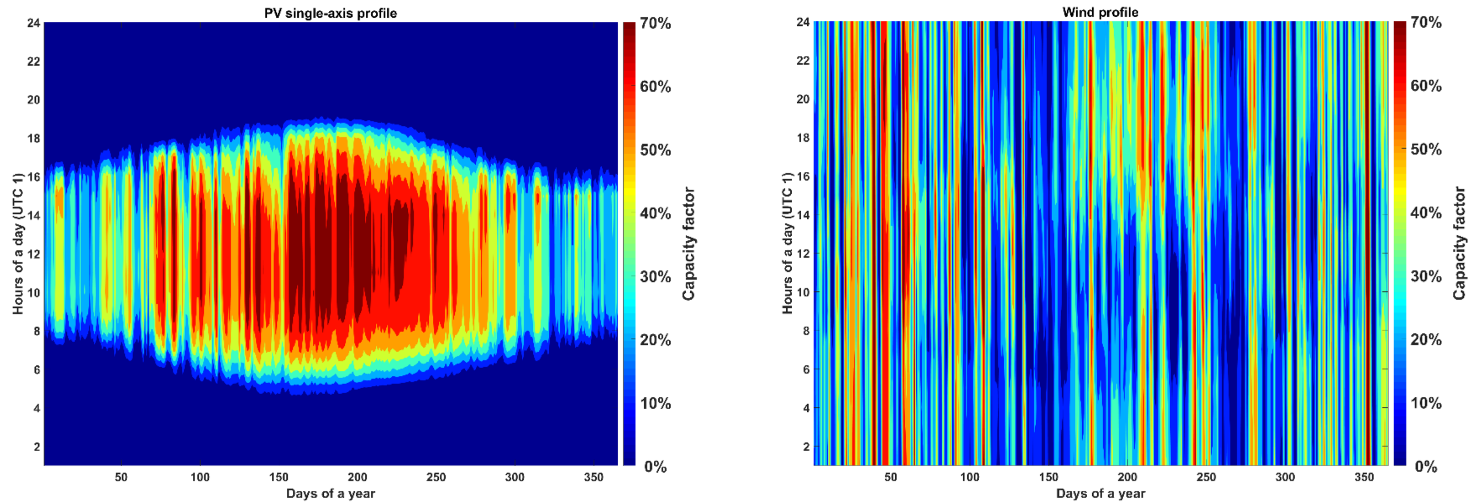

Figure 2: Solar PV single-axis tracking (left) and wind power (right) generation profiles for Turkey

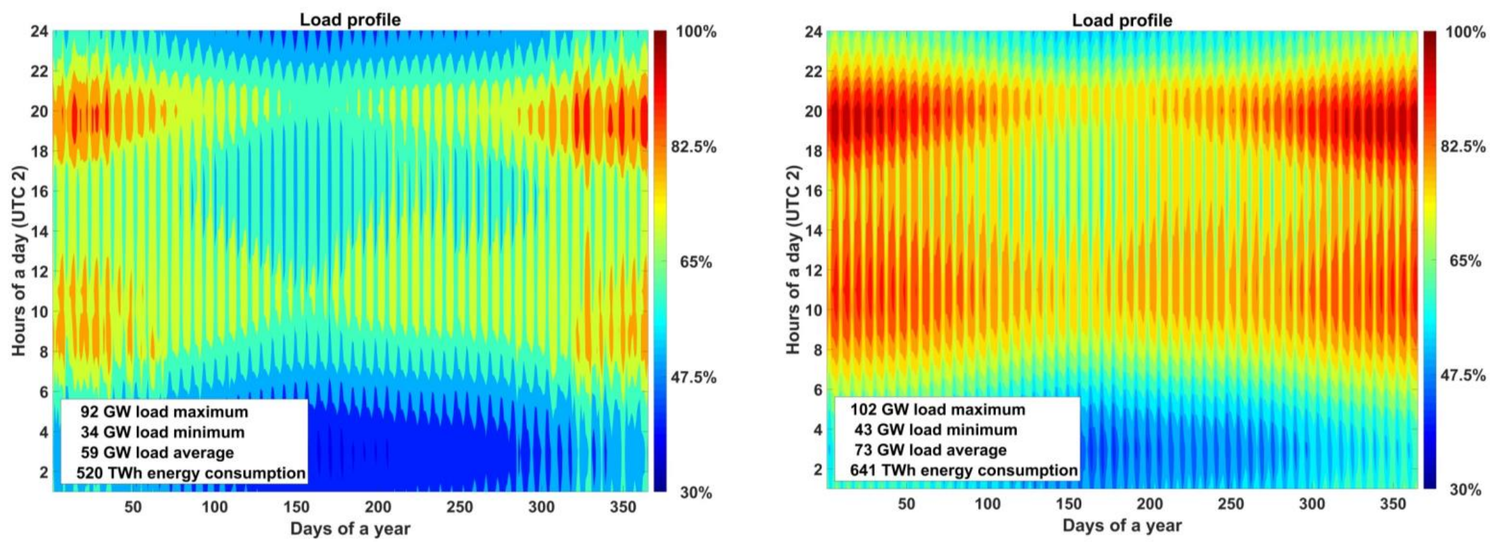

Figure 3: Aggregated load curve without (left) and load curve with prosumers influence (right) in integrated scenario for Turkey in 2050.

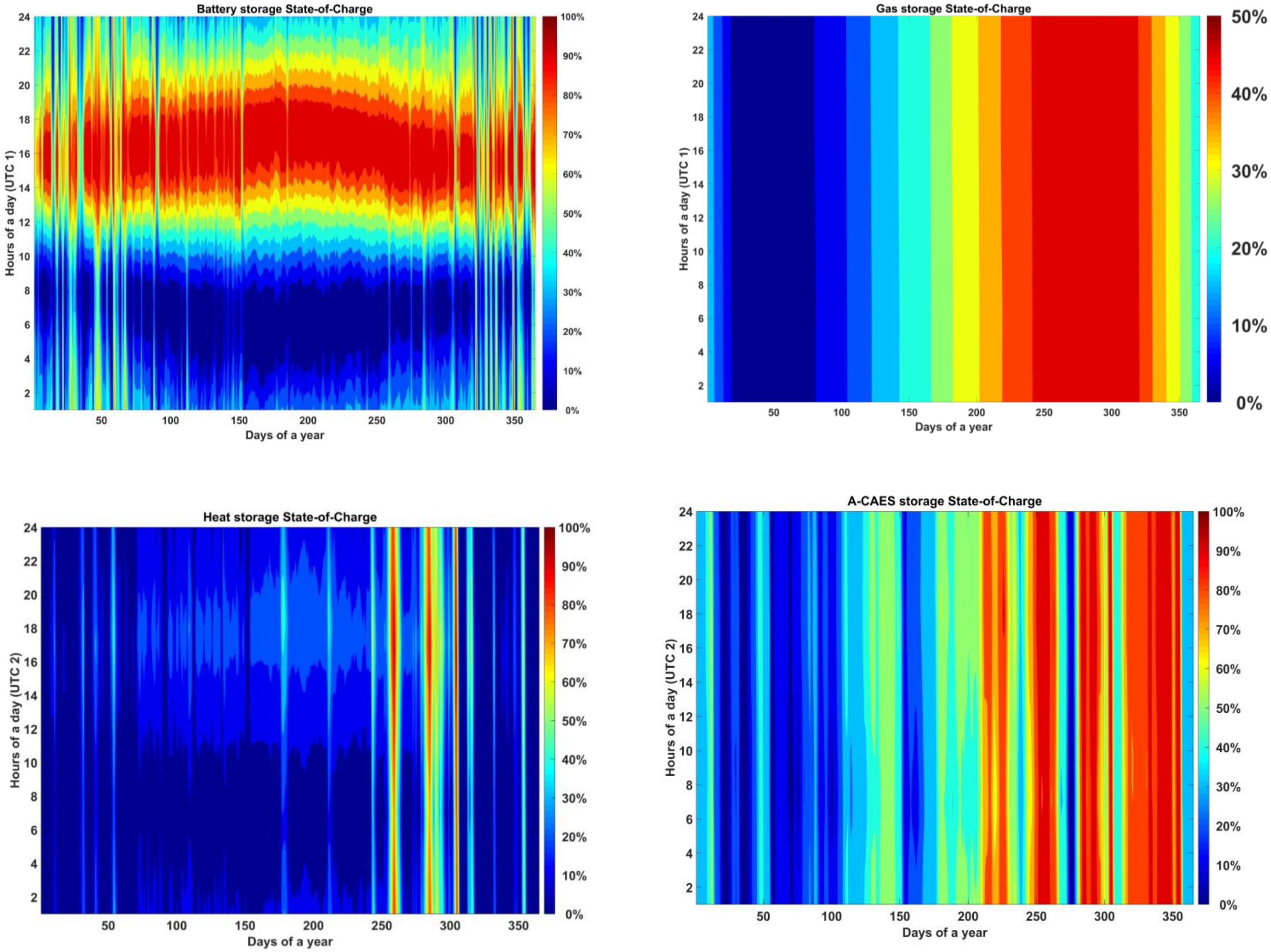

Figure 4: Aggregated yearly state-of-charge for storage technologies in 2050 for integrated scenario, battery (top left), gas storage (top right), heat storage (bottom left) and A-CAES (bottom right).

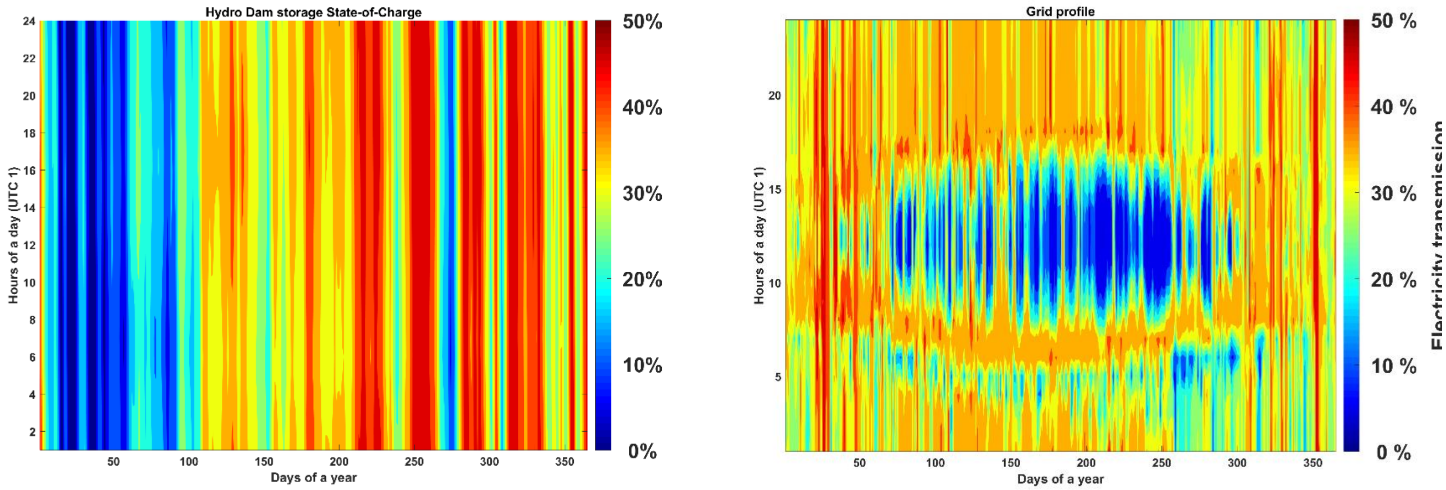

Figure 5: Aggregated yearly state of charge of hydro reservoirs storage for the power scenario (left) and grid profile for integrated scenario (right) for the year 2050.

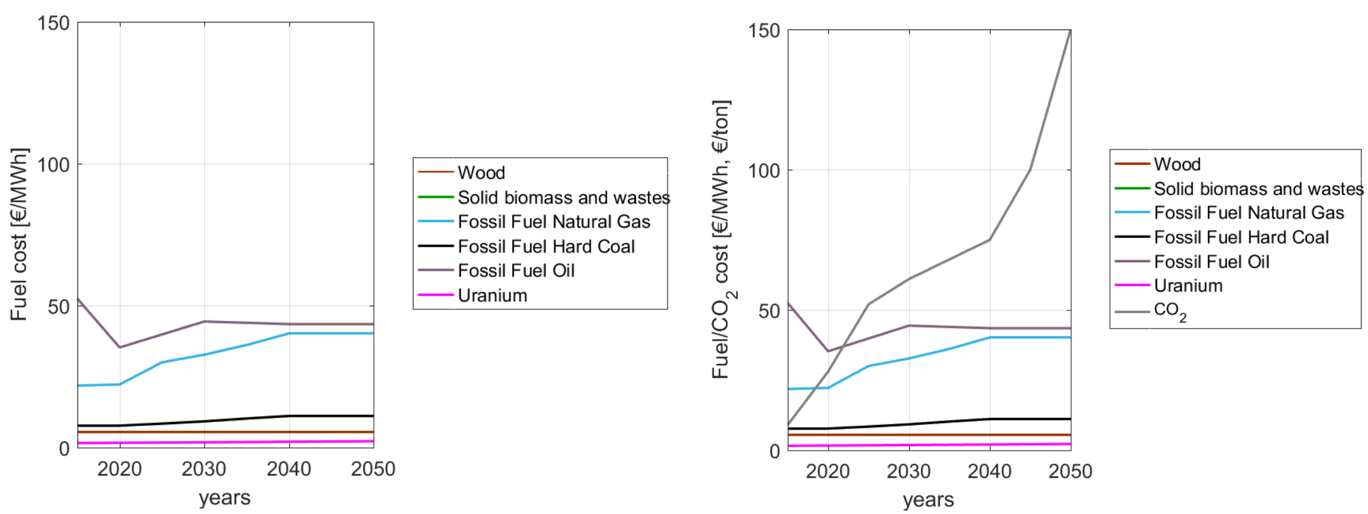

Figure 6: Fuel costs (left) and fuel/CO_2 cost (right) with for all technologies

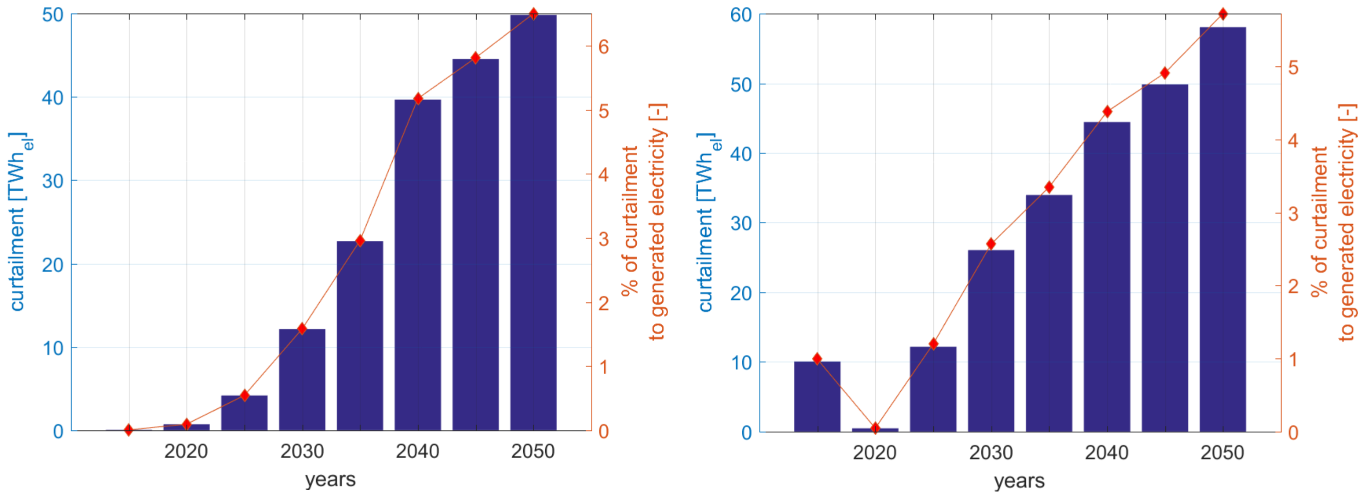

Figure 7: Curtailment of generated electricity for power scenario (left) and integrated scenario (right)

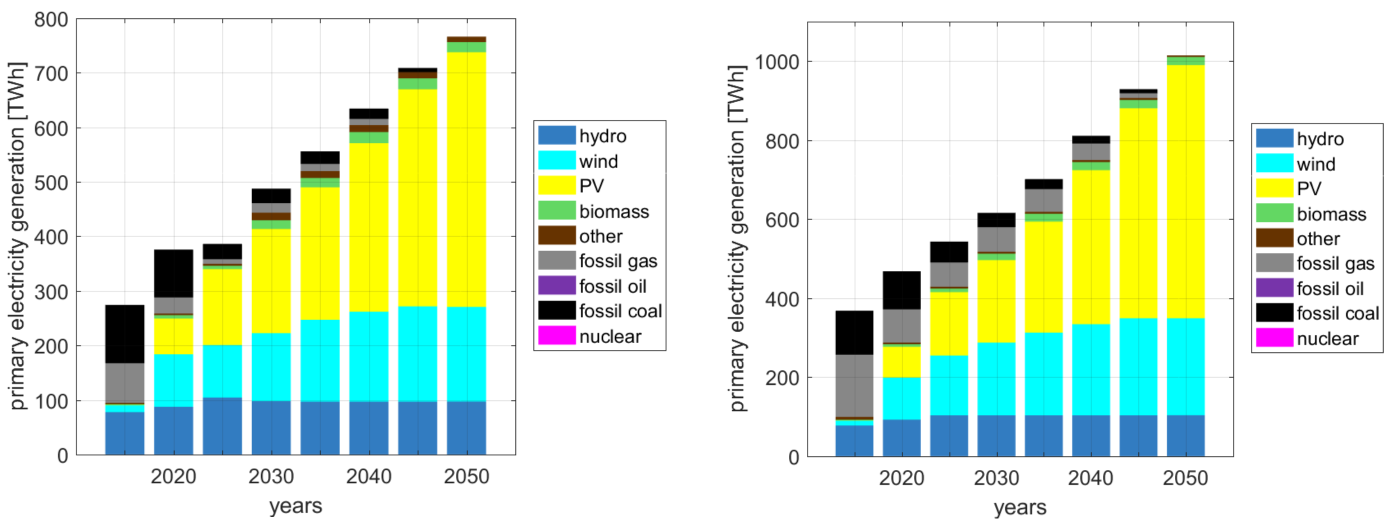

Figure 8: Primary electricity generation from different sources for power (left) and integrated (right) scenarios.

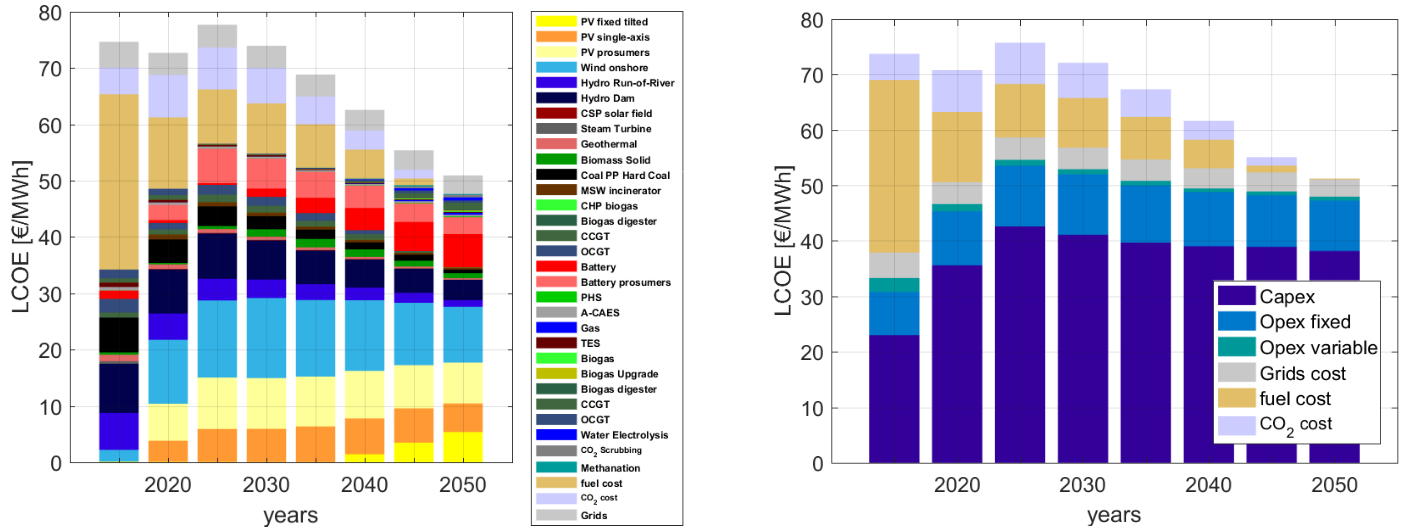

Figure 9: LCOE contribution by various technologies (left) and contribution of different components (right) to the total LCOE, from 2015 to 2050 for the integrated scenario.

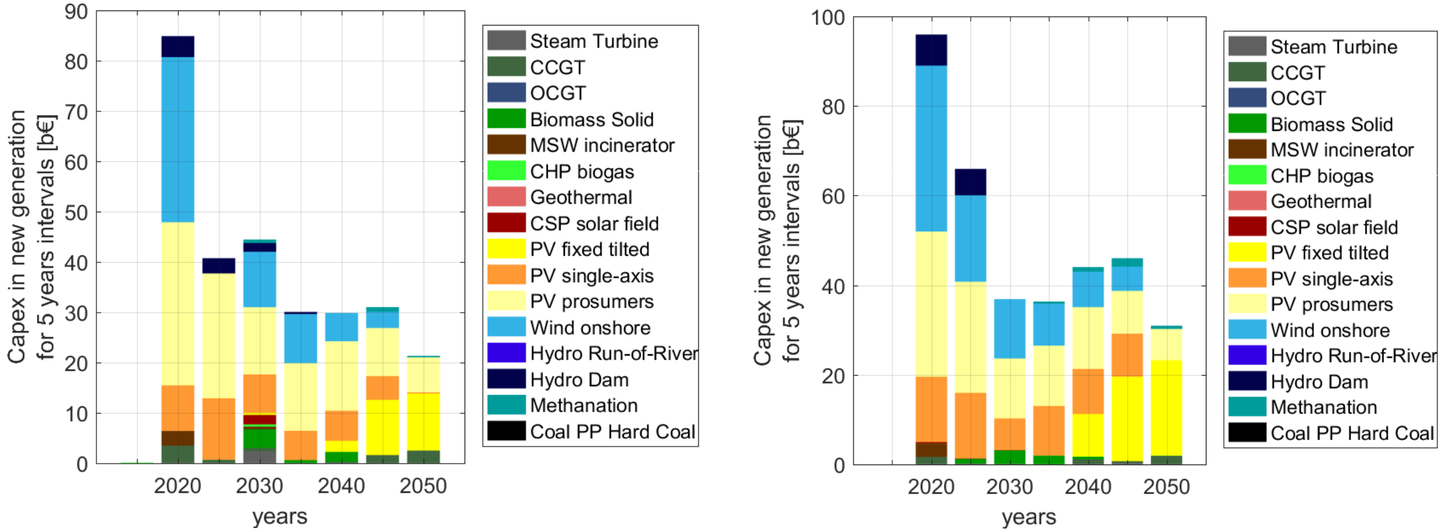

Figure 10: Capex in new generation for the 5-year intervals (b€) for power (left) and integrated (right) scenarios.

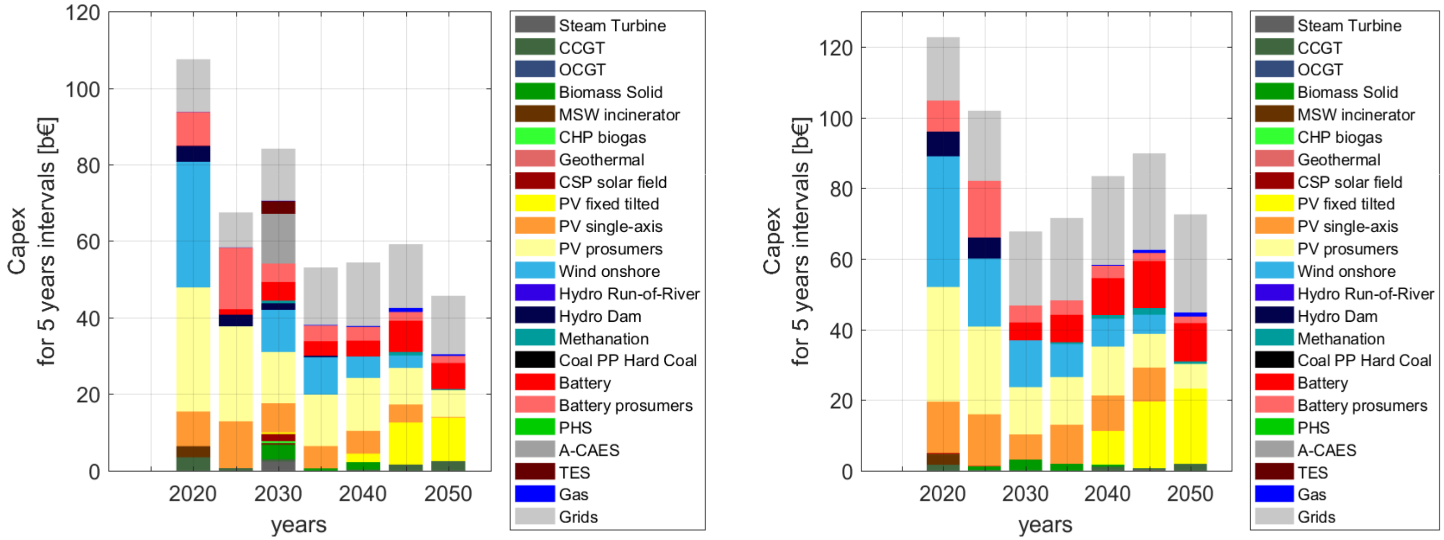

Figure 11: Capex for 5-year intervals for power (left) and integrated (right) scenarios

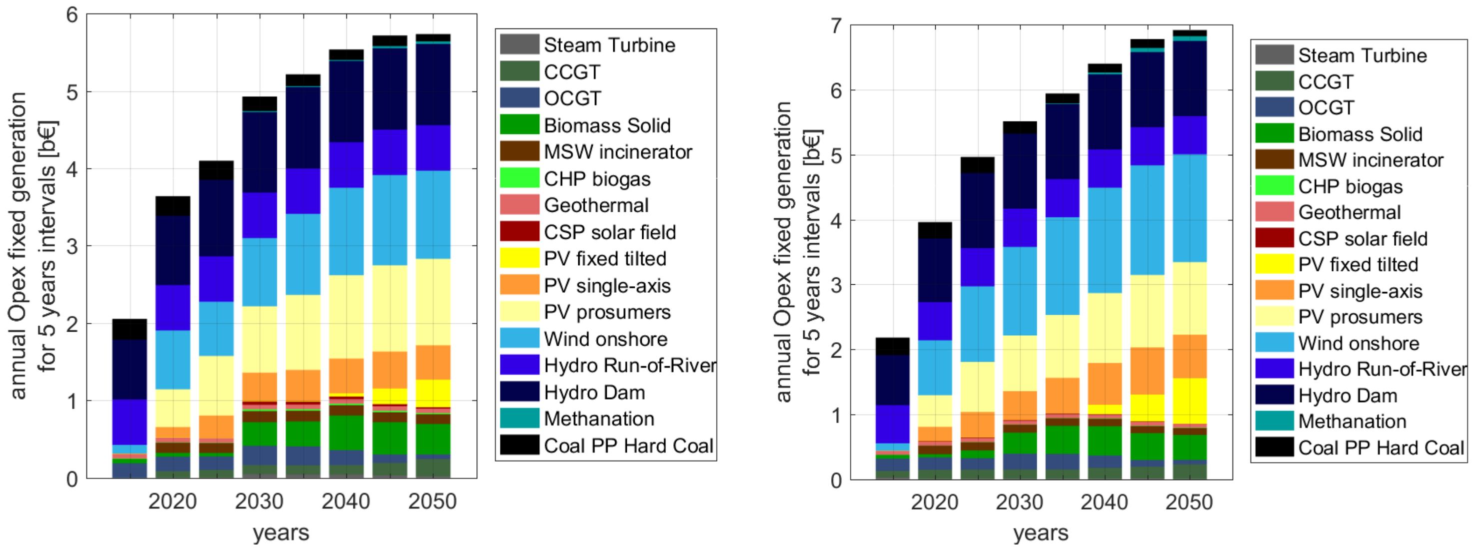

Figure 13: Variable operational costs for 5-year intervals for power (left) and integrated (right) scenarios.

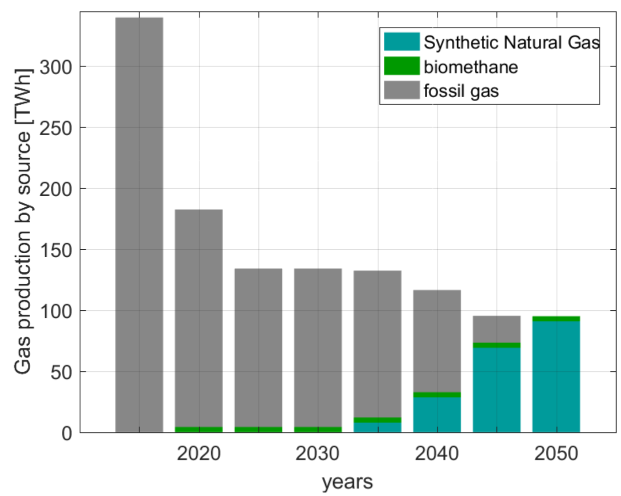

Figure 14: Input of gas by source for Turkey in the integrated scenario.

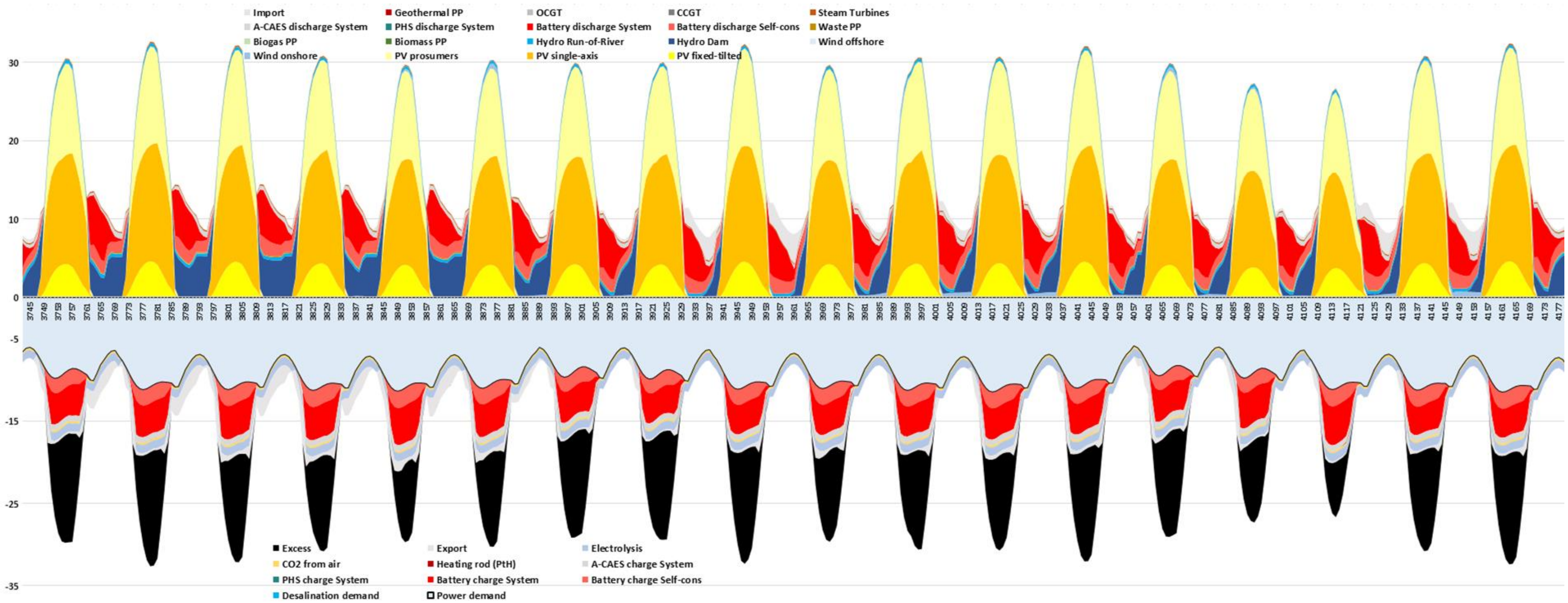

Figure 15: Hourly generation profile of power scenario for a representative week in during the raining season for Turkey in the year 2050

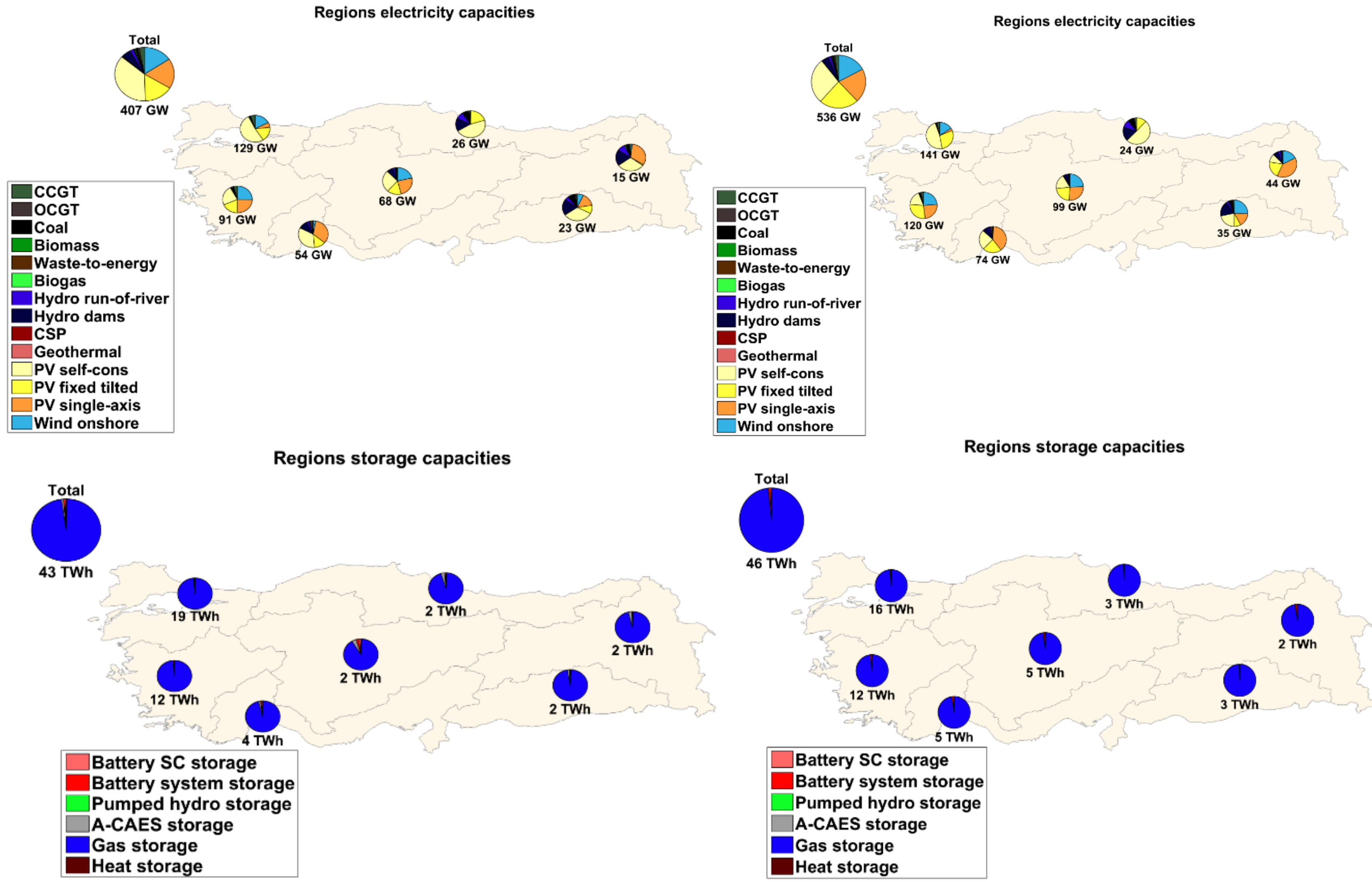

Figure 19: Installed capacities RE generation for power scenario (upper left) and integrated (upper right), storage capacities for the power scenario (bottom left) and integrated scenario (bottom right) for 2050.

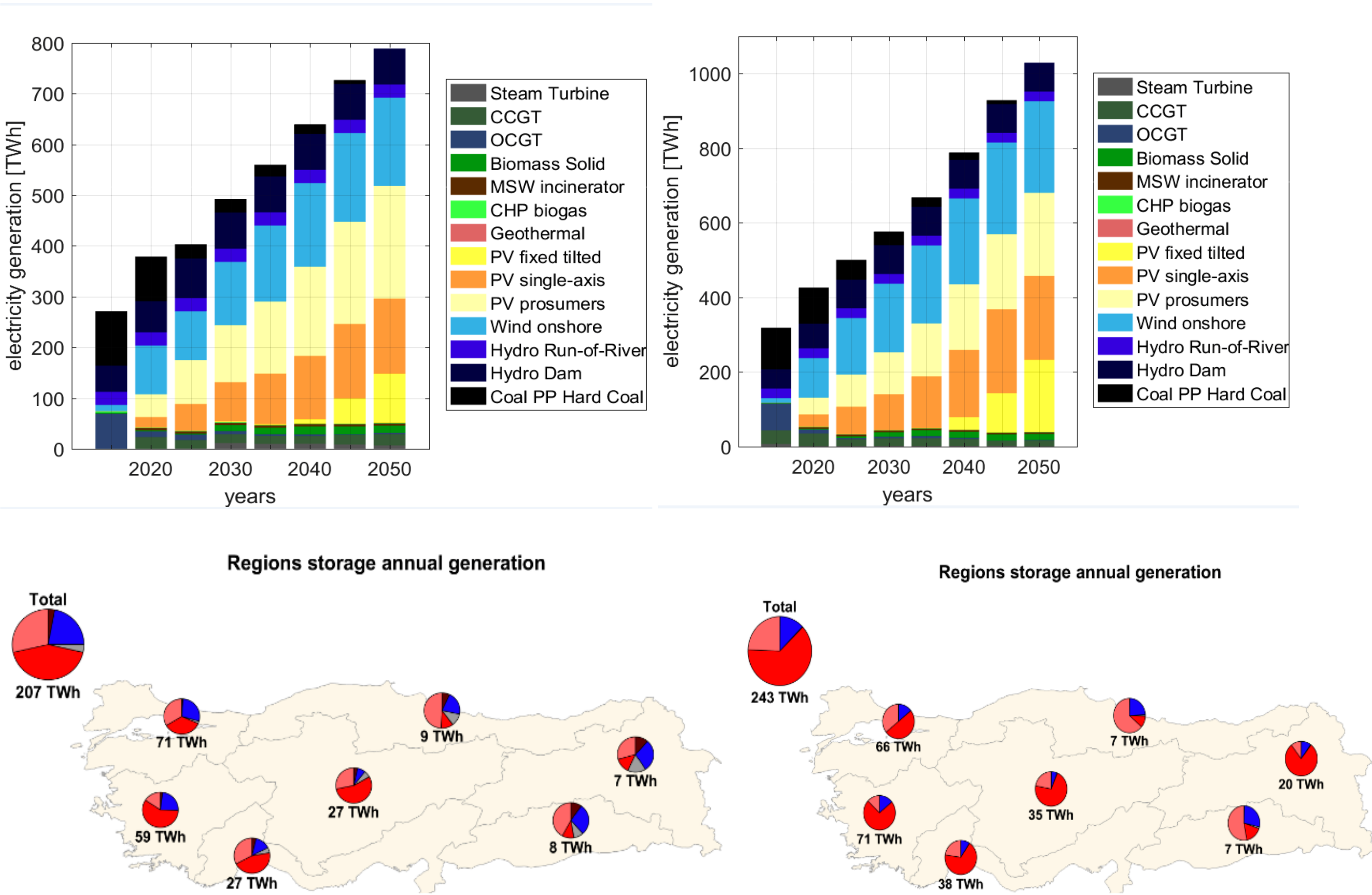

Figure 20: Installed capacities generation output for power scenario (upper left) and integrated (upper right), storage capacities output for the power scenario (bottom left) and integrated scenario (bottom right) for 2050.

Appendix – 2

Table 1: CO_2 emissions by energy resources in IEA member countries (IEA, 2016b).

	TPES (Mtce)	Energy-related CO_2 emissions (Million tonnes CO_2): Coal[1]	Oil	Gas	Other[2]	Total	% Coal in total energy-related CO_2 emissions (%)	Energy-related CO_2/TPES (t CO_2 / tce)	Energy-related CO_2/GDP (kg CO_2/ 2005 USD)	Energy-related CO_2/population (t CO_2 / capita)	Share in total OECD TPES (%)	Share in total OECD energy-related CO_2 emissions (%)
Australia	178.91	167.79	131.77	73.61	0.61	373.78	44.9	4.26	0.26	15.81	2.4	3.2
Austria	45.95	13.36	29.76	14.00	3.65	60.78	22.0	2.70	0.15	7.11	0.6	0.5
Belgium	75.39	12.07	44.51	27.54	3.24	87.36	13.8	2.36	0.17	7.83	1.0	0.7
Canada	399.83	73.89	266.00	213.89	1.03	554.80	13.3	2.83	0.31	15.61	5.3	4.7
Chile	51.58	24.34	43.65	7.82	0.00	75.81	32.1	3.00	0.29	4.25	0.7	0.6
Czech Republic	58.87	62.08	19.08	14.01	1.38	96.55	64.3	3.35	0.46	9.17	0.8	0.8
Denmark	23.16	10.21	16.06	6.64	1.60	34.51	29.6	3.04	0.11	6.12	0.3	0.3
Estonia	8.62	13.25	2.98	1.02	0.26	17.52	75.6	4.14	0.76	13.31	0.1	0.1
Finland	48.48	18.53	20.35	5.35	1.02	45.25	40.9	1.91	0.18	8.28	0.6	0.4
France	346.63	33.07	174.18	73.50	4.92	285.68	11.6	1.68	0.10	4.32	4.6	2.4
Germany	437.24	317.40	239.29	147.35	19.23	723.27	43.9	3.38	0.20	8.93	5.8	6.1
Greece	33.05	27.50	33.25	5.00	0.12	65.88	41.7	4.07	0.27	6.03	0.4	0.6
Hungary	32.62	9.00	15.51	15.28	0.49	40.28	22.3	2.52	0.29	4.08	0.4	0.3
Iceland	8.38	0.36	1.68	0.00	0.00	2.04	17.8	0.50	0.14	6.25	0.1	0.0
Ireland	18.24	8.34	16.86	8.42	0.24	33.86	24.6	3.79	0.14	7.34	0.2	0.3
Israel	32.42	26.00	21.89	16.80	0.00	64.69	40.2	4.07	0.24	7.88	0.4	0.5
Italy	209.68	51.80	145.60	117.23	5.09	319.71	16.2	3.11	0.16	5.26	2.8	2.7
Japan	631.06	464.21	453.56	260.16	10.70	1 188.63	39.1	3.84	0.21	9.35	8.4	10.0
Korea	383.45	303.78	150.99	99.80	13.25	567.81	53.5	3.02	0.46	11.26	5.1	4.8
Luxembourg	5.45	0.21	6.89	1.99	0.16	9.25	2.3	3.46	0.16	16.57	0.1	0.1
Mexico	268.54	48.04	245.40	137.36	0.12	430.92	11.1	3.27	0.37	3.60	3.6	3.6
Netherlands	104.21	35.14	47.05	63.01	3.14	148.34	23.7	2.90	0.18	8.80	1.4	1.3
New Zealand	29.38	5.69	18.00	7.55	0.00	31.24	18.2	2.17	0.19	7.01	0.4	0.3
Norway	41.07	3.01	20.65	10.78	0.87	35.31	8.5	1.75	0.08	6.87	0.5	0.3
Poland	134.31	194.60	56.39	25.21	2.85	279.04	69.7	4.24	0.52	7.25	1.8	2.4
Portugal	30.23	10.57	23.77	7.63	0.84	42.81	24.7	2.89	0.19	4.12	0.4	0.4
Slovak Republic	22.78	12.68	8.05	7.76	0.84	29.33	43.2	2.63	0.30	5.41	0.3	0.2
Slovenia	9.53	4.40	6.64	1.46	0.26	12.76	34.5	2.73	0.27	6.19	0.1	0.1
Spain	163.66	47.41	129.65	54.14	0.78	231.99	20.4	2.89	0.17	4.99	2.2	2.0
Sweden	68.79	6.87	26.44	1.72	2.39	37.42	18.4	1.11	0.07	3.86	0.9	0.3
Switzerland	35.80	0.58	27.10	6.30	3.76	37.74	1.5	2.15	0.06	4.61	0.5	0.3
Turkey	173.63	131.98	81.31	93.62	0.20	307.11	43.0	3.61	0.35	4.01	2.3	2.6
United Kingdom	256.32	113.38	153.20	138.24	3.01	407.84	27.8	3.25	0.16	6.31	3.4	3.4
United States	3 165.98	1 698.67	2 035.78	1 420.14	21.62	5 176.21	32.8	3.34	0.32	16.22	42.0	43.7
IEA Total	**7 162.79**	**3 847.06**	**4 394.05**	**2 920.92**	**107.29**	**11 269.32**	**34.1**	**3.21**	**0.25**	**10.07**	**95.1**	**95.1**
OECD Total	**7 533.24**	**3 950.20**	**4 713.31**	**3 084.36**	**107.68**	**11 855.55**	**33.3**	**3.21**	**0.25**	**9.36**	**100.0**	**100.0**
EU28	**2 235.68**	**1 056.74**	**1 276.67**	**770.09**	**56.52**	**3 160.02**	**33.44**	**2.02**	**0.18**	**6.22**	**x**	**x**

Note: Energy-related CO_2 emissions are calculated using the 2006 Tier 1 IPCC Sectoral Approach. Emissions from the combustion of biomass-derived fuels are not included in accordance with the IPCC greenhouse gas inventory methodology.

1. Coal comprises consumption of primary coals peat and oil shale and oil sands, plus imports of derived coal products

2. Other includes industrial wastes and non-renewable municipal wastes.