LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Energy Systems

Master of Science in Bioenergy Technology

Bülent Onur Peker

“The Opportunities and Limits of Bioenergy for a Sustainable Energy System in Turkey”

Examiners: Professor Christian Breyer
Professor Esa K. Vakkilainen

ABSTRACT

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The Opportunities and Limits of Bioenergy for a Sustainable Energy System in Turkey

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As an OECD member with fast growing economy and population, Turkey's energy demand has been increasing. However Turkey's current energy profile mostly depends on imported fossil fuel resulting in an unsustainable development while keeping away Turkey from COP21 targets. By the given motivation, renewable energy sources of Turkey are analyzed in an economic and technical frame for a 100% sustainable energy system for Turkey. Utilization of all the available renewable energy sources and its feasibility is analyzed and discussed. Moreover for that sustainable energy approach, the role and the amount of the available sustainable biomass potential of Turkey along with the sustainability indicators is discussed. The results clearly indicated that a 100% sustainable energy system for Turkey is possible for the year 2030 and 2050 within a 49-54 €/MWh$_{el}$ cost range.

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LIST OF ABBREVIATIONS

A-CAES	Adiabatic compressed air energy storage
Capex	Capital expenditure
CHP	Combined heat and power (Cogeneration)
COP21	Conference on Parties 21st edition, UN Climate Change Conference
CSP	Concentrating solar power
EMRA	Republic of Turkey Energy Market Regulatory Authority
ENTSO-E	the European Network of Transmission System Operators for electricity
FLHs	Full load hours
FS-UNEP	Frankfurt School-UNEP Collaborating Centre for Climate & Sustainable Energy Finance
GDP	Gross domestic product
GDRE	Republic of Turkey General Directorate of Renewable Energy
GHGs	Greenhouse gases
GWP	The Global Warming Potential
LCOC	Levelized cost of curtailment
LCOE primary	Levelized cost of electricity for primary generation
LCOS	Levelized cost of storage
LCOT	Levelized cost of transmission
MENR	Republic of Turkey Ministry of Energy and Natural Resources

MEU	Republic Of Turkey Ministry Of Environment And Urbanization
MFA	Republic of Turkey Ministry Of Foreign Affairs
MW_{el}	Megawatt electrical
OECD	Organisation for Economic Co-operation and Development
Opex	Operating expenses
PHS	Pumped hydro storage
PM	Particulate matter
PtG	Power-to-gas
TES	Thermal energy storage
TWh	Terawatthours (1000 TWh = 3600 PJ = 3.6 EJ)
UCTEA	Union of Chambers of Turkish Engineers and Architects
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital
WB	The World Bank

1 INTRODUCTION

Developing economies and industries have contributed a tremendous increment in primary energy consumption in last decades. Human beings have started to utilize and extract various energy sources in order to compensate this growing demand and support growing economies. However at a global level substantial amount of this required energy has provided from non-renewable sources. Moreover those non-renewable sources were not equally distributed by population or per land area. This led developing countries started to import fossil fuel sources in order to cover excess energy demand side. Mostly this brings a heavy burden on economy, also social and environmental challenges.

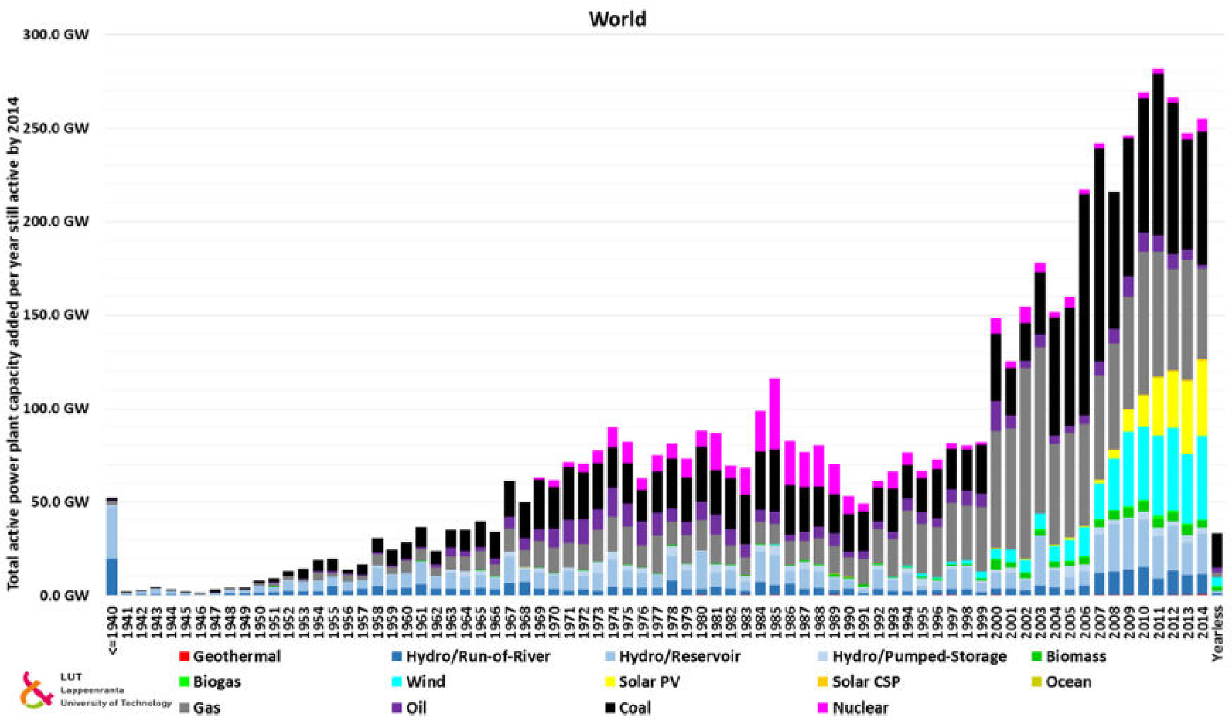


Figure 1. World active capacity installations from year 1940 to 2014 by power plant technology (Farfan and Breyer, 2017).

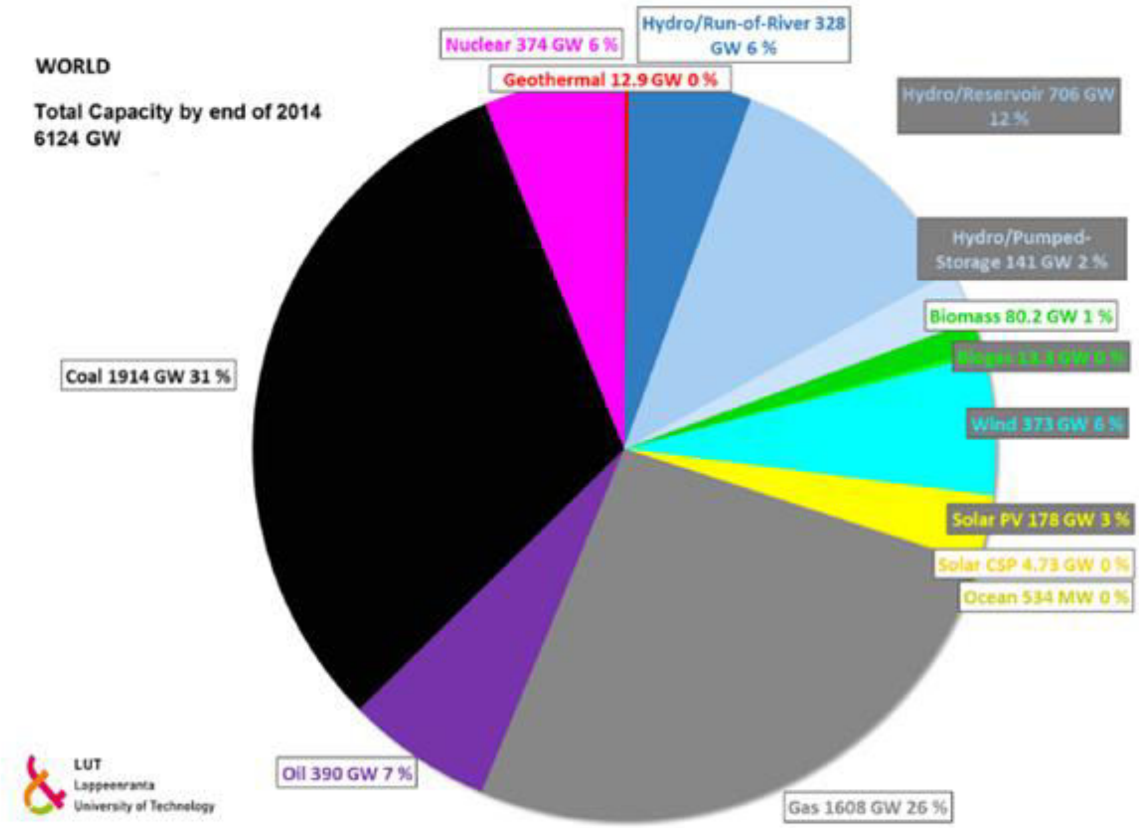


Figure 2. World total active installed capacity distribution by power plant type at the end of year 2014 (Farfan and Breyer, 2017).

As a member of the G20 and the OECD, Turkey is one of the biggest emerging countries. The income per capita has almost tripled currently exceeding 10,500 USD, in under a decade (WB, 2016).

Turkey has a poor amount of national fossil fuel sources therefore those primary energy sources are mostly being imported. By year 2015, Turkey's oil reserves are proved as 388.5 million barrels which can last only 21 years with current extraction rate. Additionally in 2015, 7% of crude oil demand and only 1% of natural gas demand supplied by national reserves (MENR, 2015).

Hence, currently Turkey is a primary energy importer. In 2014 total primary energy consumption in Turkey was 1457.2 TWh and approximately only 9.5% of the primary energy provided from hydropower and other renewable energy forms. Compared to the year 2013, renewable energy sources excluding hydro electricity provided 5.815 TWh more energy to the primary energy consumption (BP, 2015). The motivation for this was to utilize the unused potential of the country and to reduce the energy dependency.

Explicitly, the energy systems framework of Turkey mostly depends on foreign sources which defines Turkey's self reliance in terms of energy along with a burden on its economy.

Turkey has steady population growth (annual %) from 2012 to 2015 by +1.2% (WB, 2016). By the end of 2014 population of Turkey has reached almost 77.7 million resulting with rapid urbanization. It is expected to reach 93.5 million people by 2050 (Turkish Statistical Institute, 2015).

Turkey has 783,560 square kilometer total surface area and ranks 36th among other countries (WB, 2016). Moreover by the fair and favorable climatic conditions bring along high agricultural yield and remarkable husbandry.

In year 2015 at country level estimation; total amount of animal waste was estimated as 156.76 Mt, total amount of agricultural waste 142.45 Mt and total amount of municipal solid waste was estimated as 29.6 Mt per year respectively (GDRE, 2016).

Saliently, Turkey has a great biomass potential from wastes and residues to cover some share of the primary energy demand. Moreover for this study, only sustainable biomass sources are taken into account excluding energy crops.

There are several growing concerns regarding the energy crops cultivation. Those concerns include primarily the environmental impacts, land use change and loss of biodiversity. For cultivation purposes wasteland, grassland, forestry land etc. are converted into an agricultural land. This land use change is strongly connected to greenhouse gas emissions. The overall amount depends how much carbon is stored in the soil and biomass. Moreover fertilizer usage boost those emissions. Secondly cultivation of energy crops will cause decline of organic carbon, increment in water demand and erosion rates. Depending on the habitat or land replaced with dedicated biomass crop will result a level of biodiversity loss (Allen et al., 2014).

The main objective of our work was to resolve the opportunities and set the limits of bioenergy for a sustainable energy system in Turkey. Furthermore, implementing bioenergy applications also brings a solution to annually produced waste in general which will ultimately affect the environmental and economic status.

2 GLOBAL TREND IN POPULATION, ENERGY CONSUMPTION AND CLIMATE CHANGE

2.1. World's Population and Projections

According to UN “World Population Prospects The 2015 Revision” report, in mid-2015 the global population has reached 7.3 billion people; meaning another additional one billion people added to that number in the last twelve years. Moreover it is estimated that global population will increase more than one billion people in the next 15 years (UN, 2015). Table 1 presents estimations of global population and distribution for major areas in year 2015, 2030, 2050 and 2100.

Table 1. Projections of world population (UN, 2015).

Major Area	*Population (millions)*			
	2015	2030	2050	2100
World	7 3749	8 501	9 725	11 213
Africa	1 186	1 679	2 478	4 387
Asia	4 393	4 923	5 267	4 889
Europe	738	734	707	646
Latin America and the Caribbean	634	721	784	721
Northern America	358	396	433	500
Oceania	39	47	57	71

Increasing global population and welfare request more natural sources to utilize and lead more demand in terms of energy. In year 2014, world total primary energy supply was 159,319.4 TWh. Moreover according to World Energy Outlook of the IEA world TPES for year 2040 is estimated to be 174,450 TWh based on policies to keep the global warming level below 2 °C (IEA, 2016).

In the year 2000, world primary energy demand was 117,126 TWh and according to World Energy Outlook 2013 this value will increase 73% from year 2000 to 2035 (IEA, 2013).

However only 16.7% of the global energy consumption in 2010 provided from renewable energy forms. Moreover only 8.2% came from modern renewable energy technologies, the remaining 8.5% of total global energy consumption provided from traditional biomass. Traditional biomass is utilized fundamentally for heating and cooking in rustic territories of developing countries and could be considered renewable form of energy (REN21, 2016). As it can be seen from Figure 3, still major share belongs to fossil fuels in global energy frame.

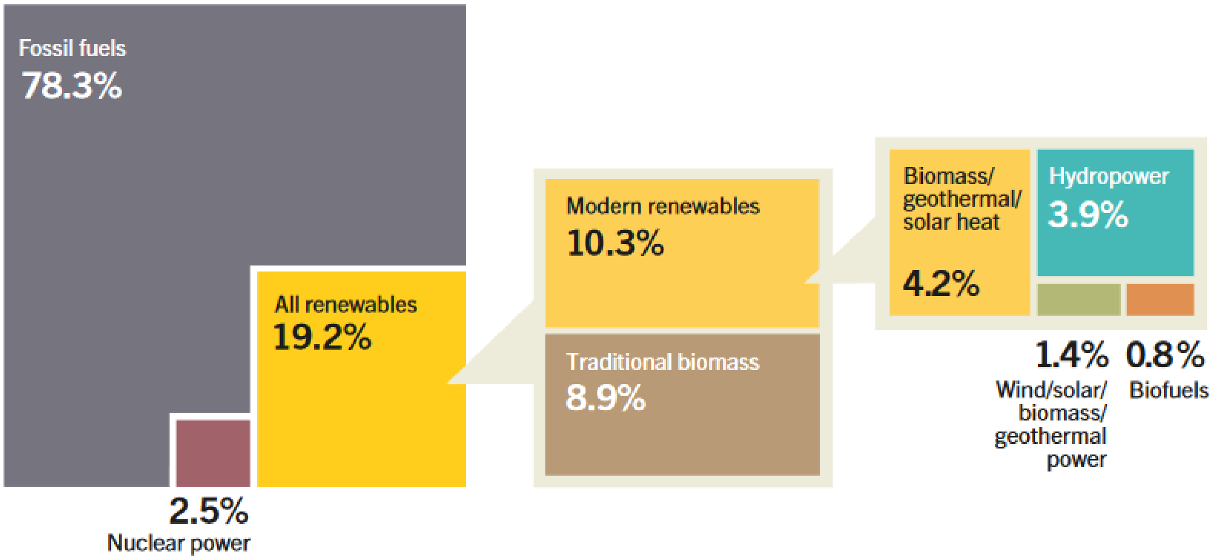


Figure 3. Estimated renewable energy distribution of global final energy consumption in year 2014 (REN21, 2016).

The global energy demand is also boosted by developing ability to create products and services for both domestic and foreign markets and expanded interest for machines and transportation machinery. However there is a high contrast in the distribution of global energy demand. It is evaluated that mostly non-OECD countries will contribute to this demand due to the strong economic growth and expending populations (EIA, 2016).

From year 2012 to 2040, the energy demand in non-OECD countries expected to rise by 71%. Opposite to that in the countries which are mature energy consumer and the OECD ones with slow expending economy, the expected energy utilization will rise by 18% from year 2012 to 2040 (EIA, 2016).

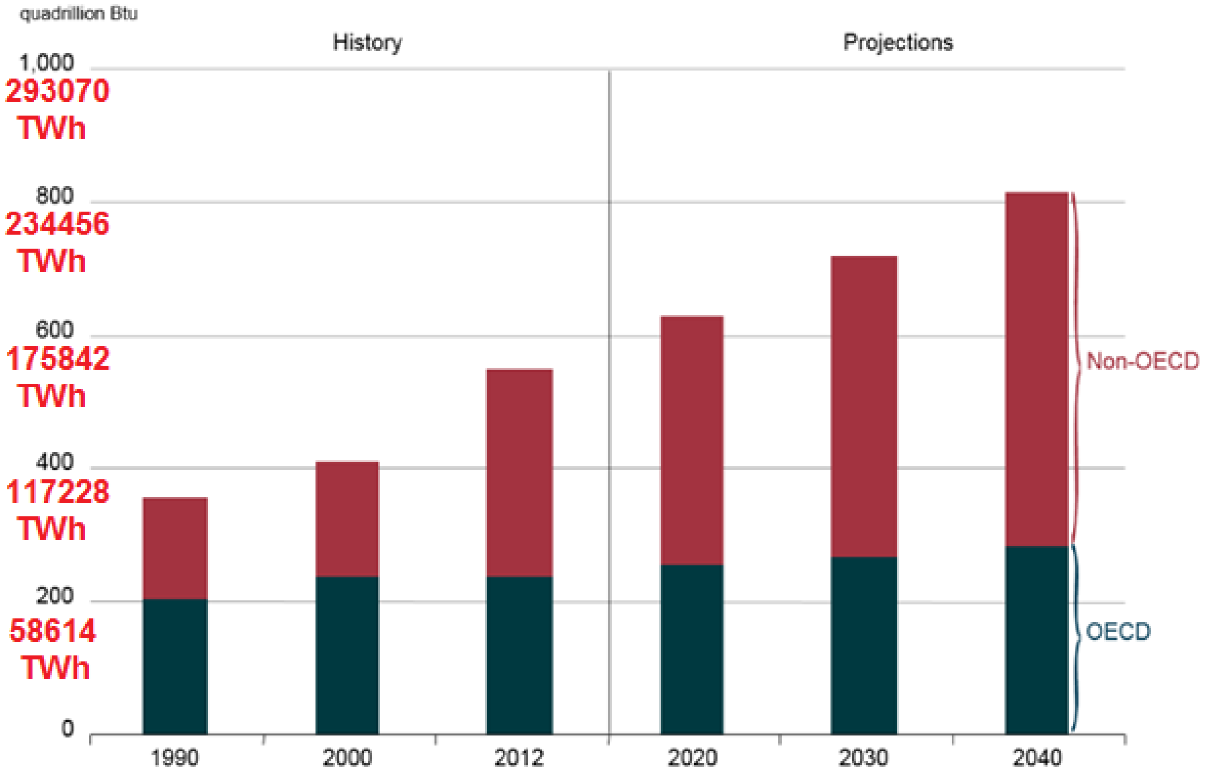


Figure 4. Global energy consumption projection for both OECD and Non-OECD countries (EIA, 2016).

Energy and other sources are highly required for the projected human population of more than 9 billion, continued growth of global economic development by year 2050. However for social, environmental and economic sustainability triple bottom line aspect, 50% more fuel and 80% CO_2 emission decline are required (Wagner et al., 2016).

2.2 Climate Change and the Paris Agreement

Climate change is one of the biggest threats all the countries in the world are facing to in this century. Emissions of anthropogenic carbon dioxide-equivalent gases cause acidification, ozone depletion and greenhouse effect in our atmosphere. Based on "The Global Warming Potential

(GWP)" measure, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) consist of the three major anthropogenic GHGs (EPA, 2016).

Since the beginning of industrial age, obviously the energy obtained from fossil fuels has been causing much more carbon yield than currently absorbed from the natural carbon cycle. Figure 5 below represents the distribution and the level of CO_2 emitted to the atmosphere in year 2010 (kg C/m^2/a).

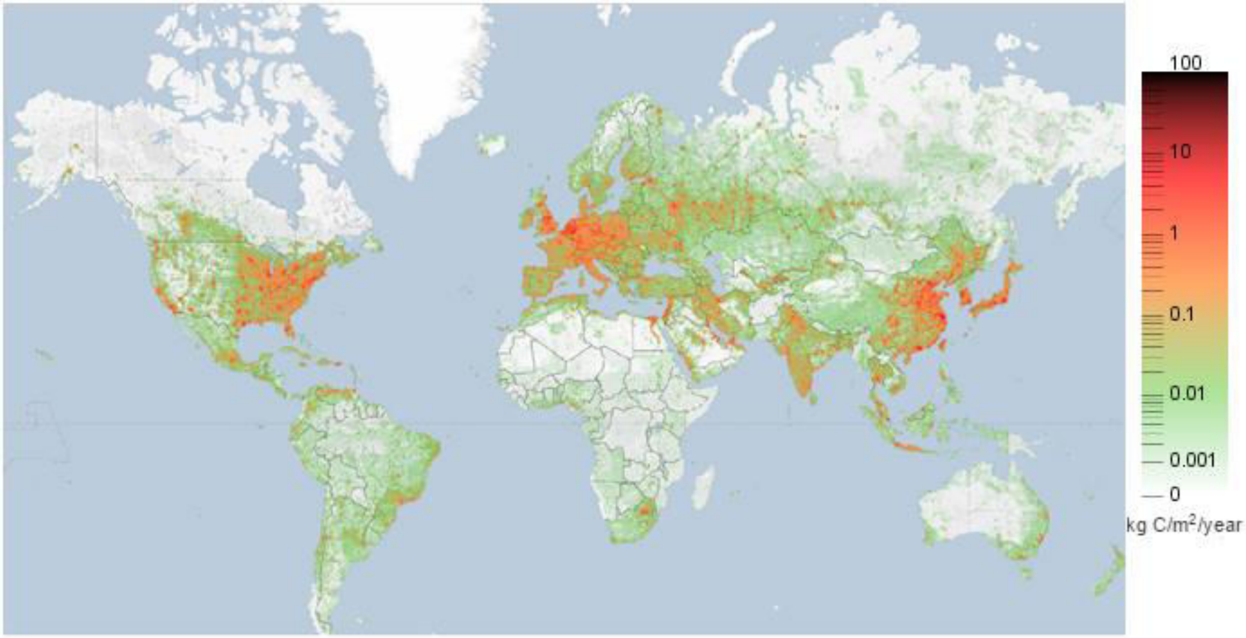


Figure 5. Distribution of CO_2 emission as a result of fossil fuel combustion (Gurney et al. 2010).

Regarding the enormous GHGs emissions caused by human beings, push the sustainability boundaries of the earth which lead to some threatening and serious responses from our planet. Record high temperatures, floods and drought have become more often than ever. Moreover the global temperature anomaly was followed by melting snow and ice along with the 17 cm global sea level increment in the last century (NASA, 2016).

Increment in renewable energy utilization worldwide in order to overcome climate change is a global unanimity and acknowledged as one of the most standout sustainability concern of our planet (Rockström et al., 2009). Concerning the issue, in December 2015 the Paris Agreement was universally agreed in UN Framework Convention on Climate Change. The 2030 Agenda for Sustainable Development and the Paris Climate Change Agreement goals was signed by almost 200 countries (FS-UNEP Collaborating Centre, 2016).

Some bullet points of the agreement are as follows:

- *"In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."*
- *“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”* (UN, 2015).

The commitment for those goals requires a significant transition towards a clean, sustainable and renewable energy systems; meaning the entire world shall shift away from fossil fuel energy sources.

3 RENEWABLE ENERGY TRANSFORMATION

As the global energy demand increased the growth in renewable energy continued in 2014. Even though the total energy usage rose parallel with global economy growth, energy production associated global CO_2 emissions were stabilized for the first time in last 40 years. The reason behind the decline in global CO_2 emissions and global economic growth is the leap in renewable energy utilization in China as well as the relevant actions has being taken in OECD countries. The separation between global CO_2 emissions and global economic growth is a great indicator of renewable energy forms have been becoming a mainstream energy supplier. In the early 2015, a total number 164 countries have represented their renewable energy targets (Teske et al., 2015).

Another great progression occurred in year 2015 in terms of investment and new installed capacity of renewable energy technologies at a global scale. Total amount of investments exceeded 6 times than in year 2004, accounting almost 286 billion USD. Furthermore, more than half of the new installed power generation capacity was renewable energy forms for the first time. Addition to those, cost of renewable energy generation has continued to fall especially solar photovoltaics system technology (FS-UNEP Collaborating Centre, 2016).

As of now, 22.8% of all global electricity consumption is provided by renewable energy technologies and this number is expected to grow further. The reason behind that expectation is declining cost of renewable energy technologies, the pattern of new installed capacities, increasing global demand and changes in policy. According to Bloomberg New Energy Finance, renewable energy technologies will cover the two thirds of the total investment spendings for the new power generation capacity from 2016 to the year 2040 - which equals around 8 trillion USD (RE100, 2016).

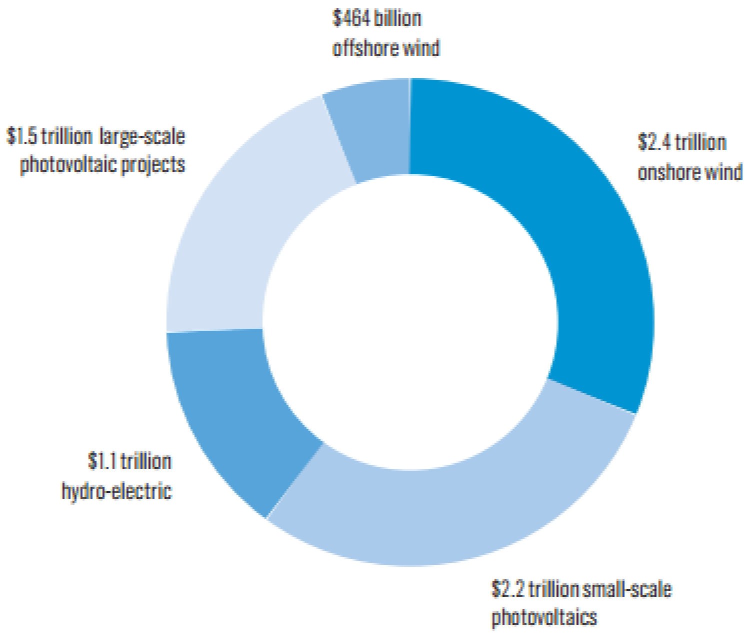


Figure 6. The envisaged investments on the electricity generation by renewable energy forms from 2016 to 2040 (RE100, 2016).

The great cost competitiveness of solar and wind energy forms a basis for this envisage above. According to another forecast, for many countries utilizing solar and wind energy will be more economical rather than the energy provided from coal and gas by year 2030. Moreover by the year 2040, 47% project cost decline in solar and 32% for wind energy is expected (RE100, 2016).

4 BIOENERGY IN GLOBAL SCOPE

Biomass refers to a form of energy source as organic material, i.e. decomposable, derived from living organisms on a renewable basis. It is carbon based and usually contains high amount of moisture with the presence of an organic compounds mixture as well as alkali, alkaline earth and heavy metals. Wood and agricultural residue are the most well-known biomass sources at a global level since human beings began to utilize them in order to cook and obtain heat. Even today wood still remains as the largest type of biomass source (NREL, 2016).

Biomass's reserved energy comes from synthesized carbon dioxide and water by absorbed sunlight via photosynthesis resulting with carbohydrates and oxygen release to the atmosphere. In order to utilize that stored energy photosynthesis process is reversed and carbon dioxide again will be released to the atmosphere. Therefore the process is repetitive as the growing plants will need that carbon dioxide again. The criteria for sustainable biomass is highly controversial and includes many aspects. Some bullet points of the criteria and principles for sustainable biomass according to Greenpeace Energy [R]evolution 2015 Outlook are:

- *"Bioenergy production must be as resource efficient as possible, and deliver significant reductions in greenhouse gas emissions compared to fossil fuel-based energy systems."*
- *"In order to close nutrient cycles and reduce* CO_2 *emissions, bioenergy should preferably be produced from regionally available biomass and satisfy regional energy need."*
- *"Biomass for bioenergy should preferably be utilized in applications where it delivers the highest* CO_2 *savings."*
- *"Any bioenergy project should replace energy produced from fossil fuels. Considering the entire production chain, above-ground and below-ground carbon stock changes and any indirect land use changes, the net greenhouse gas emission reduction of such a project must be at least 50% compared to a natural gas reference, 60% compared to an oil reference and 70% compared to a coal reference. This net emission reduction must be realized within 20 years."*
- *"Tree harvest levels in forests must not be increased as a result of bioenergy production."*

- *"Land with a high carbon stock (forests, woodlands, peatlands, grasslands) must not be converted."*
- *"Bioenergy production must not cause negative impacts on livelihoods, nor on people's access to nutritious and healthy food. land and water grabbing, land use conflicts and*
- *other social conflicts must be prevented."* (Teske et al., 2015).

Furthermore, according to UK Energy Research Centre "Energy from biomass: the size of the global resource" report (Slade, 2011); ultimately the major inclination for foodstuff, energy and ecological insurance will be critical determinants for the biomass utilization level for energy production, and whether that energy production realized in either sustainable or unsustainable practices. The debate for biomass potential estimations most frequently follows the order of theoretical; technical; economic; and realistic opportunity. The studies for biomass potential can be comprehensively partitioned into two classifications, those that push the limits of what may be physically conceivable and those that investigate the limits of what may be socially adequate or ecologically dependable. Since a large portion of the most essential variables influencing biomass potentials can't be anticipated with any sureness, what if scenarios must be the point of view rather than predictions for each of those estimations.

Regarding this debate, four scenarios were presented as what if scenarios by composing and summarizing the current data available about bioenergy potential. In the low-biomass potential case high level of environmental protection with minimized land use change (including low input agriculture) are essential pre-conditions. However for the bioenergy output the numbers are mixed. Energy crops are not totally isolated from the cropland area. Therefore the sustainable biomass potential (derived from agricultural residues) must be lower than 30 EJ (8,333 TWh) by utilization of the agricultural residues only.

For the lower-mid biomass potential case low population and limited land use change are essentials, the sustainability boundaries are challenged. Again the bioenergy output mixed with energy crops, even a tiny section of agricultural land left for energy crops. Accordingly the bioenergy output limit must be lower than 100 EJ (27,777 TWh) by utilization of all residues.

The bioenergy output limit remains unchanged (27,777 TWh) for the upper-mid and high band scenarios because the same energy output level applies for all residues. The rest of the energy output increment only caused by excessive deforestation and land use change also limiting global population. Eventually those two scenarios become highly unrealistic and unsustainable as the energy croplands invade good agricultural lands and forestry areas.

According to the most pessimistic scenario, the bioenergy supply has twice the capacity of total bioenergy utilization in the year 2015. On the other hand, the most optimistic scenario is capable of supplant and surpass all the energy provided from fossil fuels in year 2015. The huge deviation between these capacities of bioenergy arises from the energy crops allowance.

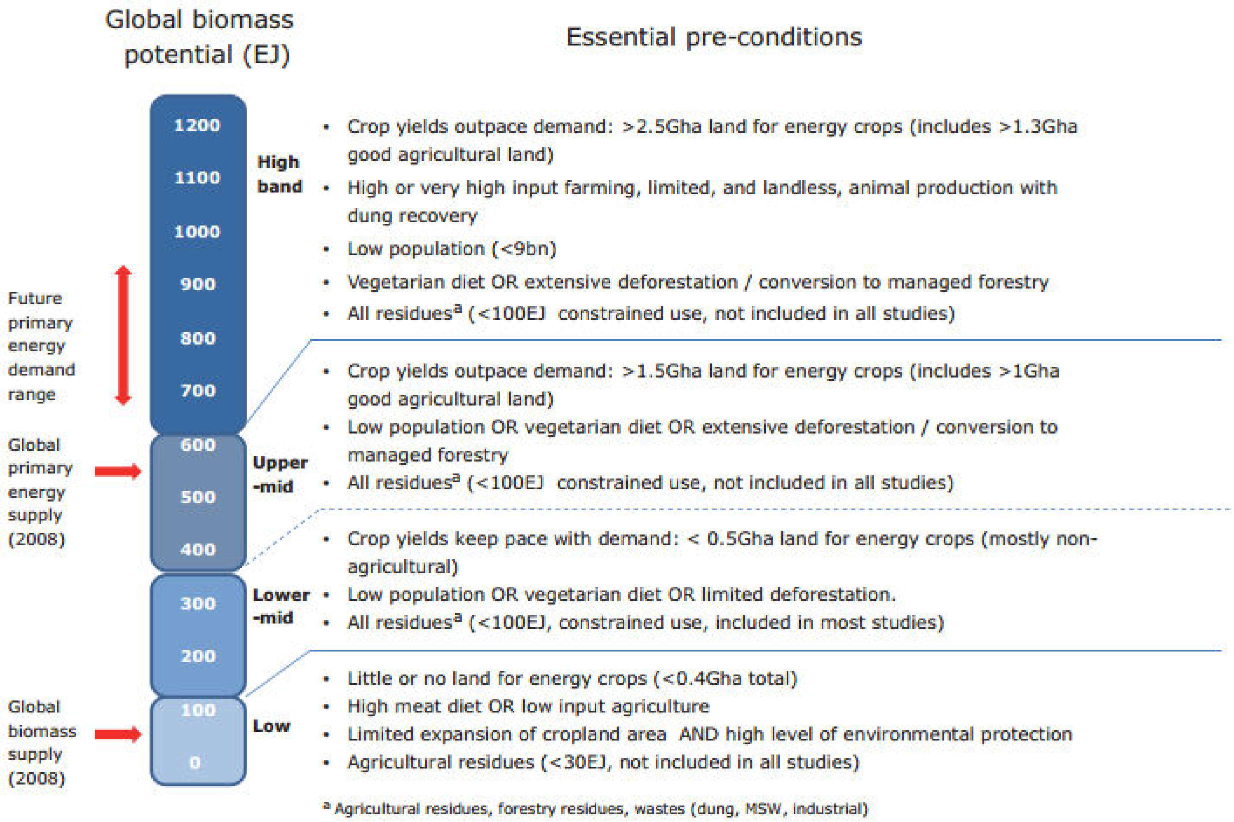


Figure 7. Environmental, social and agricultural interactions with high, medium and low global biomass potential estimations (Slade, 2011).

Roughly 10% (13,889 TWh) of world total primary energy supply is provided by bioenergy overall. Traditional biomass covers the major share of that energy supply which is often not sustainable due to utilization of wood, charcoal etc. with a very low energy conversion rate (from 10% to 20%). Moreover, 1.5% (370 TWh) electricity generation of the world was produced from bioenergy in year 2012 (IEA, 2016). Bioenergy stands as single largest form of renewable energy today. In order to obtain heat production and power generation many different technologies exist by biomass utilization. A large part of the heat produced in developing countries for cooking purposes via non-efficient methods such as very basic cookstoves, open fires etc. (IEA, 2016). From biogas applications to CHP, it is becoming more convenient put to good use the organic waste produced from any source. Addition to those, biomass co-firing in coal-fired power plants helps to reduce GHG emissions (FEMP, 2004).

In the medium term, a tremendous increment is expected for bioenergy production and installed capacity. Due to the renewable energy targets set by both OECD and non-OECD countries global bioenergy production is expected to reach 560 TWh by the year 2018 (IEA, 2016).

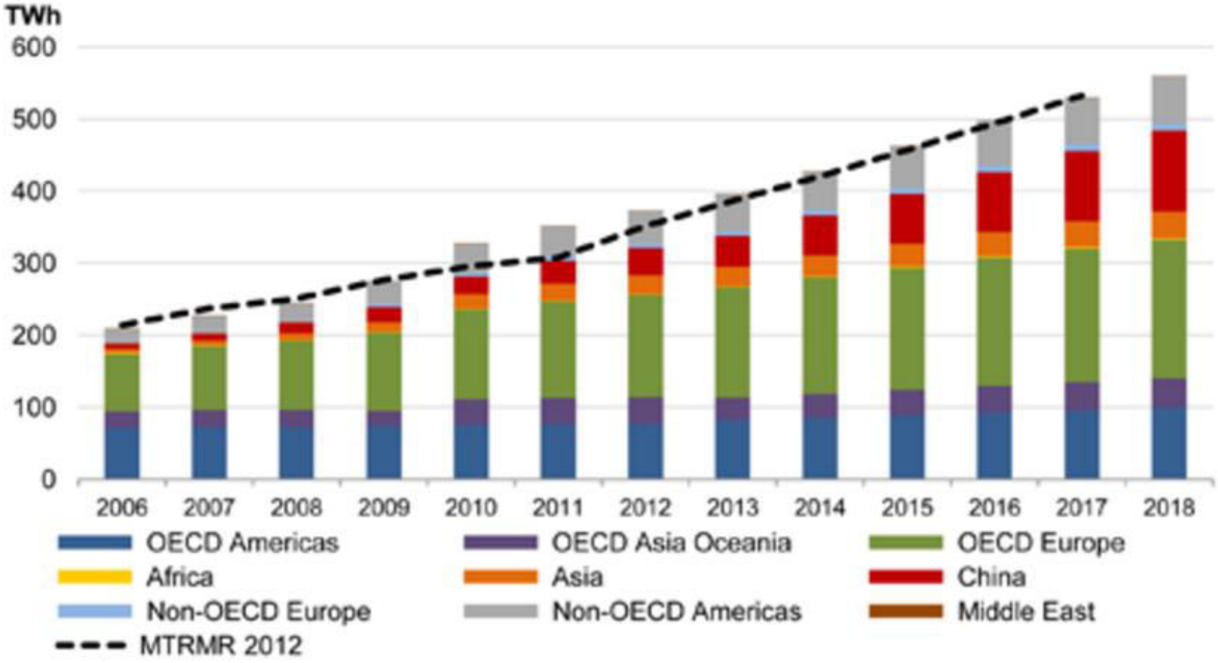


Figure 8. Bioenergy production and projection (IEA, 2016).

The other main drivers for that are many growing economies with rapidly increasing energy demand along with availability of the renewable waste and sustainable biomass. Furthermore parallel to EU-2020 targets, bioenergy utilization for heat in OECD Europe makes a great contribution for global heat production from bioenergy. According to IEA, global biomass heat utilization could reach 4448 MWh in 2018 by 3% growth annually (IEA, 2016).

By the recognition of sustainable and carbon neutral characteristics of biomass, bioenergy applications have become more and more prevalent. Advancement in technology has provided more energy conversion methods, increasing overall process efficiency as well as lowering the costs. With today's technology biomass can be utilized for heating, electricity production as well as liquid biofuels for transportation. Such diversity in energy framework may offer national energy supply security.

4.1. Bioenergy Applications

In order to characterize the form of renewable energy that can be obtained from the recent living or living biological organisms "biomass" term is widely used. As described in the Chapter 4 above, biomass may consist of forest and agricultural residues, sludge or animal excrements as well as algae. The assortment of end use of biomass utilization contains electricity production, heating applications and finally transportation. Mostly heat and electricity are generated simultaneously in biomass energy systems via cogeneration; also for transportation bioenergy is stored as biogas or biofuels in liquid form. Bioenergy also considered as CO_2 neutral only if sustainable biomass source conditions are meet (Teske et al., 2015).

The principle of biomass power plants that generating power work simply like characteristic gas or coal power stations with the exception of that the fuel must be handled before it can be incinerated. Typically these power plants are not as large as coal fired power plants in the light of the fact that minimum biomass transportation is desired; meaning that their fuel shall be obtained from just around the facility location (Teske et al., 2015).

Biomass can be turned into advantageous types of energy forms by utilization of various distinctive procedures. However there are some important elements that influence the choice of biomass conversion process. Economic and environmental restrictions, quantity and the features of biomass fuel, desired output energy form and characteristic factors of the project etc. are the main factors involved in decision-making process (McKendry, 2001).

For obtaining heat from bioenergy systems following alternatives can be applied: heat piping to neighbouring industry or habitation; by using dedicated heating systems or simply taking advantage of a combined heat and power (CHP) system.

Utilizing the energy from biomass can result either biological methods or thermochemical processes. Biological methods cover solid biomass decomposition by fermentation and anaerobic digestion processes yielding fuel in liquid or gaseous form. On the other hand thermochemical processes consist of gasification or pyrolysis in order to perform a direct combustion.

4.1.1. Thermochemical processes

4.1.1.1. Biomass combustion

The most widely recognized method to turn biomass into both heat and power is direct biomass combustion representing more than 90% of biomass operations (Teske et al., 2015). Essentially the combustion process based on the reaction of hydrogen and carbon provided from the biomass fuel with excess oxygen resulting water and CO_2 and heat to utilize.

Currently the available technology for such a process can be broadly distinguished into fixed bed and fluidised bed combustion options. New technologies are also under development in order to get higher efficiencies, decreasing the costs as well as overall emission levels and to utilize uncommon fuel types (Veringa, 2009).

Primary air is allowed to pass through firstly through a fixed bed to perform drying, gasification and charcoal combustion in consecutive stages. Secondary air is used in a separate combustion zone to burn the produced combustible gases.

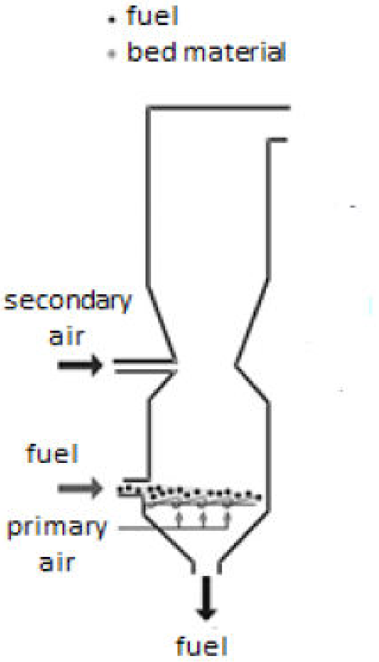


Figure 9. Fixed bed combustion (grate furnace) technology for biomass (Duffy, 2012).

On the other hand the primary combustion air enters from the below of the furnace bed material in fluidised bed combustion. The tremendous velocity of the intake air creates an intense mix of seething gas and solid particles. Therefore fluidised bed combustion technology makes available to utilize fuel types in little particles (sawdust, fine shavings e.g.) that are fed into the furnace pneumatically.

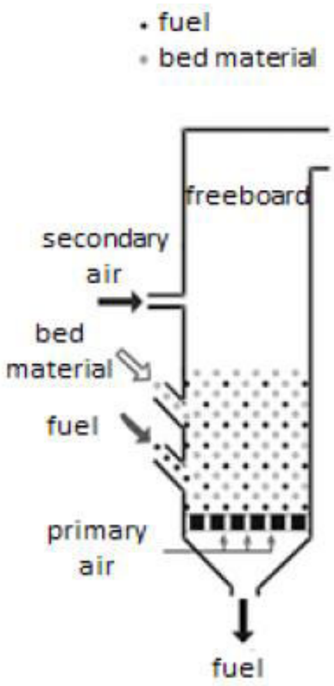


Figure 10. Bubbling fluidised bed combustion technology for biomass (Duffy, 2012).

4.1.1.2. Biomass gasification

Gasification systems are rather advanced and more efficient conversion technology compared to conventional power production. Gasification begins with heating process in order to get blended combustible gases by achieving biomass partial oxidation. This combustible gas mixture (termed fuel gas or product gas) contains remarkable amount of H_2 and CO compounds. The energy content of this gas mixture highly depends on the type of the raw material and the methods applied. Additionally syngas or biomass synthesis gas can be obtained by upgrading this initial fuel gas (Chum et al., 2011).

Wood or woody biomass are most widely raw biomass materials that gasified, on the other hand non-woody biomass also can be converted by employing uniquely designed gasifier systems (Chum et al., 2011).

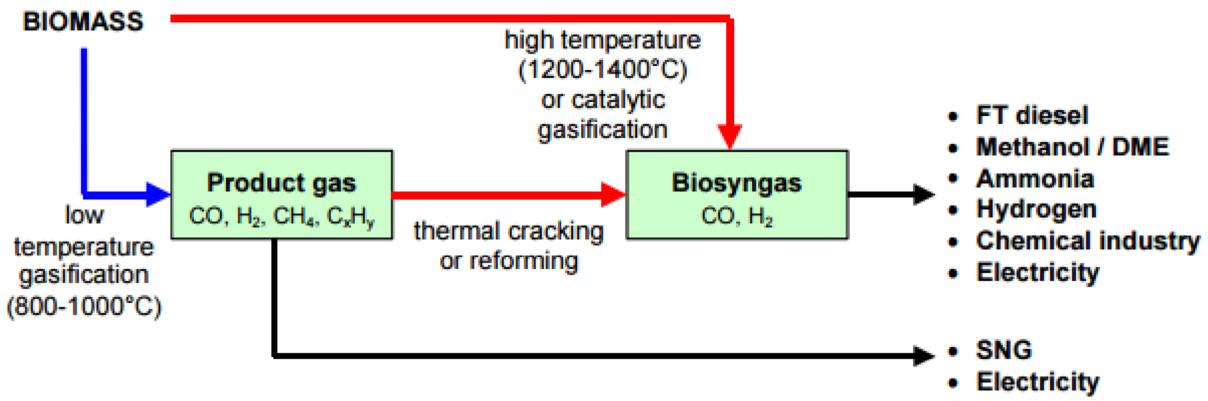


Figure 11. Production of ‘biosyngas’ and ‘product gas’ and their end-use applications (Boerrigter and Rauch, 2005).

Gasification technology offers more control in heating stage, increased overall efficiency and producing fuels and chemicals as well in comparison to combustion. Moreover during power generation process the overall emission levels are also declined by comparison with a steam cycle and direct combustion technology (Chum et al., 2011).

4.1.1.3. Pyrolysis

By the heating process exposure in an anaerobic environment (without the presence of Oxygen) thermal decomposition occurs in biomass that yielding a carbon-rich solid and material in both in liquid (pyrolysis oil) and gas form. The carbon rich material (titled differently as charcoal or coke, char and biochar gathers almost the half amount of carbon of the raw biomass material. Furthermore non-condensable gases is the term for the mixture created by the volatiles that are partially condensed.

The relative measures of output of the three coproducts rely on upon the process temperature and the overall amount of time utilized as a part of the procedure. When the process runs in higher temperature values, more biogas is obtained as process output. Alternatively the process held in lower temperature values results in more solid and liquid products (Teske et al., 2015).

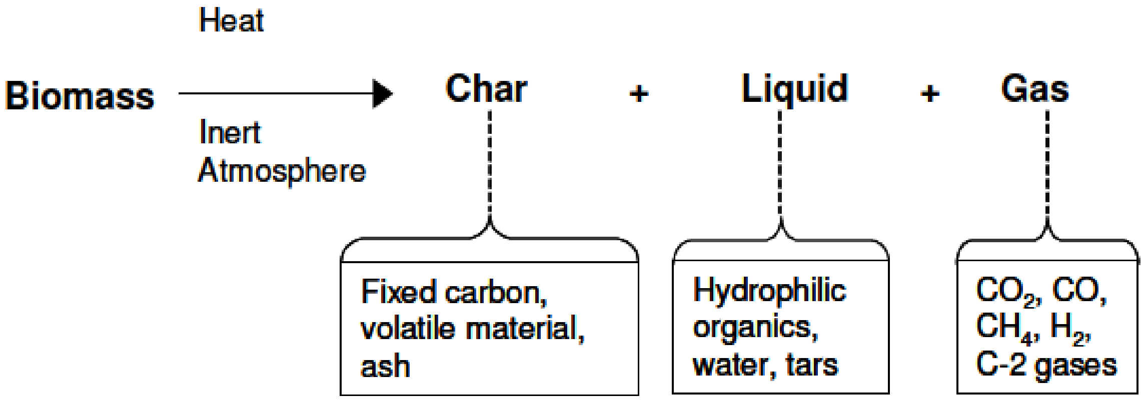


Figure 12. Representation of pyrolysis and Process output (Brownsort, 2009).

4.1.2. Biochemical Processes

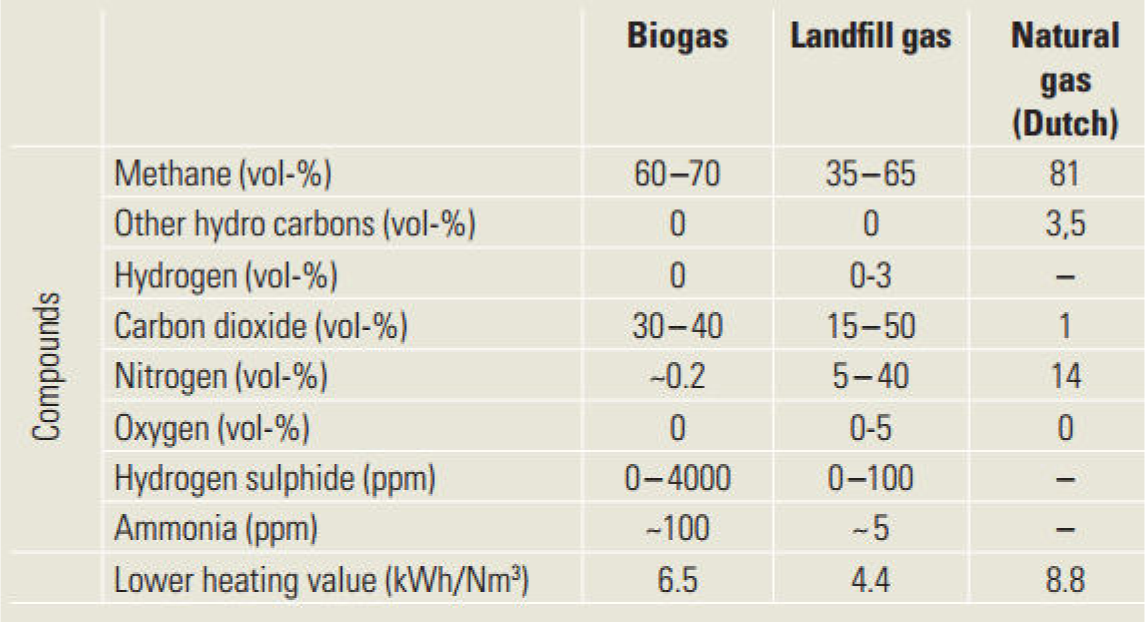
Anaerobic digestion and fermentation biological processes explained below are considered as very suitable for highly wet organic biowaste (sludge, livestock slurry, agricultural waste etc.) (Teske et al., 2015).

4.1.2.1. Anaerobic digestion

Biodegradable waste is broken down under necessary anaerobic digestion conditions by the help of microorganisms. Organic materials are digested by the anaerobic bacteria without the presence of oxygen. Finally anaerobic digestion process that is applied to organic waste yields biogas which generally contains around 35 - 45% carbon dioxide and 60 - 70% methane (Rasi, 2009). The biogas obtained in anaerobic digestion plant also usually may include slight volume of hydrogen sulphide and ammonia and additionally remnant of different gases (H_2, NH_3, N_2, and O_2) (Ahmad et al., 2015).

The composition percentage of biogas, landfill gas and natural gas in Dutch standards are given respectively in Table 2 below. Natural gas contains larger amounts of methane along with hydrocarbons compared to biogas or landfill gas. The rate of carbon dioxide is another distinction that has influence on lower energy content per unit volume of each gas source.

Table 2. Comparison of general composition of different gas sources (Petersson and Wellinger, 2009).



		Biogas	Landfill gas	Natural gas (Dutch)
Compounds	Methane (vol-%)	60–70	35–65	81
	Other hydro carbons (vol-%)	0	0	3,5
	Hydrogen (vol-%)	0	0-3	–
	Carbon dioxide (vol-%)	30–40	15–50	1
	Nitrogen (vol-%)	~0.2	5–40	14
	Oxygen (vol-%)	0	0-5	0
	Hydrogen sulphide (ppm)	0–4000	0–100	–
	Ammonia (ppm)	~100	~5	–
	Lower heating value (kWh/Nm^3)	6.5	4.4	8.8

The dissimilarity of fraction of each biowaste results as divergent output. The predicted amounts of CH_4 and biogas content based on total solid amount of different biowaste sources are indicated in Table 3 below.

Table 3. Composition of different biowaste sources given in percentage (Ahmad et al., 2015).

Feed stock	Total solid (TS %)	Volatile solid VS (% of TS)	Biogas (m^3/kg of VS)	CH_4 content (%)
Cow Slurry	5 - 12	75 - 85	0.20 - 0.30	55 - 85
Chicken Slurry	10 - 30	70 - 80	0.35 - 0.60	60 - 80
Food Waste	10	80	0.50 - 0.60	70 - 80

The biogas obtained is to be upgraded for transportation usage in buses and vehicles. Eventually biogas can be purified in order to utilize both for electricity production and heating purposes by a CHP plant. The use of a co-digestion plant with various types of waste is shown in Figure 13 below.

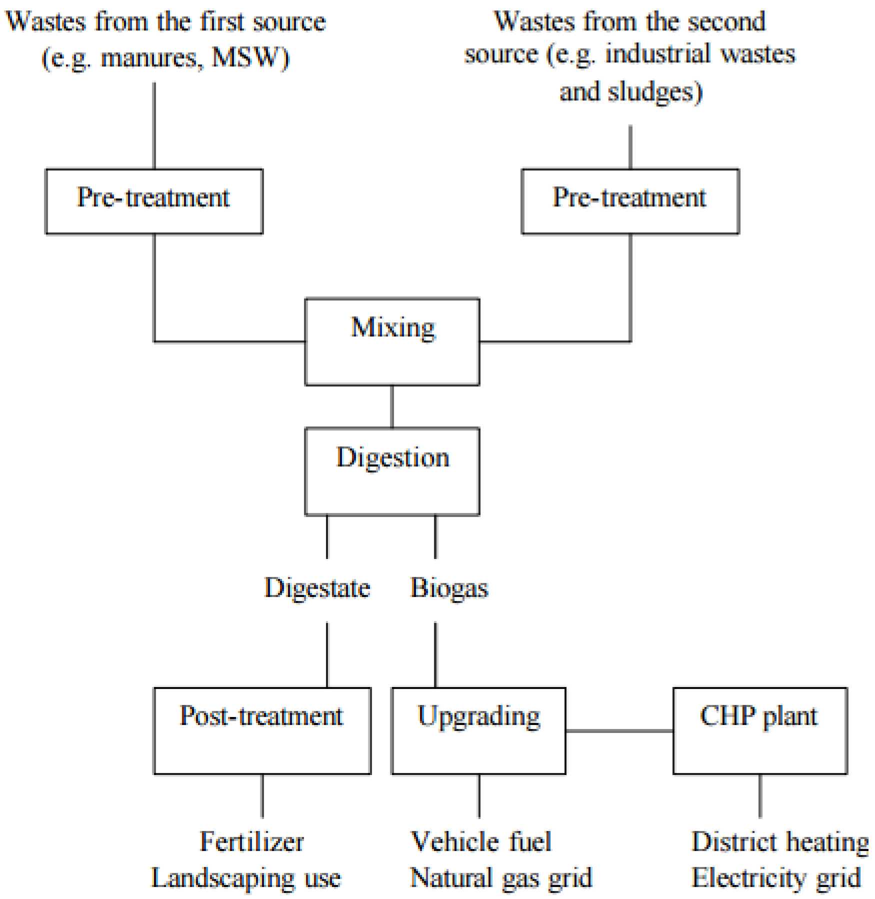


Figure 13. Overall process of anaerobic digestion in a co-digestion plant (Monnet, 2003).

4.1.2.2. Fermentation

Fermentation means the breakdown of organic biomass which contains a high amount of starch and sugar by microorganisms in an oxygen-free environment. The process yields methanol and ethanol as end product which then can be utilized as fuel for internal combustion vehicles.

The regular capacity range of biomass power stations is up to 15 MW with the possible applications for larger capacities. Keeping in mind the end goal to utilize the energy of the biomass as much as possible, the heat shall be used by the biomass power station too. Hence the electric capacity should not exceed 25 MW_{el} (Teske et al., 2015).

Currently there are many technologies in order to convert a wide range of biomass sources can be employed to obtain heat and power for many end-use applications. Figure 14 below illustrates an overall route map.

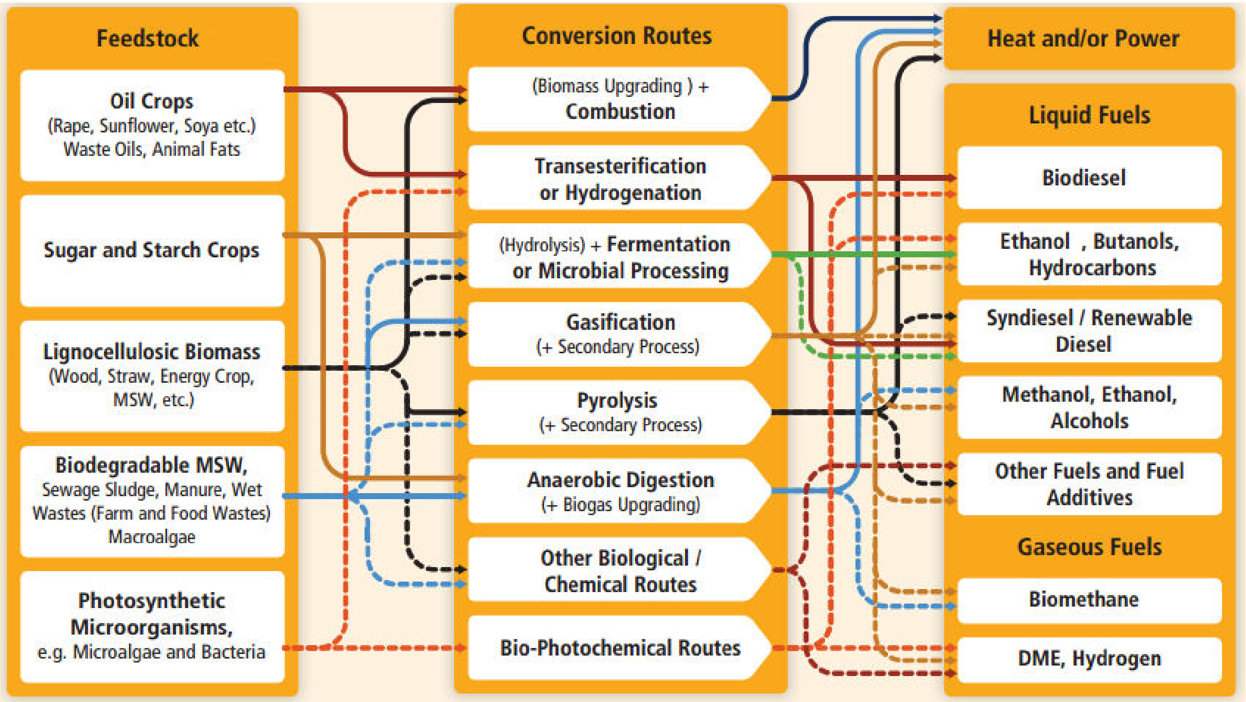


Figure 14. Assortment of commercial (shown as solid lines) and developing (shown as dotted lines) technologies for biomass conversion (Chum et al., 2011).

Co-products are also produced by employing each conversion routes. Additionally any type of feedstock can be utilized as a part of different conversion routes.

5 CURRENT SITUATION IN TURKEY

Turkey is divided into 7 geographic regions (Marmara, Black Sea, Aegean, Mediterranean, Central Anatolia, Eastern Anatolia and Southeastern Anatolia Region) based on each region's climatic, economic and social status. Apart from those geographic regions, Turkey is divided into 81 provinces. Among the geographic regions the Marmara Region the largest population along with the most developed industry, consequently it has the highest energy consumption. Type and level of husbandry, the agricultural yield and forest land rather varies on the features of the geographic regions. Its geographical position allows The Republic of Turkey make a bridge between Europe and Asia continents.

Over the past decade, GDP of Turkey increased exceptionally among the other OECD countries. Its economy expanded 5% on the average from year 2000 to 2007 (IEA, 2009). Rapidly growing economy has created one of the fastest growing energy market in Turkey. In year 2014, electricity consumption increased 3.6% compared to previous year in Turkey and reached 257.2 TWh. In addition to this, electricity import share increased 119.7% and reached 2.7 TWh compared to year 2013 (EMRA, 2014).

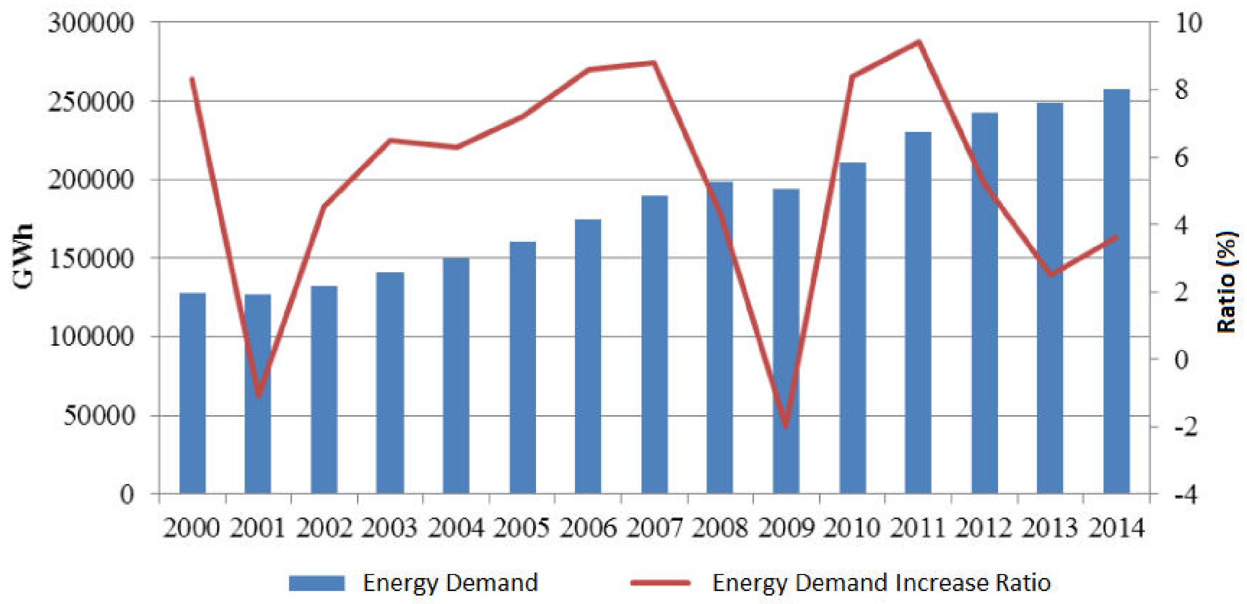


Figure 15. The continuous energy demand in Turkey shown in GWh except year 2009, however energy demand increase ratio seems to be slowed down in recent years (EMRA, 2014).

Turkey has a sharply expanding natural gas market, as energy source for primary energy production, natural gas (which is also mostly imported) did dominate the market again with 48% of total share and imported coal had the share of 14%. Only around 20.5% of total electricity production was provided from renewable energy sources in 2014 (EMRA, 2014).

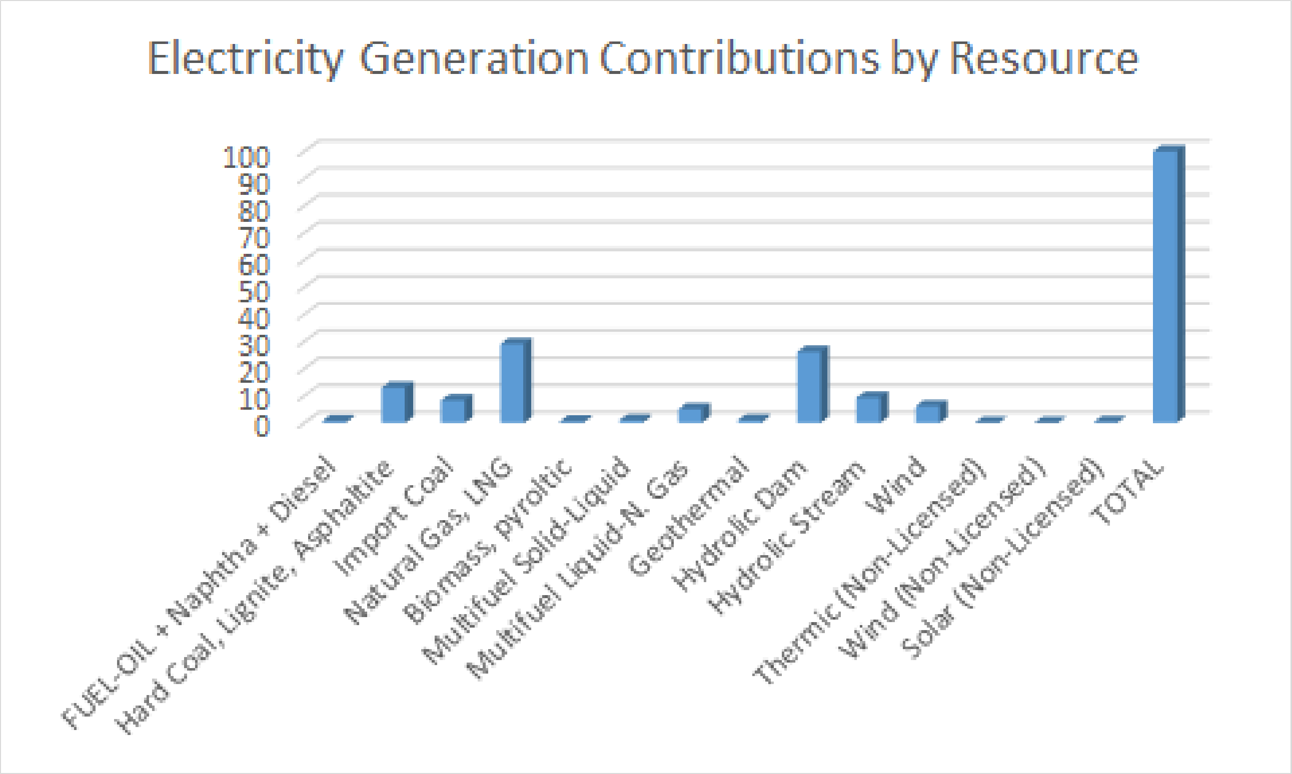


Figure 16. Turkey's electricity production proportions for each type of energy source for year 2015 (UCTEA, 2016).

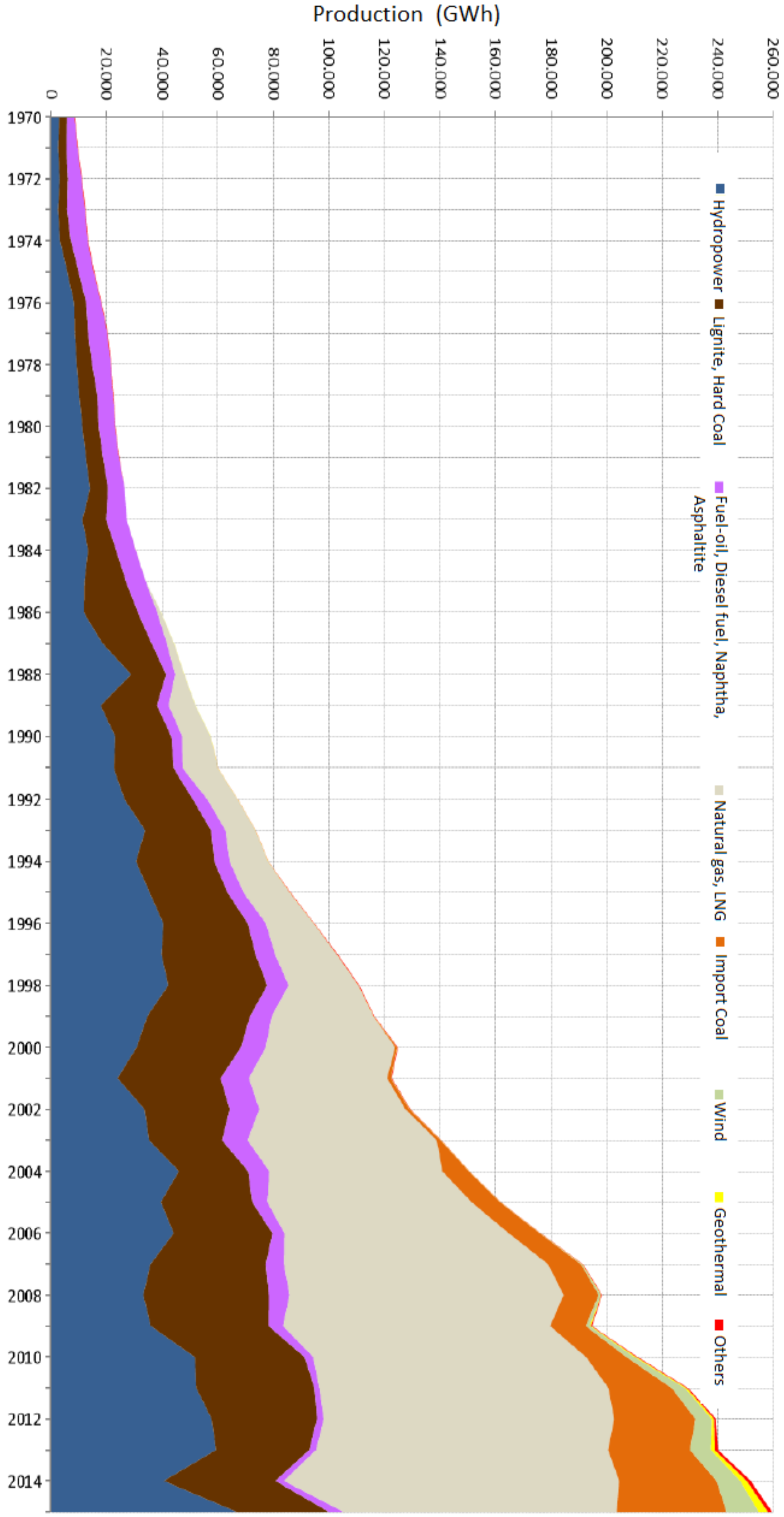

Production (GWh)
0
20.000
40.000
60.000
80.000
100.000
120.000
140.000
160.000
180.000
200.000
220.000
240.000
260.000
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Hydropower
Lignite, Hard Coal
Fuel-oil, Diesel fuel, Naphtha, Asphaltite
Natural gas, LNG
Import Coal
Wind
Geothermal
Others

Figure 17. Electricity production change according to energy source in Turkey from 1970 to 2015 (UCTEA, 2016).

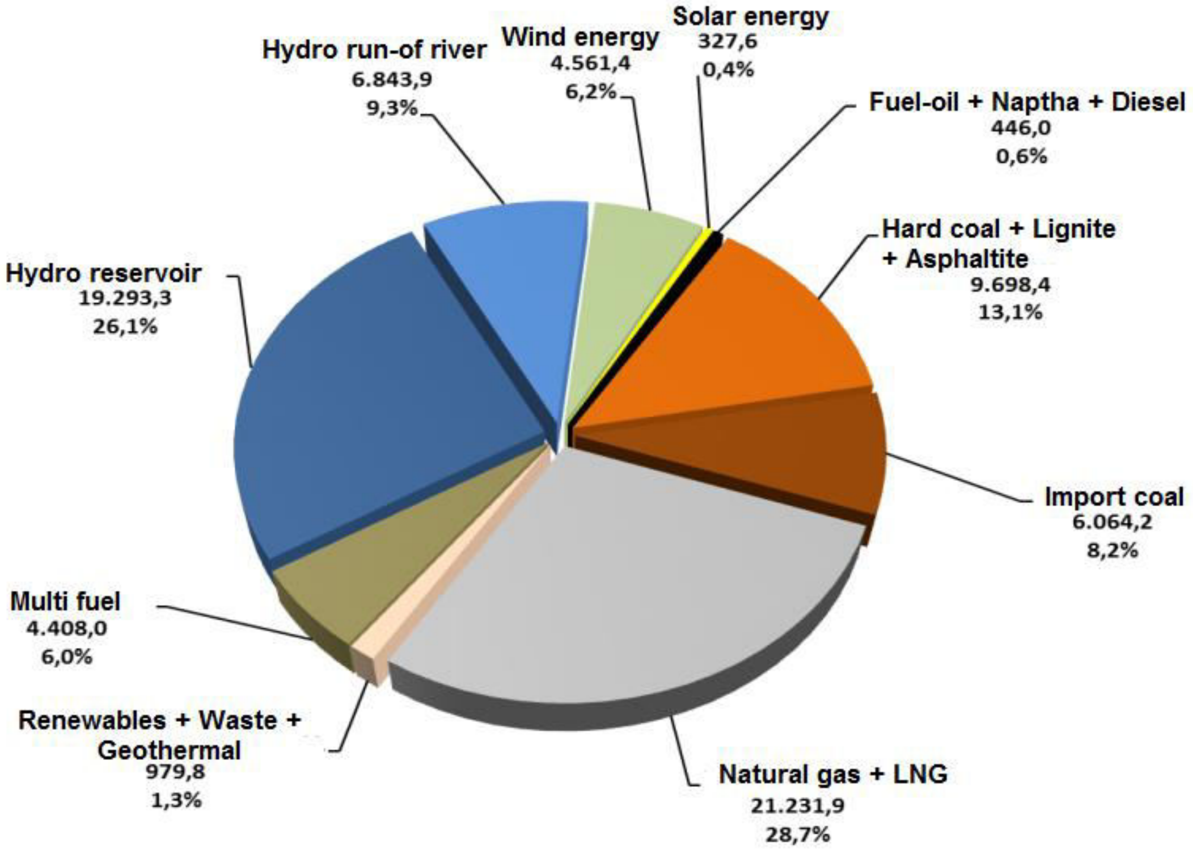


Figure 18. Electricity generation installed capacity of Turkey in MW by the end of February 2016 (UCTEA, 2016).

As it can be seen from Figures 16-18, the energy systems profile of Turkey rely heavily on foreign sources and mainly fed from non-renewable sources. Approximately only 26% of total energy demand is being provided by domestic energy resources presently, while for the rest Turkey is importing a wide range of energy sources. Also the energy demand in Turkey has been growing in all energy sector segments over the decades. Moreover for the increment in electricity and natural gas demand, Turkey has the second place right after China over the last decade. The forecast for the total energy demand indicates that Turkey will have one of the most vigorous energy economy (MFA, 2011).

5.1. Energy Policy and Regulations in Turkey

It is evaluated by the International Energy Agency (IEA) that Turkey will probably see the speediest medium to long term vitality in energy demand development among the other IEA part nations (IEA, 2009).

Regarding that issue, guaranteeing adequate energy supply to its developing economy still exists as an ongoing issue of the government's main energy strategy concern. Apart from that some convenient steps were achieved in all other areas of Turkey's energy policy in recent years.

According to Ministry of Foreign Affairs website, realizing energy security is the top priority for Turkey. In order to accomplish those Turkey will increase the share of renewable energy forms and start utilizing nuclear energy; energy supply routes and source countries of Turkey to be diversified and energy efficiency must be increased tremendously (MFA, 2011). Furthermore utilizing European transmission network, ENTSO-E is another current policy for the government to handle overcoming supply security problem.

Turkey has started a long-term and inventive energy supply frame approach where renewable energy assumed as a noteworthy part. Firstly the arrangements in Turkey will be done by the year 2023 to have a blended power structure in which the offer of renewable energy represents 30% of general need and in addition covering 10% share of the transportation segment by renewable energy forms. Secondly there is likewise a promise to lessen by no less than 20% (with reference to the national state in year 2008) the volume of energy used per unit of GDP in 2023 (concerning the energy intensity) (EIE, 2014).

The installed total capacity of Turkey has reached 74,000 MW by the end of year 2015. This capacity consist of 35.4% hydro power, 6.2% wind energy, 0.8% geothermal energy and finally the other sources 1.7% in terms of renewables (MFA, 2011).

Addition to these, reaching 125,000 MW total capacity as well as installing many forms of renewable energy plants are some of the remarkable parts of overall national target for the year 2023. The renewable energy section of this national target includes, installing 1 GW of biomass, 1 GW of geothermal energy, 5 GW of solar energy (concentrated solar power and photovoltaics), 20 GW of wind energy and 34 GW of hydropower at a minimum level. Turkey is a member of United Nations Framework Convention on Climate Change (UNFCCC) and in year 2009 Turkey approved The Kyoto Protocol (EIE, 2014) and COP21 in 2015.

The regulations mechanism regarding the renewable energy utilization has started by the beginning of 2005 in Turkey. However due to lower feed-in tariff and fewer legislation regarding the renewable energy technologies, the investments were very limited.

Starting with the amendment in the Renewable Energy Law in year 2010, higher feed-in tariff levels were initiated for several of the renewable energy technologies along with the various incentives (EIE, 2014).

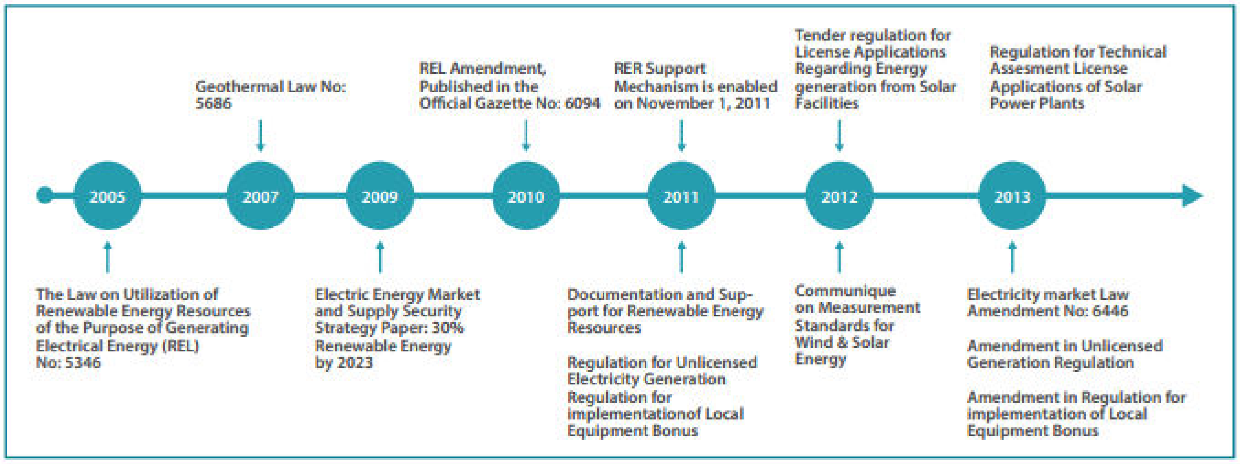


Figure 19. Progression of the policies and regulations regarding the "use of renewable energy" in Turkey (EIE, 2014).

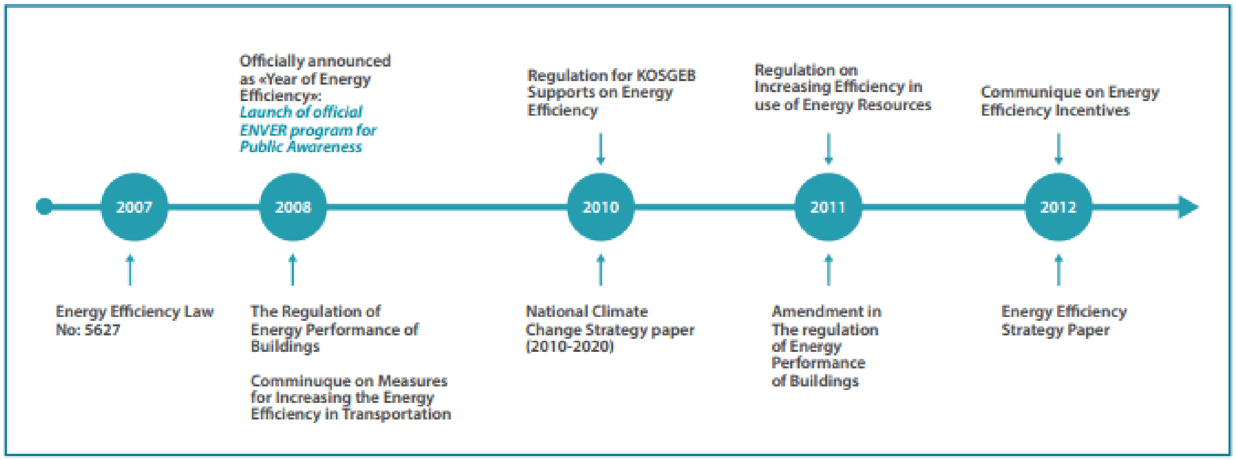


Figure 20. Progression of the policies and regulations regarding the "energy efficiency" in Turkey (EIE, 2014).

By doing so investments and utilization of the renewable energy technologies highly boosted compared to previous 5 years period. Those modified feed-in tariff rates highly encouraged the both foreign and local investors (EIE, 2014).

5.2. Air Pollution in Turkey

Mixture of gases and various size solid particles create air pollution. They can be natural (mold spores or pollen) or human-made substances. The air pollution categorized into indoor air pollution and outdoor air pollution (NIH, 2016). Moreover it has remarkable effects on human health and the ecosystem.

Parallel to the increment in energy demand in Turkey, CO_2 emissions due to energy production exceeded double time compared to year 1990 and foreseen to increase dramatically both in medium and long term (IEA, 2009).

Rapid urbanization causes a serious air quality decline for urban areas in Turkey. Around 30% of the total population lives in three major metropolitans, İstanbul, Ankara and İzmir (Turkish Statistical Institute, 2015). Addition to the largest urban areas, the cities where industry takes part also display highest pollution indicators. Studies showed that air quality monitoring in big cities of Turkey provided data which are below the EU standards. For instance the worst air quality reached in Manisa-Soma where six coal fired power plants operating nearby. Similar to that, the best air quality was reached in İzmir-Bornova where the province is away from all energy systems.

The biggest contributor for decreased air quality index is coal fired power plants. For the anthropogenic CO_2 release, they are the biggest single source. Due to the combustion, they also release particulate matter (PM), noxious gases (sulphur dioxide (SO_2), nitrogen oxides (NO_x) etc.) and various trace metals to atmosphere. Coal fired power plants also release a great amount of Mercury, which is a neurotoxin and causing impacts on nervous system and brains. Particulate matters are tiny unburned compounds which are very harmful to inhale. They are released from the power plant directly and 800,000 premature deaths are linked to those particles. After releasing coal combustion, nitrogen oxides and sulphur dioxide form nitric and sulphuric acid which make contribution to acid rain eventually damage plants, forests and soil (Greenpeace, 2016).

Fossil fuels, coal and oil contain different levels of sulfur dioxide (SO_2) which is released due to combustion of such fuels in the industry or power sector. It has harmful effects for both environment and health. Similarly another toxic gas, carbon monoxide (CO), is released due to incomplete combustion of such fuels (coal, road transport fuels, natural gas and wood).

Advanced agricultural technology which allows machinery, intense farming and usage of chemical fertilisers culminates increased air pollution along with other environmental impacts. Waste management and agricultural operations result ammonia (NH_3) release which is another root cause for acid rain along with NO_X and SO_2 (IEA, 2016).

For the general trend in Turkey, economic growth has been the priority for taking actions rather than environmental concerns. Regarding the air pollution problem in Turkey, many attempts have been done in order to reduce air pollution; yet still large part of population in Turkey lives under low air quality conditions which are way below the EU standards (Büke and Köne. 2016).

6 BIOENERGY SOURCES OF TURKEY

Utilizing biowaste-to-energy has started in Turkey in year 1996 with 10.4 MW installed capacity from two power plants. The following two decades bioenergy gained its importance and by the end of 2014, total installed active capacity has reached to almost 260 MW with seventeen bioenergy facilities (Farfan and Breyer, 2017).

In this chapter, the sustainable biomass potential according to Ministry of Energy and Natural Resources' Turkey Biomass Energy Potential Atlas (BEPA) source is analyzed.

6.1. Animal Waste

The organic material existing inside the animal manure allows it to keep some amount of energy depending on portion of organic components. It is conceivable to extract that sustainable energy by a manure-to-energy process since the waste is produced steadily.

In the Turkey Biomass Energy Potential Atlas the livestock is divided into three categories according to living's size. Addition to that, husbandry level differs in different regions of Turkey due to climatic conditions. The waste derived from bovine is shown in green color in the pie chart which does the major contribution overall. Brown color inside the pie chart represents waste produced by ovine and finally the pink color presents the waste acquired from poultry. The size of the pie chart is proportional to the animal waste produced in that province. Red, orange, dark blue, green and yellow colors filled in provinces indicate the sorting respectively. All in all, it is estimated that 15.4 TWh can be obtained annually from animal waste utilization (GDRE, 2016).

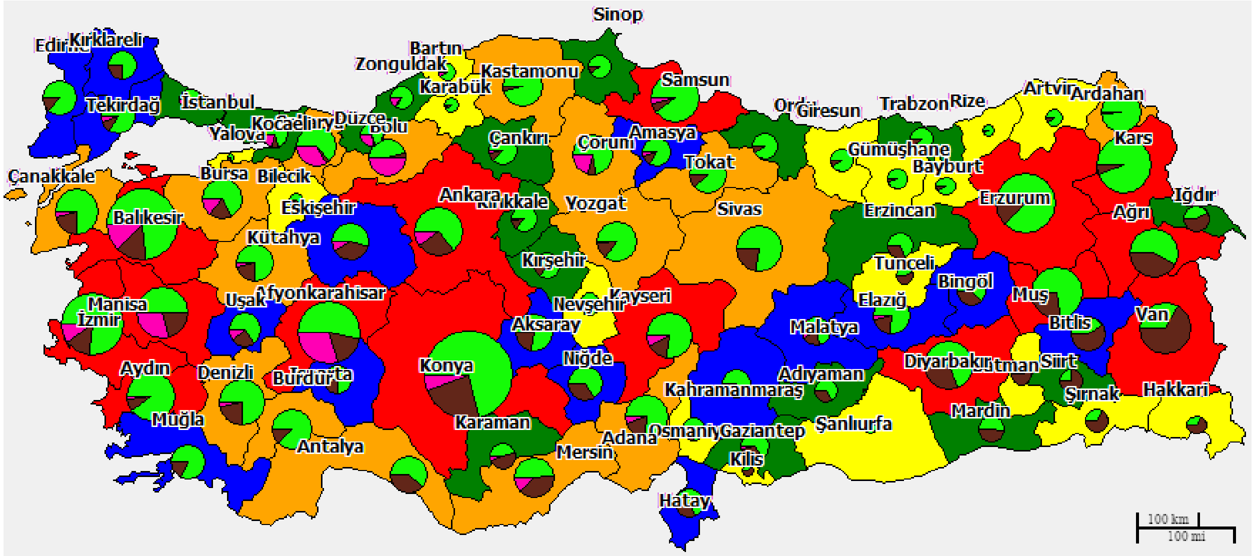


Figure 21. The amount of animal waste produced annually divided into all 81 provinces for year 2015 (GDRE, 2016).

6.2. Plantal Waste

Improved living standards, growing population and advance in technology have caused intensive agriculture practices in Turkey. As a result of relatively high temperatures and climate diversity all around the country land yield high and diverse agricultural products. The increased agricultural waste becomes a problem during the rotting process as it creates methane and leachate emissions and usually the waste ends up with open burning in the land by the farmers.

Turkey Biomass Energy Potential Atlas divides those agricultural products into three categories; the first category consist of vegetable plants (presented as green inside the pie charts), second category mostly includes the products can be collected from trees (hazelnut, citrus fruits etc. presented as brown inside the pie charts) and the third category contains field crops (presented as pink color inside the pie charts) that require planting seeds (wheat, sunflowers etc.) and vegetables are excluded from this group. The size of the pie chart is proportional to the plantal waste produced in that province.

The provinces filled with red and orange color have the majority of agricultural waste produced, where dark blue, green and yellow colors filled in provinces indicate the sorting respectively. Therefore Central Anatolia Region has the biggest share in terms of agricultural waste. By the utilization of the agricultural waste 185.4 TWh of energy can be obtained annually (GDRE, 2016).

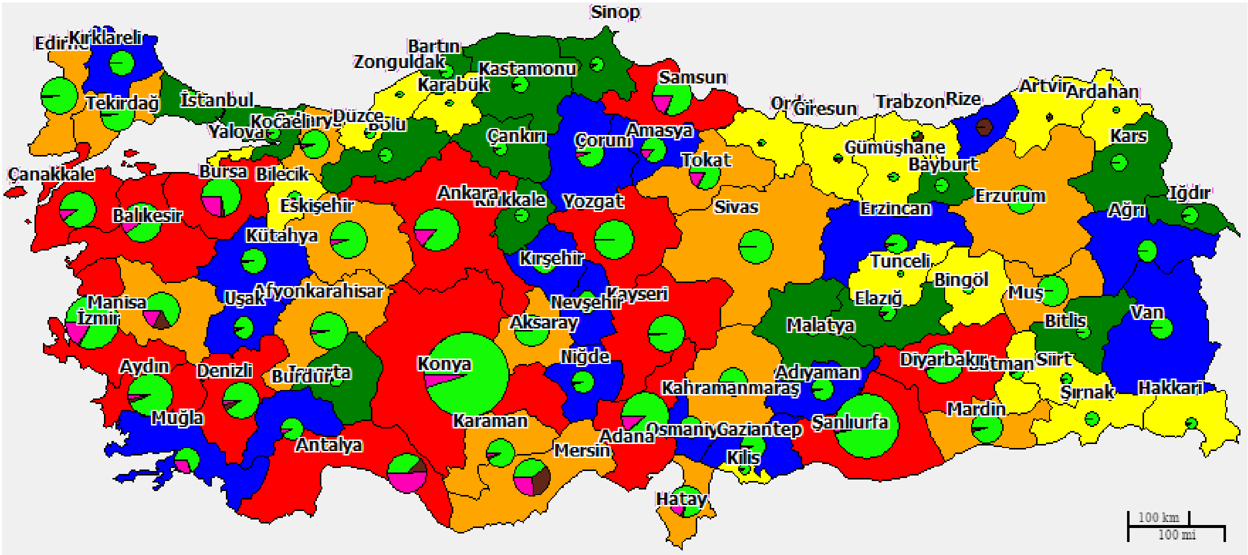


Figure 22. The amount of agricultural waste produced annually divided into all 81 provinces for year 2015 (GDRE, 2016).

6.3. Municipal Solid Waste

Addition to that, developing industry and rapid urbanization produce great amount of municipal solid waste that needs to be taken care of. The municipal solid waste consist of daily common products that we use and durable goods (e.g. furniture) discarded from homes, businesses and hospitals. Hazardous, construction and industrial waste types are not included to municipal solid waste.

Waste in general has the potential to produce primary types of greenhouse gas emissions (e.g. methane, nitrous oxide and carbon dioxide). In year 2008, 9.25% of greenhouse gas emissions released from Turkey were originated from waste excluding land use and land use change effect emissions (MEU, 2010). Other growing concern is the total volume of waste generated in Turkey as it is increased 21.5% since 2008 and has reach 29.6 Mt in 2015 (GDRE, 2016).

Apart from the environmental burden of the municipal waste, it is somehow a sustainable form of biomass since the waste is produced daily from cities. The organic part of municipal waste can be utilized to produce both heat and electricity. According to Republic of Turkey Ministry of Energy and Natural Resources, 45% of the total municipal waste contains organic compounds therefore has a energy utilization potential. The proportion of organic waste was shown as green color in the pie charts Figure 23 below. The brown color share inside the pie charts are classified as other type municipal waste by Ministry of Energy and Natural Resources. Red, orange, dark blue, green and yellow colors filled in provinces indicate the sorting respectively.

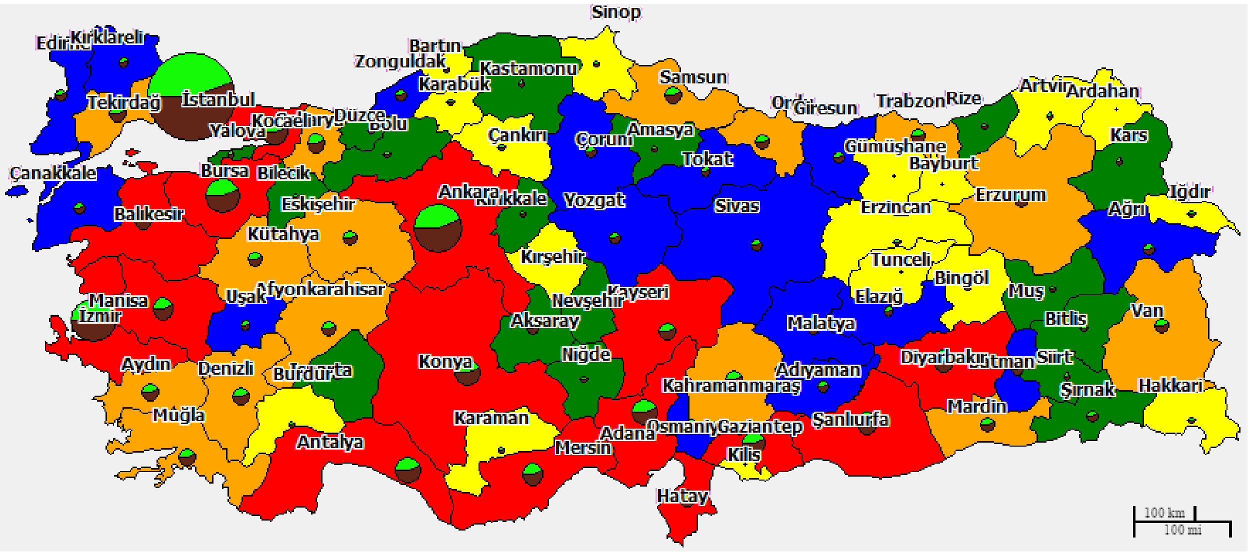


Figure 23. The amount of municipal waste generated annually divided into all 81 provinces for year 2015. İstanbul produces the biggest amount of municipal waste due to its remarkable population (GDRE, 2016).

The provinces filled with red and orange color produces the big fraction of municipal waste. The amount of municipal waste is also proportional to the population of that area. It is estimated that from the organic waste utilization 25.4 TWh energy can be obtained annually (GDRE, 2016).

6.4. Forestry Residues and Wood Waste

Turkey has various climate conditions in a same season of the year. Those conditions have affect on rainfall, temperature etc. Turkey has relatively rich forest areas both south and north seashore. Therefore Mediterranean and Black Sea regions represent the bigger woodland. Forestry residues and wood waste data also provided from Turkey Biomass Energy Potential Atlas which there are only two types of waste are taken into account. Those are residues from wood manufacturing and the excess layer of biomass covering the forestry areas' ground (branches, leaves etc.). In general, residues from wood manufacturing covers 90% of total amount of forestry waste by proportion. By utilizing the forestry residues and wood waste it is estimated that 9.95 TWh of energy could be recovered annually (GDRE, 2016). The interactive online map is also available on Republic of Turkey General Directorate of Renewable Energy website. However the proportion of available sustainable forestry residues and wood waste is not shown for the various provinces.

7 MODELLING OF TURKISH ENERGY SYSTEMS

7.1. Input data, methods and applied technologies

To begin with, officially divided 81 provinces (sub-regions) of Turkey combined in order to create 7 regions. Some of the provinces are interrupted by more than one geographical regions of Turkey. In order to avoid that those provinces were accounted to the most invaded land territory of the geographical region. However dataset of currently installed power plants was examined in micro level meaning by province based.

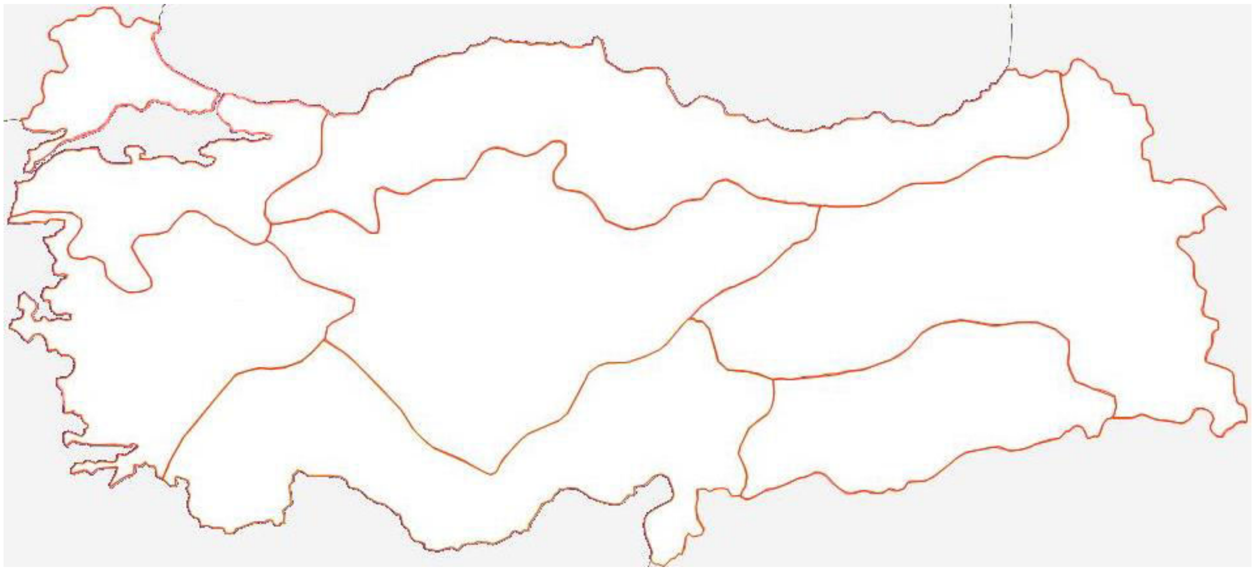


Figure 24. 7 regions of Turkey as used by the model (Own created for the model).

For the model; PV fixed titled system, PV 1-axis system, concentrated solar power (CSP), wind onshore, hydro run-of-river, hydro reservoir, geothermal, biogas power plant and waste-to-energy power plant technologies are employed for energy generation. For storage of that energy, adiabatic compressed air energy storage (A-CAES), pumped hydro storage, thermal energy storage, gas storage, battery technologies are employed. The input data were obtained from Bogdanov and Breyer (2016). Further data are available in the appendix of this thesis.

Many forms of renewable energy sources are available throughout Turkey as indicated previous chapters above, inclusively solar, wind, bioenergy and hydropower resources. Resource map for solar PV can be seen in Figure 25 below.

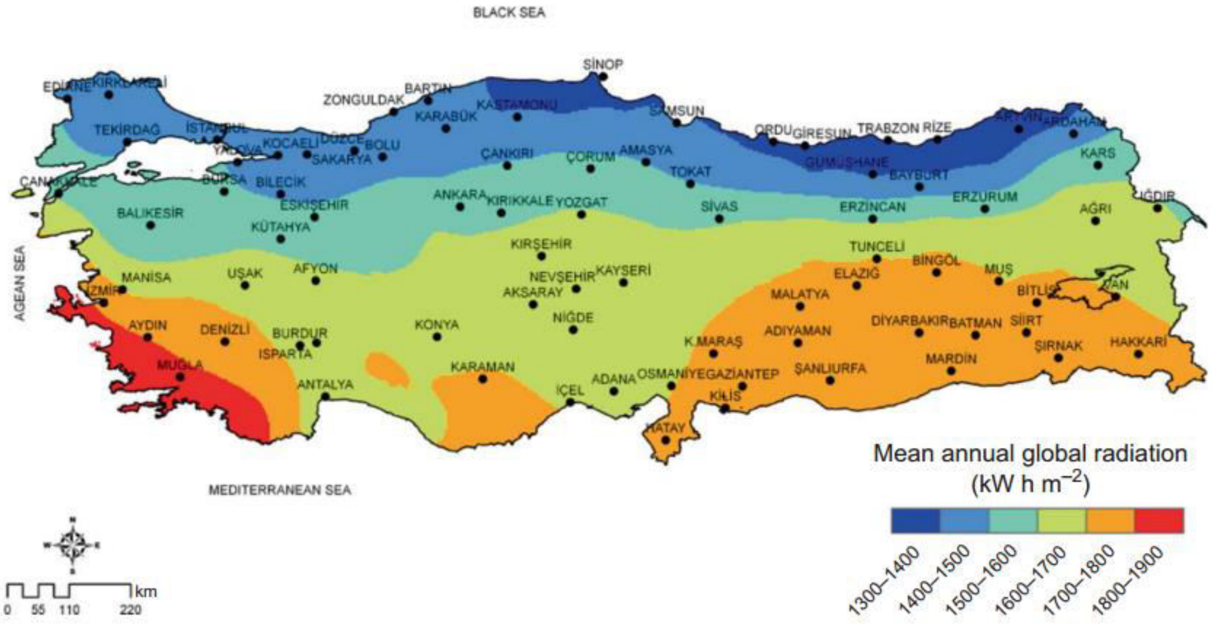


Figure 25. Average of 22 years of Turkey's annual global solar irradiation distributed geographically (Aksoy, 2011).

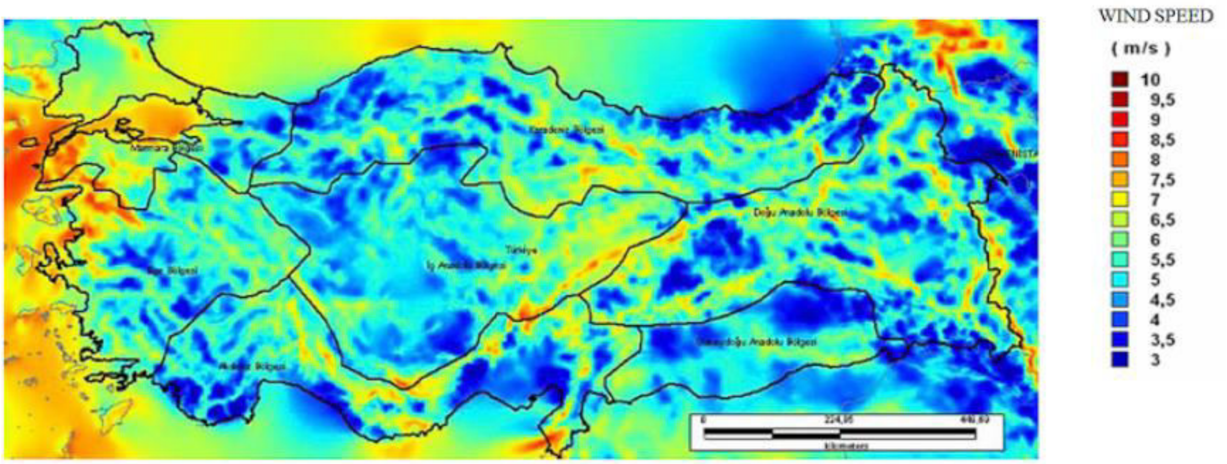


Figure 26. The estimation of average Wind Speed in 50 m. of Elevation Above Ground in Turkey distributed on map (Akova, 2011).

Several scenarios are created with an appropriate renewable energy source supply to meet the energy demand for Turkish energy systems frame. They are consist of a Basic scenario (Power sector only) and an Integrated scenario (power sector, gas and desalination demand). A set of power generation and storage technologies were also employed in those scenarios. The input data were obtained from Bogdanov and Breyer (2016). Further data are available in the appendix of this thesis. Moreover an economical assessment was made including levelized cost assumptions for some system components. All the information about lower limit of installed capacity and list of power plants were obtained from (Farfan and Breyer 2017).

7.2. Overview of energy system model for Turkey

For this research, the applied technologies consist of conversion of renewable energy forms into electricity, energy storage, and electricity transmission. The technologies that utilized for electricity generation from renewable energy sources includes a wide range of commercial PV systems along with concentrating solar power (CSP) plants, onshore wind farms, reservoir and run-of-river hydropower systems and finally bioenergy systems (classified as biomass in solid waste form, solid biomass, biogas and biogas which can be upgraded to methane).

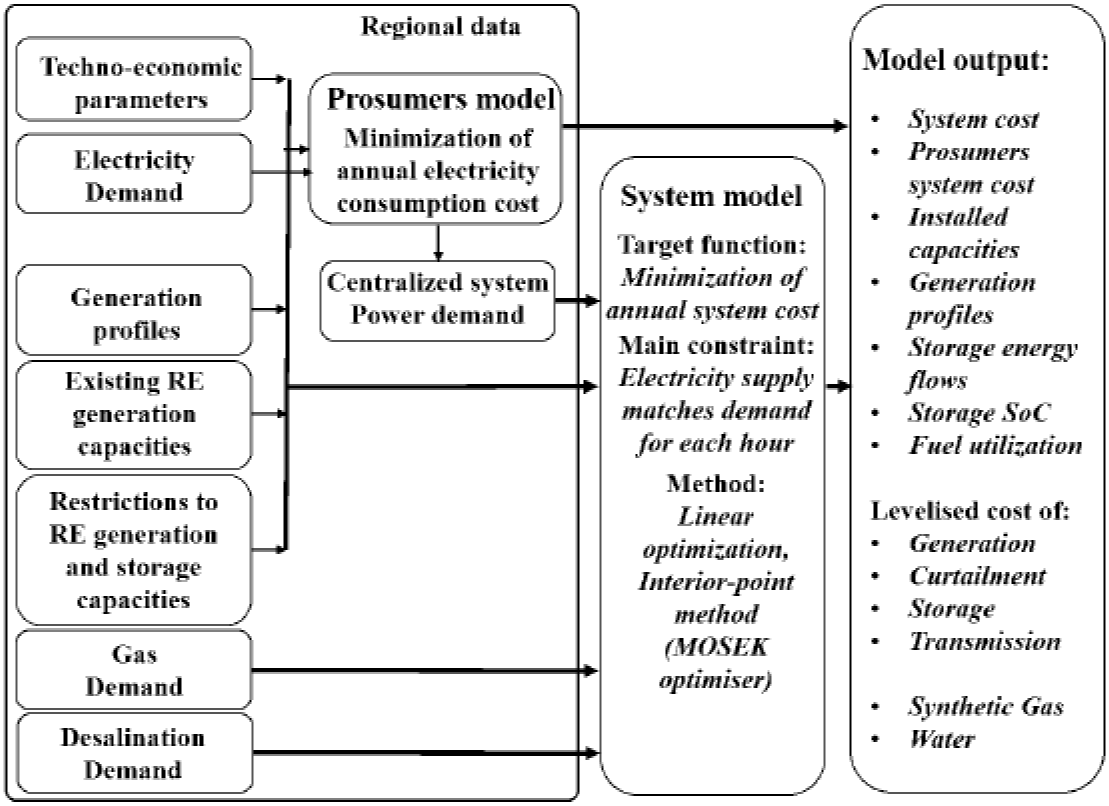


Figure 27. Model operation flowchart that is concerned in this research (Bogdanov and Breyer, 2016).

Additionally for the energy storage purpose, power-to-gas (PtG), pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and finally battery technologies were employed by the model. More detailed diagram and the full flowchart of the model represented in the Figure 27 and 28.

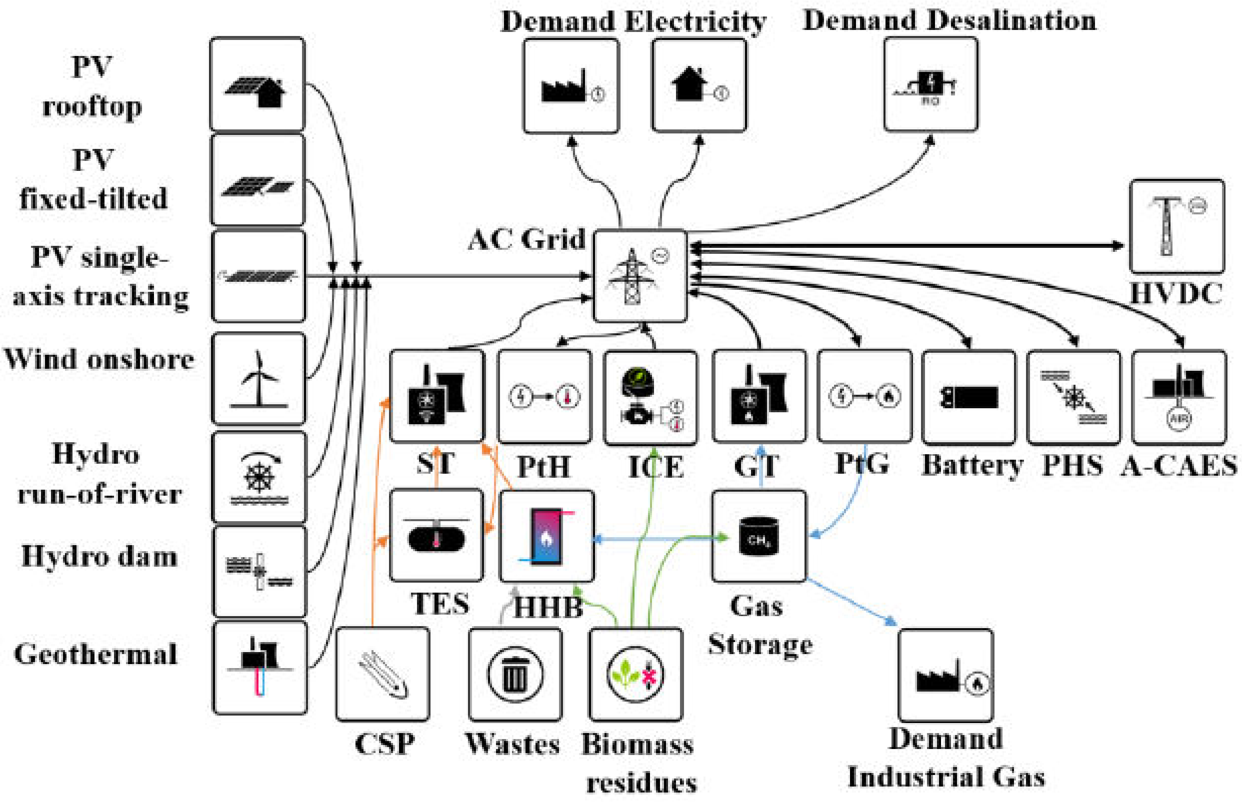


Figure 28. Block diagram of the energy system model for Turkey (Bogdanov and Breyer, 2016).

In this research the energy scenarios built on overnight approach. Overnight approach indicates that, the model does not take into account transition within years. The model directly goes to 2030 or 2050 values to meet electricity demand with an appropriate renewable energy source. Moreover for both the model does not take into account transition within years. Model directly goes to 2030 or 2050 values to meet electricity demand with an appropriate renewable energy source.

For each scenario residential, commercial and industrial electricity cost assumptions are based on extrapolation by using (Gerlach et. al., 2014) approach. The potential for biomass and waste resources are taken from DBFZ (2009) and divided into different categories as described in Bogdanov and Breyer (2016).

Table 4. Comparison of available sustainable biomass potential of Turkey according to DBFZ (2009) and BEPA (2016) sources.

DBFZ	TWh	BEPA	TWh	Deviation (%)
Excreta	1.8	Animal Waste	15.4	+755.5%
Straw	41	Plantal waste	185.4	+352.2%
Biowaste	6	MSW	25.4	+323.3%
Used wood and industrial wood residues	13.9	Forestry Residues and Wood Waste	9.95	-29%

Categorization of annual available sustainable biomass is shown in Table 4 above as they are given in two different sources (DBFZ and BEPA). 100% of the excrements are assumed to be utilized from all around Turkey in BEPA. Therefore this theoretical approach may be the reason for that huge deviation. In terms of agricultural waste, only straw plant is taken into account in DBFZ (2009), on the other hand all kind of agricultural plant's waste assumed to be 100% utilized in BEPA (2016).

The cost associated with all the biomass resources is calculated using data from International Energy Agency (IEA, 2012) and Intergovernmental Panel on Climate Change (IPCC, 2011). Also bioenergy source divided as biogas (consist of municipal bio-waste, bagasse and excrement), solid biomass (wood and straw residues) and solid biowaste (municipal and industrial used wood).

Table 5. The available sustainable biomass potential of Turkey according to DBFZ (2009) source.

	[TWh,th,a]
Biomass, solid waste, available resource	13.9
Biomass, solid biomass, available resource	41.6
Biomass, for biogas, available resource	6.2
Biomass, all, available resource	61.7

The latest numbers of Turkey for electricity, gas and desalinated water demand are obtained from Greenpeace report (Teske et al., 2015) and applied to calibrate the start for the model.

Table 6. The demand for electricity, gas and desalinated water for year 2015 are shown.

	Unit	2015
Electricity demand	[TWh]	268.8
Gas demand	[TWh]	85.1
Desalination Demand	[m^3/day]	13,654,273

8 RESULTS AND DISCUSSION

For every scenario electrical energy system structure formed with an optimization in terms of cost. Optimized installed capacities of RE electricity generation, storage and transmission for every technology employed in the model shaped and characterized those structures together with some existing constraints. Accordingly the final results consist of import, export between regions of Turkey and curtailment of electricity, storage charging and discharging and hourly electricity generation profile.

For the energy modelling, Turkey analyzed according to 7 regions as already mentioned in Chapter 5. Therefore the results are presented in all figures accordingly. The main parameters for model provided results for generation capacities, the full system cost total RE capacity and the storage throughput.

Table 7. Key results for the basic scenario of Turkish energy systems.

	units	2030	2050	Difference from 2030 to 2050 (%)
Area	1000 km^2	814.5	814.5	-
Population	mil	87.7	95.8	+9.2%
Total electricity demand	[TWh,el]	462	641.3	+38.8%
Total electricity generation demand – all sectors	[TWh,el]	462	641.3	+38.8%
Gas demand	[TWh]	0	0	-
Total SNG demand – all sectors	[TWh,el]	0	0	-
Curtailment losses total	[TWh,el]	23.6	60.8	+118.5%
LCOE total	[€/MWh,el]	59	48.5	-18.0%
Peak load incl. prosumers	[GW]	71	94.5	+33.1%
Peak load excl. prosumers	[GW]	73.5	102	+38.8%
Desalinated water	[m^3]	0	0	-

Table 8. Key results for the integrated scenario of Turkish energy systems.

	units	2030	2050	Difference from 2030 to 2050 (%)
Area	1000 km^2	814.5	814.5	-
Population	mil	87.7	95.8	+9.2%
Total electricity demand	[TWh,el]	462	641.3	+38.8%
Total electricity generation demand – all sectors	[TWh,el]	709.9	883.4	+24.4%
Gas demand	[TWh]	88.5	64.8	-27.0%
Total SNG demand – all sectors	[TWh,el]	88.5	64.8	-27.0%
Curtailment losses total	[TWh,el]	29.3	62.2	+112.3%
LCOE total	[€/MWh,el]	67.9	53.9	-21.0%
Peak load incl. prosumers	[GW]	71	94.5	+33.1%
Peak load excl. prosumers	[GW]	73.5	102	+38.8%
Desalinated water	[m^3]	12,478,501,556	24,042,715,654	+92.7%

The estimated population, electricity demand (including all sectors) and peak load profiles are presented in Table 7 and 8. Total electricity generation demand consist of power demand, desalination sector, gas synthesis. Regarding the electricity generation and grid system, Turkey was handled as an island. However the electricity demand for gas sector and desalination sector does not have a value in Basic scenario. Curtailment losses total implying the electricity excess on the system which has to be considered for each scenario. Total synthetic natural gas (SNG) demand for gas sector (excluding the demand for mobility sector) expected to decline by 2050 and it doesn't take place in Basic scenario. Prosumers are connected to the grid and they do self-consumption by their PV system on the residential rooftops, rooftops of commercial buildings and firms etc. 3 different electricity prices applied as prosumers classified as residential, commercial and industrial. PV system on the other hand, indicates larger scale PV power plants (not consumers), in fixed tilted and single-axis tracking design just to produce electricity as a normal power plant.

The huge solar energy potential of Turkey is utilized for both integrated and basic scenarios as it can be seen from the Table 9 below. The installed PV capacity (including both system and prosumers) is almost doubled from 2030 to 2050 in Integrated scenario and it exceeds doubling in Basic scenario. However there is only slight investment for concentrating solar thermal power technology for each case. Utilization of wind onshore technology slowing down from year 2030 to 2050 specifically for the integrated scenario. Finally, the installed capacity of hard coal power plants tails off until year 2050 for each case. As some given bullet points of COP21 in Chapter 2.2, coal phase out matches to reduce anthropogenic emissions, preventing greenhouse gas effect therefore to limit global temperature increase at a level of 2 °C to reduce the impacts of climate change.

Table 9. Installed renewable energy and hard coal power plant capacities for basic scenario.

	units	2030	2050	Difference from 2030 to 2050 (%)
PV prosumers total	[GW]	75.3	149	+97.8%
PV System	[GW]	56.1	141.3	+151.8%
PV Total	[GW]	131.3	290.3	+121.0%
CSP	[GW]	0.01	4.5	+45,000%
Wind onshore	[GW]	66.5	61.3	-8.0%
Hard coal PP	[GW]	0	0	-
Wind onshore Usage	[percents]	24.4	22.5	-8.0%
Hydro ROR Usage	[percents]	67.2	66.6	-1.0%

Hydro dams Usage	[percents]	99.9	99.3	-
Geothermal Usage	[percents]	100	100	-
Biomass Usage	[percents]	94.2	82.4	-13.0%

Table 10. Installed renewable energy and hard coal power plant capacities for integrated scenario.

	units	2030	2050	Difference from 2030 to 2050 (%)
PV prosumers total	[GW]	75.3	149	+97.8%
PV System	[GW]	128	262.4	+105.0%
PV Total	[GW]	203.9	411.4	+101.7%
CSP	[GW]	0	2.05	-
Wind onshore	[GW]	109	77.7	-29.0%
Hard coal PP	[GW]	0	0	-
Wind onshore Usage	[percents]	40.1	28.5	-29.0%
Hydro ROR Usage	[percents]	67.2	66.6	-1.0%
Hydro dams Usage	[percents]	99.9	99.9	-
Geothermal Usage	[percents]	100	99.9	-
Biomass Usage	[percents]	94.1	52.9	-44.0%

For renewable energy technologies (excluding bioenergy), usage numbers indicate that particular renewable energy installed capacity divided by total installed capacity. By year 2050 solar PV technology dominates the installed capacity with a huge increment from year 2030 to 2050 for both basic and integrated scenarios. Hydro dams and geothermal sources are working with 100% capacity and they remain unchanged from year 2030 to 2050.

Solid biomass, biomass solid waste and biogas are taken as biomass sub-categories for the energy model. In accordance with the energy model all the waste should be burned. For the case of biogas, it can either be burned or upgraded to bio-methane and then burned. All the biogas should be utilized. On the other hand, for the case of biomass system decides if it is useful to utilize that source or not. Because utilizing other renewable energy technologies can be more beneficial instead of biomass burning.

Parallel to main intention, 100% renewable Turkish energy system frame is possible. Due to that reason utilization of hard coal as well as full load hours (Flh) of hard coal power plant does not take place. Wind offshore technology is not employed in model due to too high cost, compared to wind onshore, therefore total wind energy indicated onshore wind farm technology only. The energy output of all renewable energy technologies utilized in model and Flh of conversion technologies are presented in Table 11 below.

Table 11. Total energy output of renewable energy technologies and Flh of energy conversion technologies for basic scenario.

	units	2030	2050	Difference from 2030 to 2050 (%)
Flh Hard coal PP	[h]	0	0	-
Flh PtSNG	[h]	5056.1	5151.1	+1.8%
Flh CCGT	[h]	1250	1259	+0.7%
Flh OCGT	[h]	236	553	+134.3%
PV Total	[TWh]	365.7	672.7	+84.0%
Wind total	[TWh]	181.8	168.5	-8.0%
Hydro ROR	[TWh]	26.3	26	-1.1%
Hydro dams	[TWh]	77.4	76.8	-0.8%
Hydro total	[TWh]	103.7	102.9	-0.8%

Geothermal	[TWh]	0.343	0.343	-
Biomass PP	[TWh]	13.4	14.7	+9.7%
Waste PP	[TWh]	4.7	5.8	+23.4%
Biogas PP	[TWh]	0.619	1.098	+76.0%
Biogas Upgr	[TWh]	4.2	3.7	-12.0%
Total electricity generation	[TWh]	532.2	766.3	+44.0%

Table 12. Output of renewable energy technologies presented as percent of total electricity generation for basic scenario.

	Percent of total generation for year 2030	Percent of total generation for year 2050
PV Total	68.7%	87.8%
Wind total	34.6%	22.0%
Hydro ROR	5.0%	3.4%
Hydro dams	14.5%	10.1%
Hydro total	19.5%	13.5%
Geothermal	0.064%	0.044%
Biomass PP	2.5%	1.9%
Waste PP	0.883%	0.757%
Biogas PP	0.116%	0.142%
Biogas Upgr	0.79%	0.483%

Table 13. Total energy output of renewable energy technologies and Flh of energy conversion technologies for integrated scenario.

	units	2030	2050	Difference from 2030 to 2050 (%)
Flh Hard coal PP	[h]	0	0	-
Flh PtSNG	[h]	5524.5	5603.5	+1.4%
Flh CCGT	[h]	2047	175.3	-15.0%
Flh OCGT	[h]	309	530	+71.5%
PV Total	[TWh]	225	465.7	+106.0%
Wind total	[TWh]	284.7	211	-26.0%
Hydro ROR	[TWh]	26.3	26	-1.2%
Hydro dams	[TWh]	77.4	77.4	-
Hydro total	[TWh]	103.7	103.5	-
Geothermal	[TWh]	0.343	0.343	-
Biomass PP	[TWh]	13.4	6	-55.0%
Waste PP	[TWh]	4.7	5.8	+23.4%
Biogas PP	[TWh]	0.619	1.041	+68.0%
Biogas Upgr	[TWh]	4.2	3.8	-10.0%
Total electricity generation	[TWh]	775.2	1004.8	+29.6%

Table 14. Output of renewable energy technologies presented as percent of total electricity generation for integrated scenario.

	Percent of total generation for year 2030	Percent of total generation for year 2050
PV Total	29.0%	46.3%
Wind total	34.7%	21.0%
Hydro ROR	3.4%	2.5%
Hydro dams	10.0%	7.7%
Hydro total	13.4%	13.4%
Geothermal	0.044%	0.044%
Biomass PP	1.7%	0.597%
Waste PP	0.606%	0.577%
Biogas PP	0.079%	0.103%
Biogas Upgr	0.541%	0.378%

Storage of the energy in terms of both long and short term is crucial to achieve stable, sustainable energy systems frame. The technologies mentioned above that are considered in this research and storage throughput values in TWh are presented in Table 15 below.

Table 15. Storage technologies and storage throughput of the energy system model for basic scenario are presented.

	units	2030	2050	Difference from 2030 to 2050 (%)
indirect, Storages output	[TWh]	72.7	173.7	+138.9%
indirect, Batt. output	[TWh]	60.1	160.3	+166.7%
indirect, PHS. output	[TWh]	0.015	0.012	-20.0%
indirect, TEStP. output	[TWh]	0.005	0.026	+420.0%
indirect, A-CAES. output	[TWh]	0.008	0.014	+75.0%
Battery total cycles	[]	269	264.5	-2.0%
A-CAES cycles	[]	23.1	24.8	+7.3%
Gas cycles	[]	1.2	1.1	-9.0%
Gas for Storage	[%]	100	100	-
Gas for Industry	[%]	0	0	-

Table 16. Throughput of storage technologies presented as percent of total electricity generation for basic scenario.

	Percent of total generation for year 2030	Percent of total generation for year 2050
indirect, Storages output	13.6%	32.6%
indirect, Batt. output	11.3%	30.1%
indirect, PHS. output	0.002%	0.002%
indirect, TEStP. output	0	0.004%
indirect, A-CAES . output	0	0.002%

Table 17. Storage technologies and storage throughput of the energy system model for integrated scenario are presented.

	units	2030	2050	Difference from 2030 to 2050 (%)
indirect, Storages output	[TWh]	87.7	250.7	+185.8%
indirect, Batt. output	[TWh]	80.6	244.6	+203.4%
indirect, PHS. output	[TWh]	0.01	0.014	+40.0%
indirect, TEStP. output	[TWh]	0	0.106	-
indirect, A-CAES. output	[TWh]	0	0.096	-
Battery total cycles	[]	276	280.9	+1.7%
A-CAES cycles	[]	21.9	22.1	+0.9%
Gas cycles	[]	0.484	0.652	+35.8%
Gas for Storage	[%]	15	30.5	+103.3%
Gas for Industry	[%]	84.9	69.4	-19.0%

Table 18. Throughput of storage technologies presented as percent of total electricity generation for integrated scenario.

	Percent of total generation for year 2030	Percent of total generation for year 2050
indirect, Storages output	11.3%	24.9%
indirect, Batt. output	10.4%	24.3%
indirect, PHS. output	0.001%	0.001%
indirect, TEStP. output	0	0.01%
indirect, A-CAES. output	0	0.009%

The cost calculations cover levelized cost of electricity (LCOE) for primary generation (LCOE primary), levelized cost of curtailment (LCOC), levelized cost of storage (LCOS) and finally levelized cost of transmission (LCOT) values. Hard coal power plants and internal combustion generator capex is not taken into account in the system cost as they do not operate.

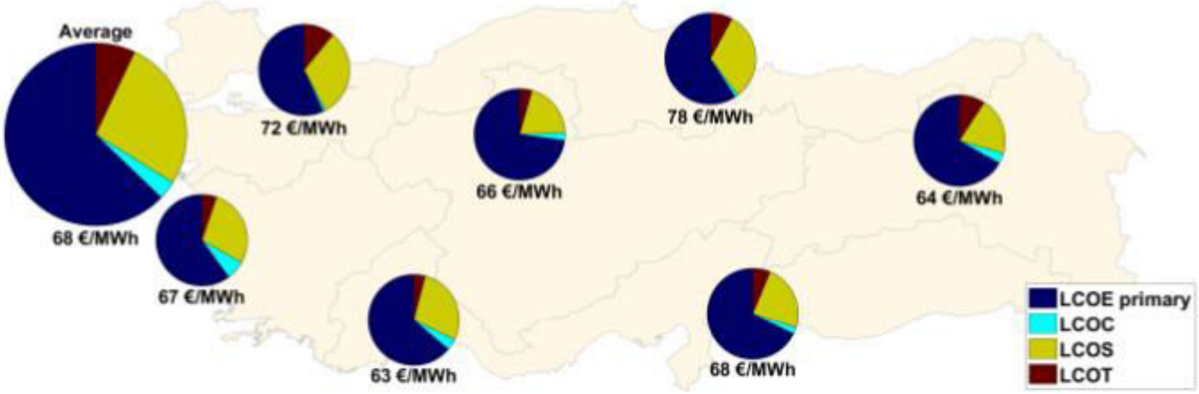


Figure 29. Components of levelized cost of electricity of basic scenario for year 2030.

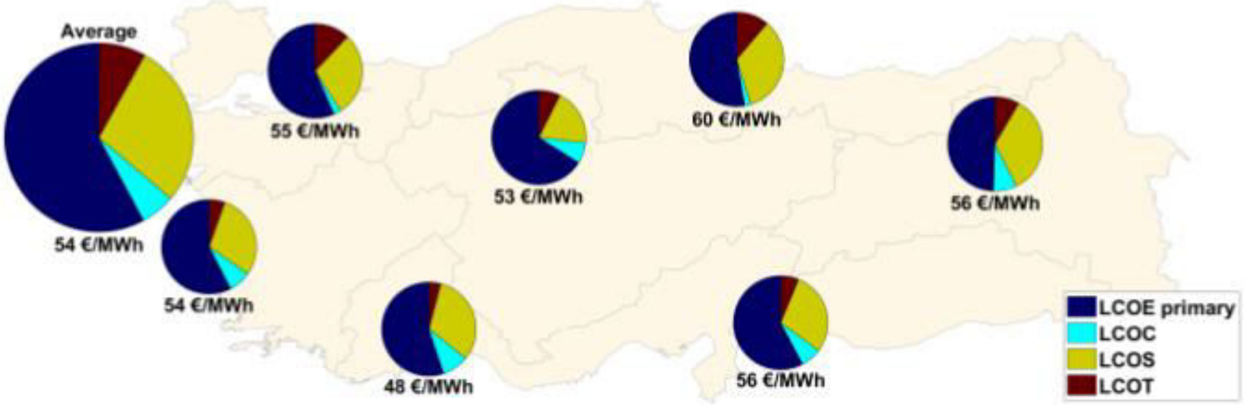


Figure 30. Components of levelized cost of electricity of basic scenario for year 2050.

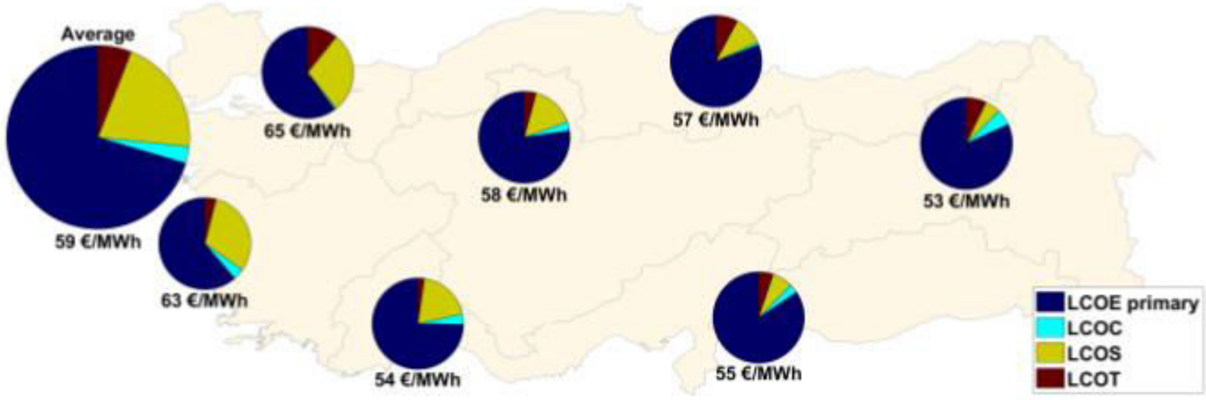


Figure 31. Components of levelized cost of electricity of integrated scenario for year 2030.

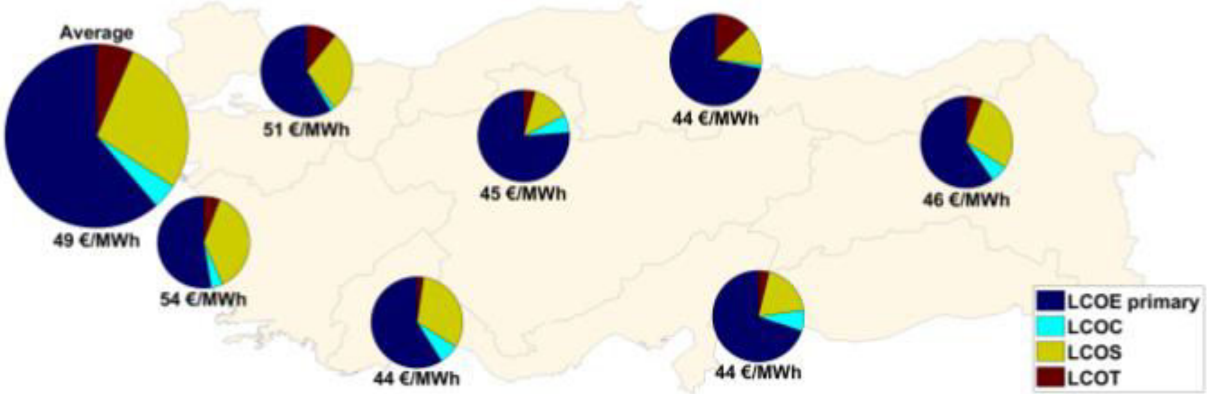


Figure 32. Components of levelized cost of electricity of integrated scenario for year 2050.

The cost components of levelized cost of electricity of both scenarios are shown separately in the Figure 29 - 32 above. LCOE average is 15.2% higher in basic scenario when LCOE difference for year 2030 for basic and integrated scenarios are compared. Apparently that is mainly derived from the levelized cost of storage difference in the North (Blacksea Region) of

Turkey. In a similar manner, the LCOE is 10% higher in the average for the basic scenario compared to integrated scenario for year 2050 and again the big difference is in the North (Blacksea) region.

The difference actually arises from the levelized cost of storage. In a 100% renewable scenario, gas needs to be stored as much as possible in order to be utilized in winter time. If there is not a huge industrial gas demand system production of additional gas becomes more expensive. Flexible demand from SNG demand production affects gas synthesis industry and decrease total electricity cost in the system.

If LCOE difference between 2030 and 2050 for both basic and integrated scenarios to be compared, LCOE for all regions decreases till 2050 unexceptionally. LCOE for year 2050 is lower in comparison to 2030 because of ‘learning curve’ effect – lower capacities costs for all technologies. LCOE for integrated scenario is lower mainly because of lower storage utilisation (levelised cost of storage - LCOS), due to flexible demand from industrial gas synthetic gas generation.

119.3 TWh of the electricity is transmitted by power lines among the regions in basic scenario for year 2050, on the other hand 167.3 TWh of the electricity is transmitted by power lines among the regions in integrated scenario.

Storage throughput mostly realized by battery system storage for 6 sub-divisions of Turkey except the North (Blacksea Region); where battery storage and gas storage covers over 90% of the region's storage annual generation. Batteries SC are the batteries which are installed in the private households, commercial buildings, or industrial buildings, together with PV. This is a part of prosumers system. Battery System is Li-ion batteries based storage connected to the grid directly. Addition to this region, gas storage technology is widely used overall in the energy system model. However heat storage, A-CAES storage and pumped hydro storage technologies pale beside for both scenarios.

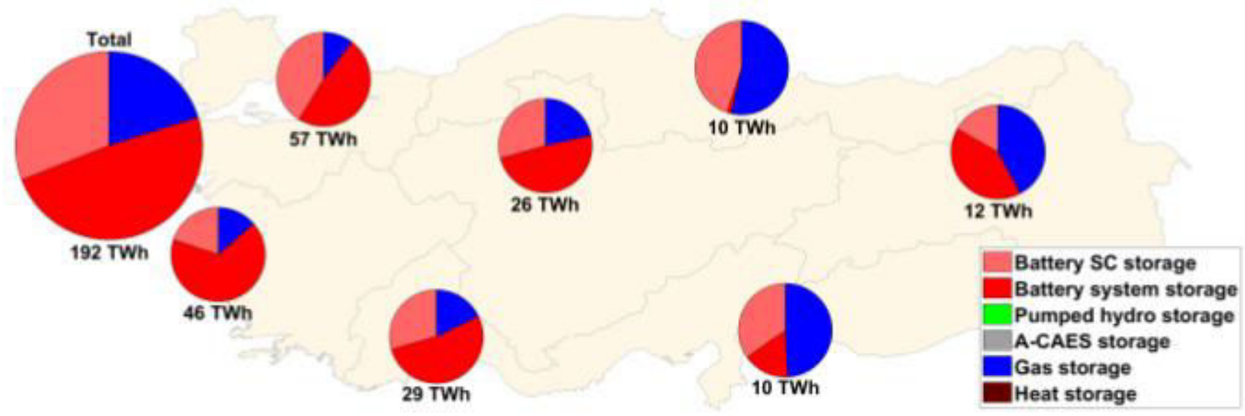


Figure 33. Regions storage annual throughput of basic scenario for year 2050.

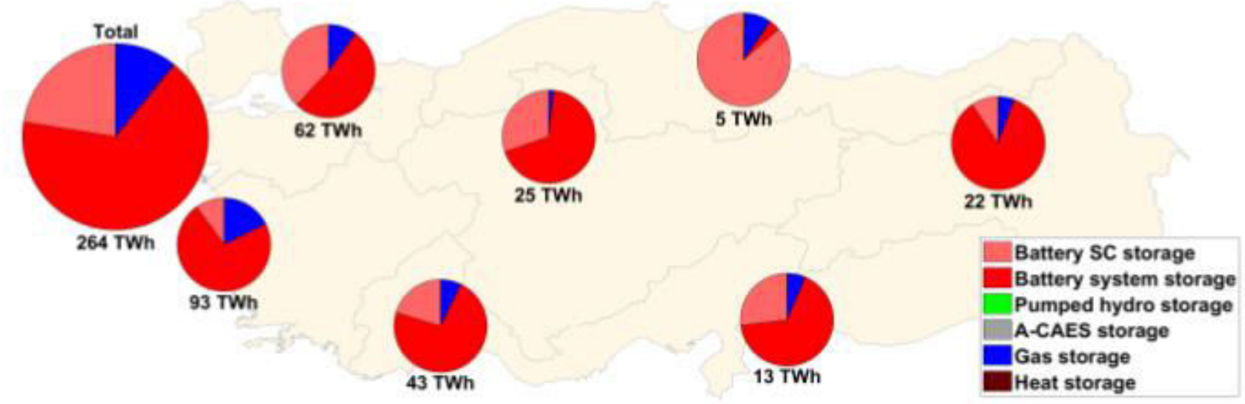


Figure 34. Regions storage annual throughput of integrated scenario for year 2050.

As it can be seen from Figure 33 and 34, there is around 40% increment in storage throughput in the integrated scenario. The difference mostly occurs in the West (Aegean) and South (Mediterranean) regions of Turkey. 173.7 TWh (22.6%) of the final demand is provided by storage for year 2050 in basic scenario and 250.7 TWh (25%) of the final demand is provided by storage for year 2050 in integrated scenario.

Storage capacities of basic and integrated scenarios for the year 2030 and 2050 are shown below. As it can be seen, there is a 137.5% capacity increment from year 2030 to 2050 in basic scenario. Similarly 147% capacity increment from year 2030 to 2050 in integrated scenario. The main reason for that difference is the cost assumptions set, for year 2050 the cost assumptions are lower for almost all technologies because of 'learning curve' effect. At the same time there is increasing electricity prices in the distribution network which pushes installation of prosumers PV and batteries (PV SC and Battery SC) in year 2050. That is why demand in batteries system increases in the year 2050.

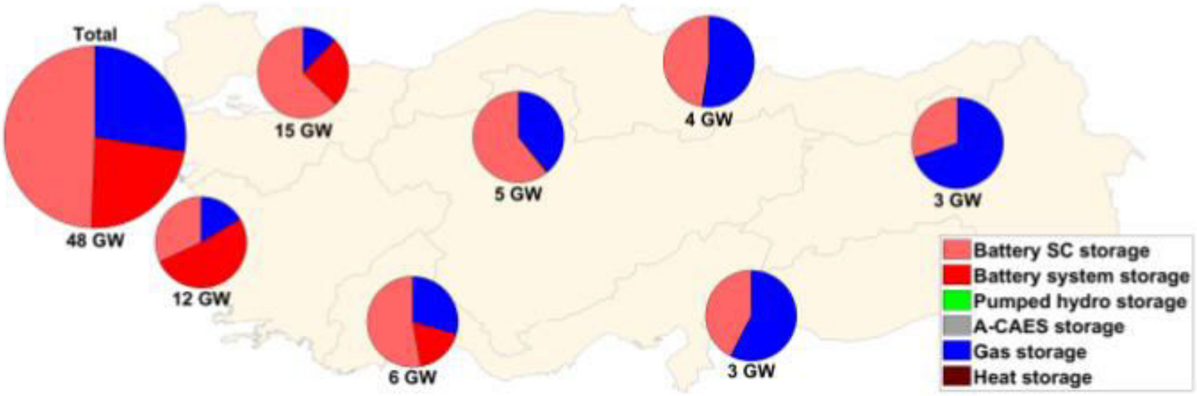


Figure 35. Regions storage capacities of basic scenario for year 2030.

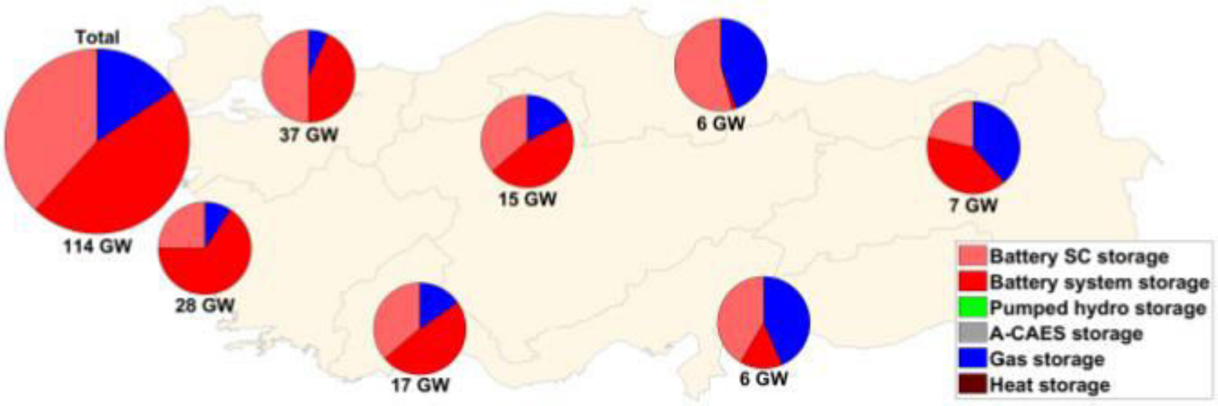


Figure 36. Regions storage capacities of basic scenario for year 2050.

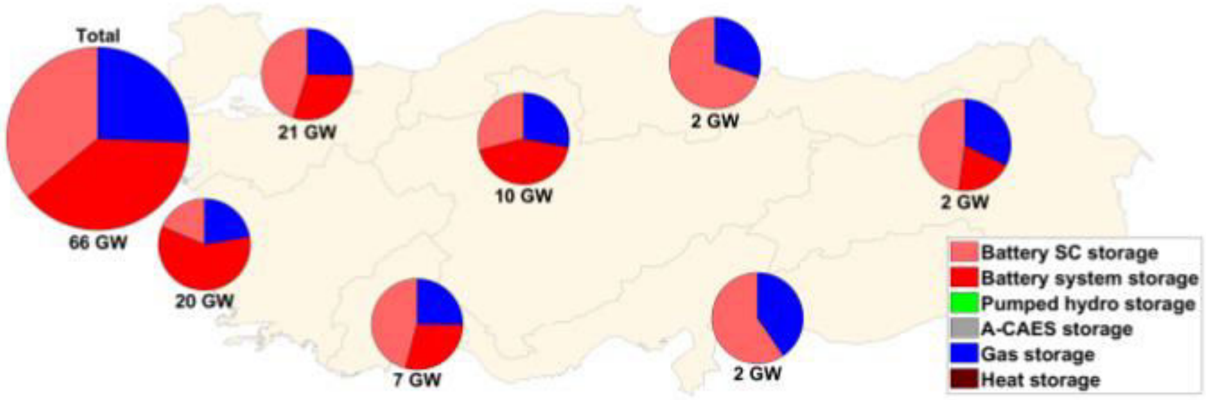


Figure 37. Regions storage capacities of integrated scenario for year 2030

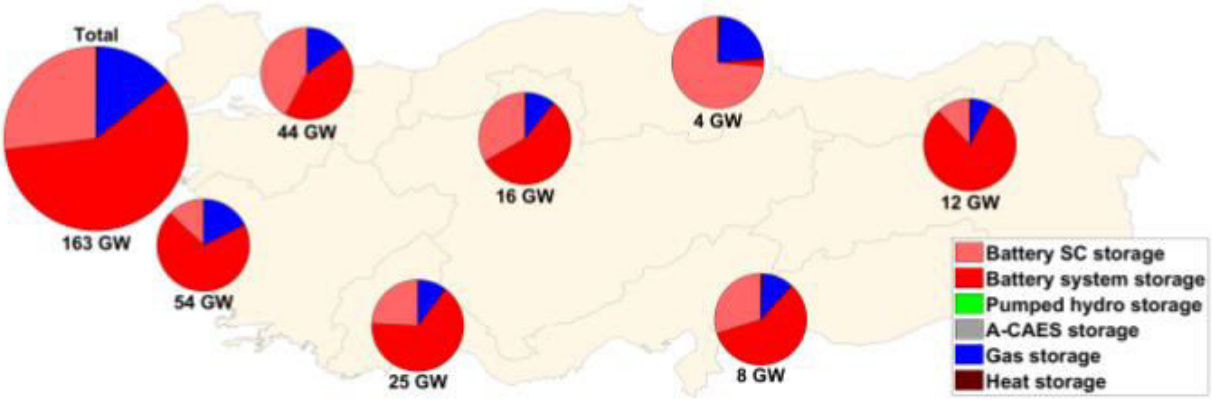


Figure 38. Regions storage capacities of integrated scenario for year 2050

There is excess energy in the model, which is 23.6 TWh and 60.7 TWh for the years 2030 and 2050 respectively in the basic scenario. This amount actually represents 5.1% of year 2030 and 9.5% of year 2050 total electricity demand value. On the other for integrated scenario the excess energy value is 29.2 TWh and 62.1 TWh for the years 2030 and 2050 respectively. For this case this amount represents 6.3% and 9.7% of the total electricity demand value for year 2030 and 2050. Heat and mobility is not part of the modeling in this reseach, however the excess energy value discussed above, can be used to cover heat and mobility demand.

Geothermal energy potential (consequently the installed capacity) only limited with West, Central and North West regions of Turkey. Since geothermal utilisation is always 100% both in year 2030 and 2050 for basic and integrated scenarios, installed capacity (in GW) provides the same value. However geothermal power plants represent only slight amount of contribution to electricity generation.

Table 19. Regions with geothermal installed capacity for year 2050.

	Basic Scenario 2050	Integrated Scenario 2050
Regions	Geothermal Installed Capacity [GW]	Geothermal Installed Capacity [GW]
South	0	0
North West	0.015	0.015
West	0.567	0.567
North	0	0
Mid (Central)	0.065	0.065
South East	0	0
East	0	0
Total	0.648	0.648

Similarly hydropower is also limited with some regions. However it has remarkable contribution to total electricity generation and it is more widespread compared to geothermal energy locations. Among all the regions North West and West regions are lack of hydropower potential as well as installed capacity.

Solar PV takes a major share of electricity generation in all regions except the North region of Turkey. Not surprisingly this region takes the most amount of rainfall compared to the other regions and due to climatic conditions the region has limited solar potential. Addition to that wind energy potential (hence the wind onshore installed capacity) is only limited with North West, West and Central regions of Turkey.

Not all regions are self-sufficient in terms of local energy demand. As presented in Table 20 and 21 below, for both basic and integrated scenarios explicitly North West region is in position of importing from the grid due to its high population and industry. On the contrary West and Central regions are explicitly exporting regions for both basic and integrated scenarios.

Table 20. Importing and exporting regions in basic scenario for year 2050.

	Basic Scenario 2050	Basic Scenario 2050
Regions	Grid, import [TWh]	Grid, export [TWh]
South	8.4	7.5
North West	88.8	0.792
West	1.1	37.3
North	15	3.3
Mid (Central)	0.563	48.7
South East	4.3	9.7
East	1.1	16.8
Total	119.3	124

Table 21. Importing and exporting regions in integrated scenario for year 2050.

	Integrated Scenario 2050	Integrated Scenario 2050
Regions	Grid, import [TWh]	Grid, export [TWh]
South	6	10.4
North West	126.5	0.4
West	0.7	94.4
North	26.2	0.143
Mid (Central)	2.9	35.2
South East	3.5	10.6
East	1.3	22
Total	167.3	173.1

Biogas power plant (additionally biogas digester and biogas upgrade), solid biomass and biowaste-to-energy power plant total installed capacities are stayed at 3.58 GW in the basic scenario for 2050. On the other hand that total installed capacity reached 6.07 GW in the integrated scenario for 2050. Parallel to that, overall bioenergy output is around 25.5 TWh in the integrated scenario and 16.8 TWh in the basic scenario as shown in Table 14.

Sustainability criteria are the actual determinant for Turkey's bioenergy potential. Much debate have been made by many different parties, therefore the overall amount of Turkey's bioenergy potential varies from one source to another.

As discussed earlier in Chapter 4, "sustainable biomass potential" is highly controversial and the line of vision highly varies from one source to another accordingly. For this report DBFZ (2009), "Regionale und globale räumliche Verteilung von Biomassepotenzialen" was taken as reference for sustainable biomass potential of Turkey. Compared to Ministry of Energy and Natural Resources' "Turkey Biomass Energy Potential Atlas" source, DBFZ (2009) is even more strict in terms of sustainability (see Chapter 7.2). Therefore the discrimination of the estimated bioenergy potentials derives. Additionally the cost calculation algorithm of the model that is resulting to the bioenergy utilization has been already discussed in Chapter 7.2. Therefore even there is sustainable bioenergy potential of Turkey that exists at a cost level on which utilizing other forms of renewable energy technologies is more economically beneficial. That is the main reason of declined biomass usage percents from year 2030 to 2050 for both basic and integrated scenarios.

The deviation of distribution of available sustainable biomass source is not remarkable among the regions, especially when the difference is compared to total generation of each region's. Still the North, East and South East regions have the lowest available biomass capacity compared to the others. On the other hand North West, West and Central regions have the biggest capacity of available biomass.

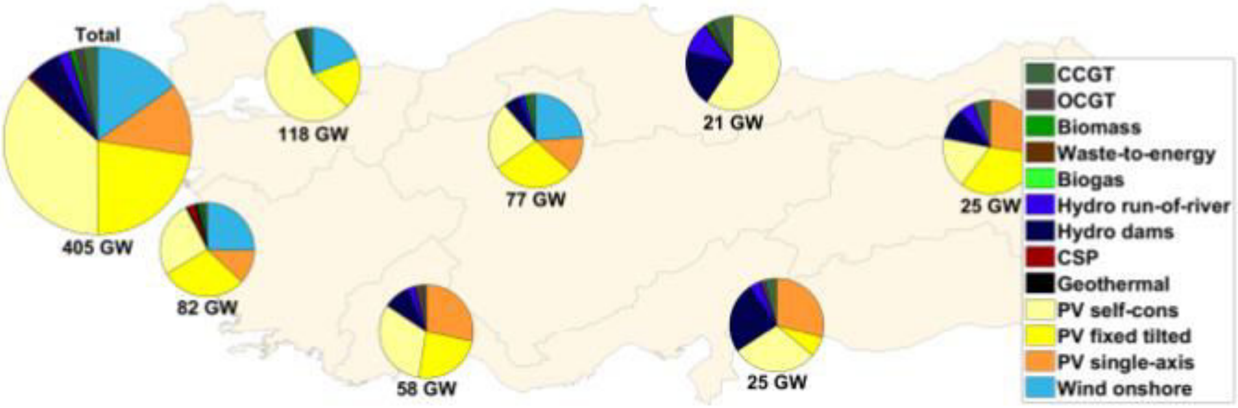


Figure 39. Regions electricity capacities of basic scenario for the year 2050.

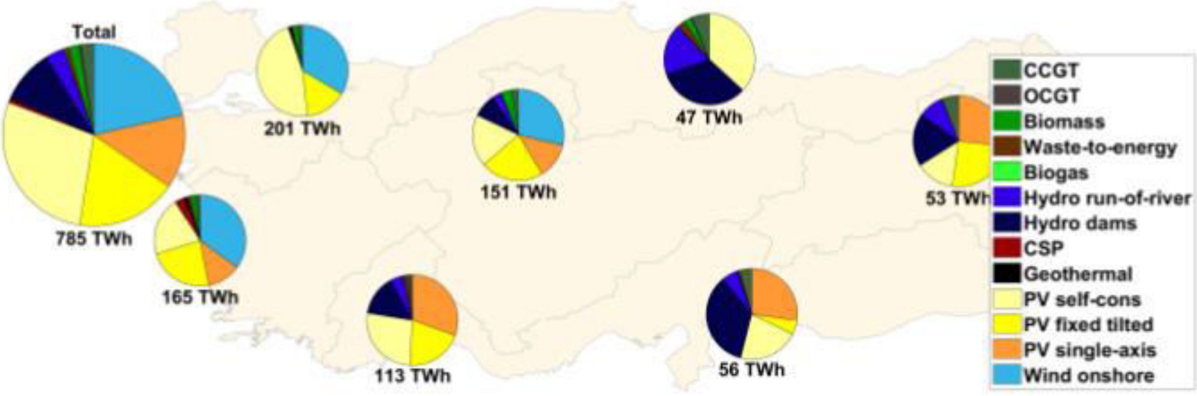


Figure 40. Regions electricity generation of basic scenario for the year 2050.

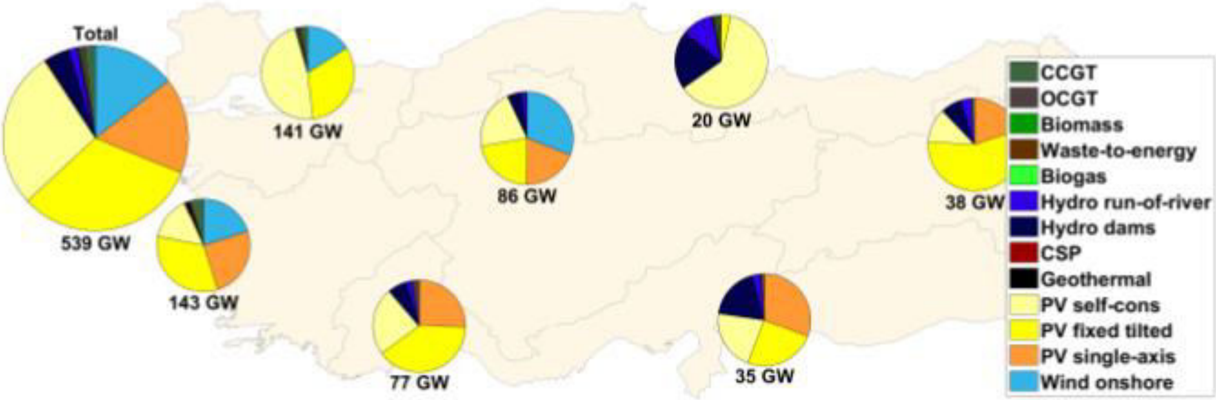


Figure 41. Regions electricity capacities of integrated scenario for the year 2050.

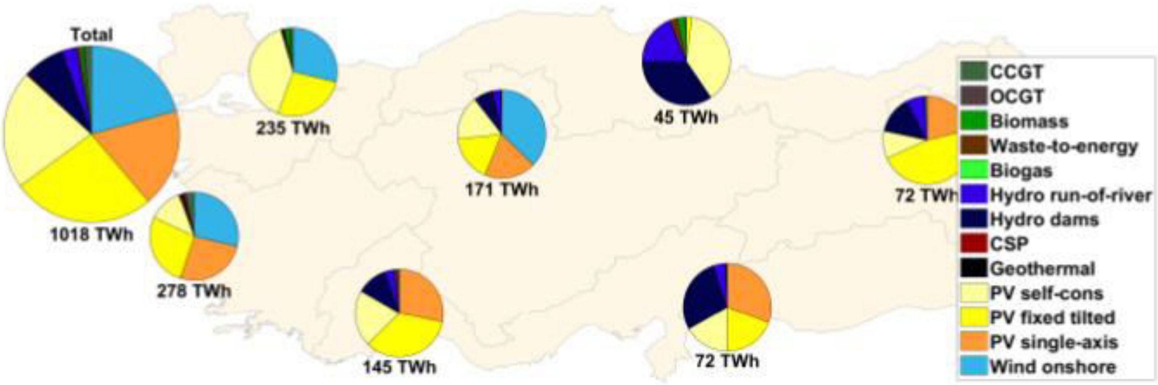


Figure 42. Regions electricity generation of integrated scenario for the year 2050.

As it can be seen from both Figure 39 and Figure 41, the generation capacities profile is dominated by PV and wind onshore technologies on their own. However no remarkable CSP capacity exists in both cases.

Hourly generation of summer and winter profiles of Turkey for both basic and integrated scenarios for the year 2030 are shown in figures below. As it can be seen, the energy generated from solar PV making peak values resulting excess energy generation in summer profiles as the sun insolation hours are higher compared to winter profiles. The solar energy obtained is mainly used used for charging the batteries and electrolysis during daytime. On the other hand for the winter profiles, hydro dams are covering remarkable share of the energy demand.

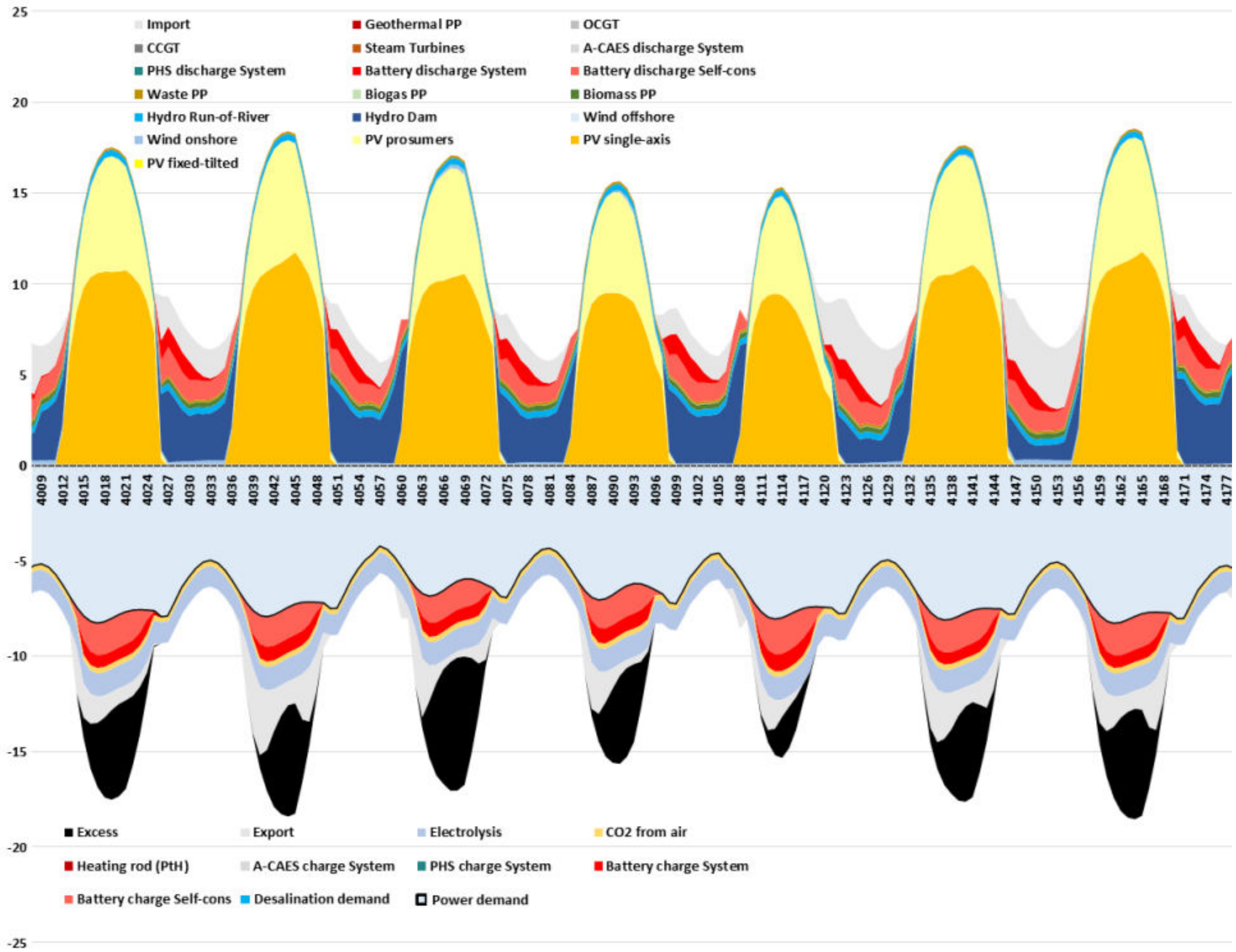


Figure 43. Hourly resolution of summer profile for Turkey overnight basic scenario for the year 2030. Above the figures generation of different RE resources, CCGT and OCGT in hourly resolution are shown and bottom storage options and excess electricity generations are shown.

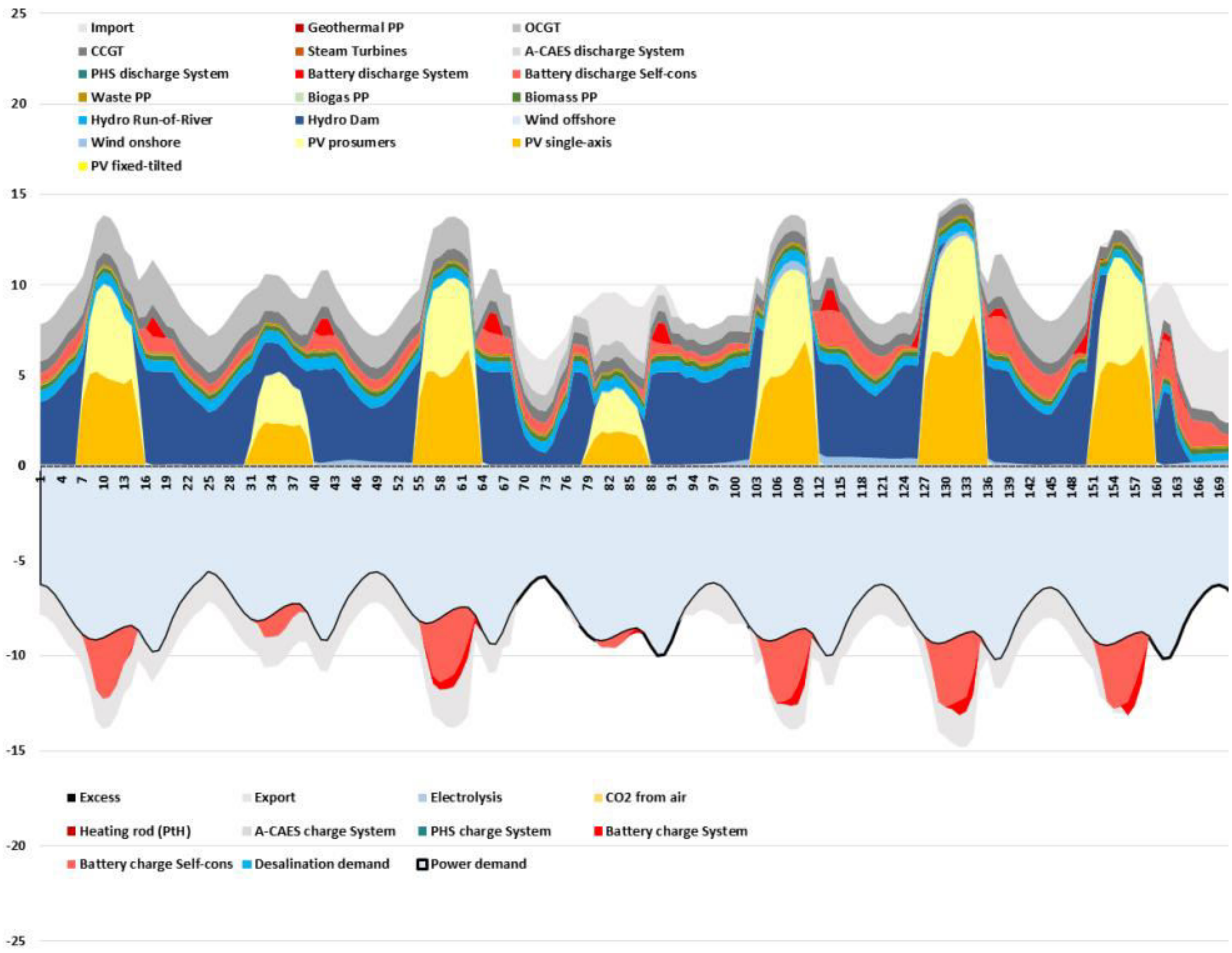


Figure 44. Hourly resolution of winter profile for Turkey overnight basic scenario for the year 2030. Above the figures generation of different RE resources, CCGT and OCGT in hourly resolution are shown and bottom storage options and excess electricity generations are shown.

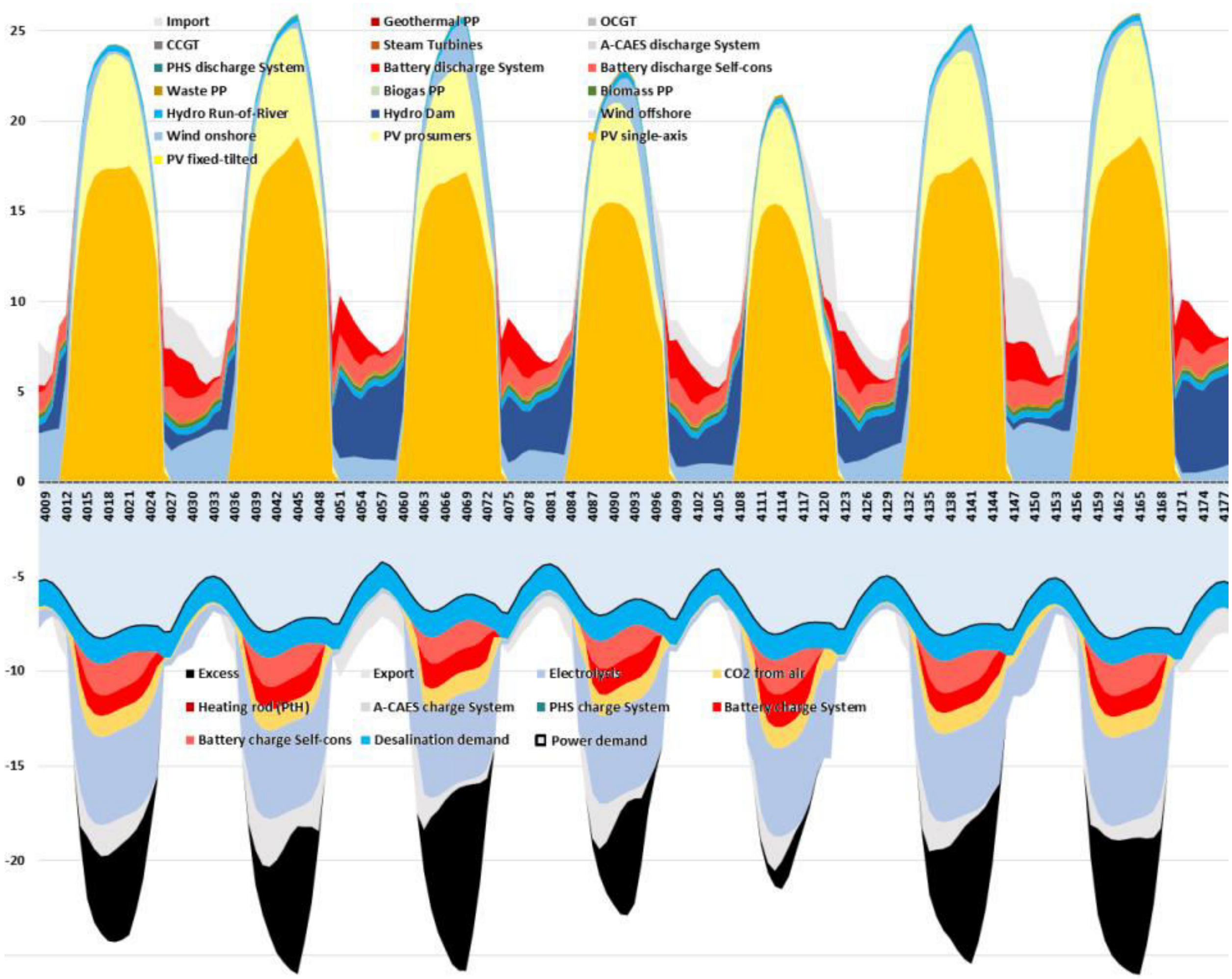


Figure 45. Hourly resolution of summer profile for Turkey overnight integrated scenario for the year 2030. Above the figures generation of different RE resources, CCGT and OCGT in hourly resolution are shown and bottom storage options and excess electricity generations are shown.

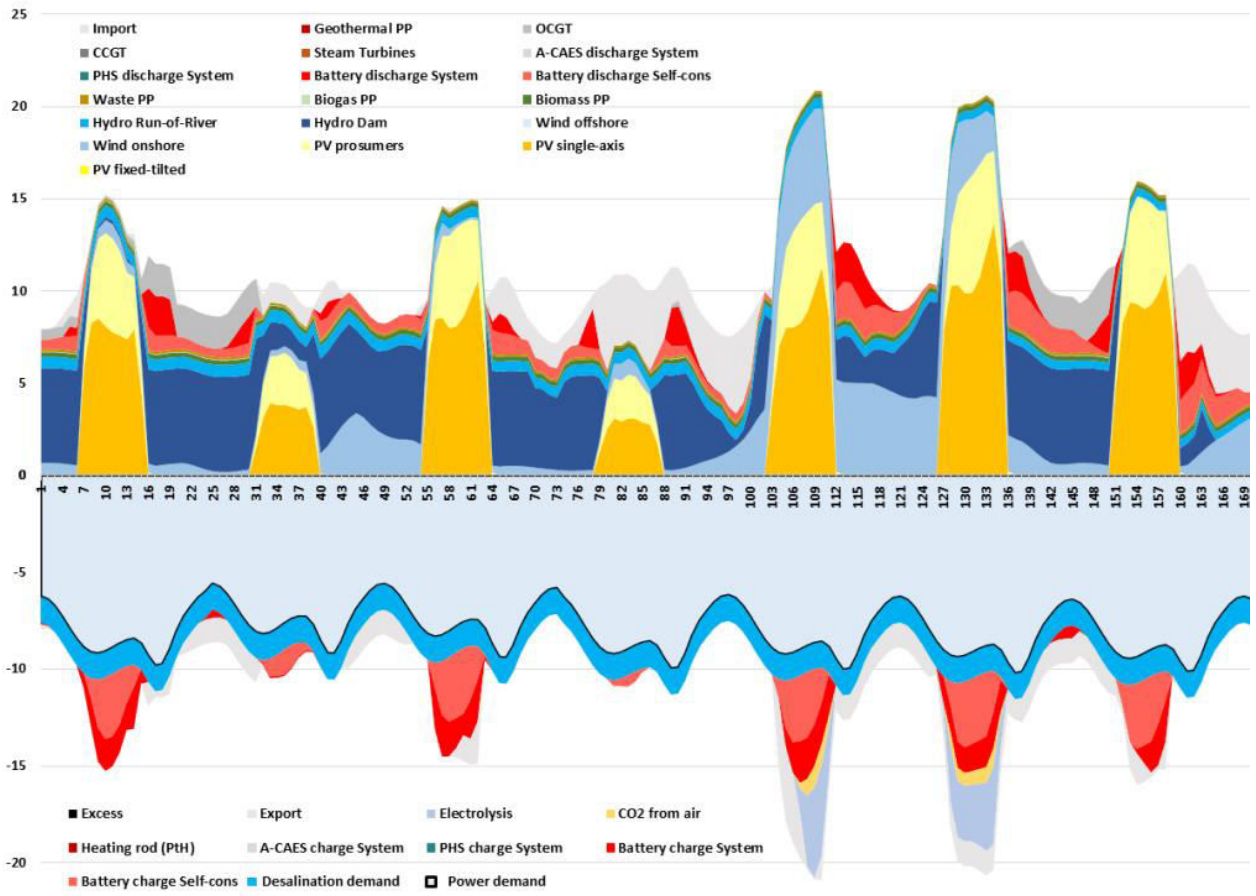


Figure 46. Hourly resolution of winter profile for Turkey overnight integrated scenario for the year 2030. Above the figures generation of different RE resources, CCGT and OCGT in hourly resolution are shown and bottom storage options and excess electricity generations are shown.

The findings for the both basic and integrated energy scenarios for the year 2030 and 2050 were summarized in energy flow diagrams below. The energy flow diagrams were comprised of the primary RE generation, total demand of each sector and losses and the energy storage technologies. The usable heat is mainly obtained from biomass and biogas heat, curtailment, methanation and electrolysis losses for each of energy flow diagrams.

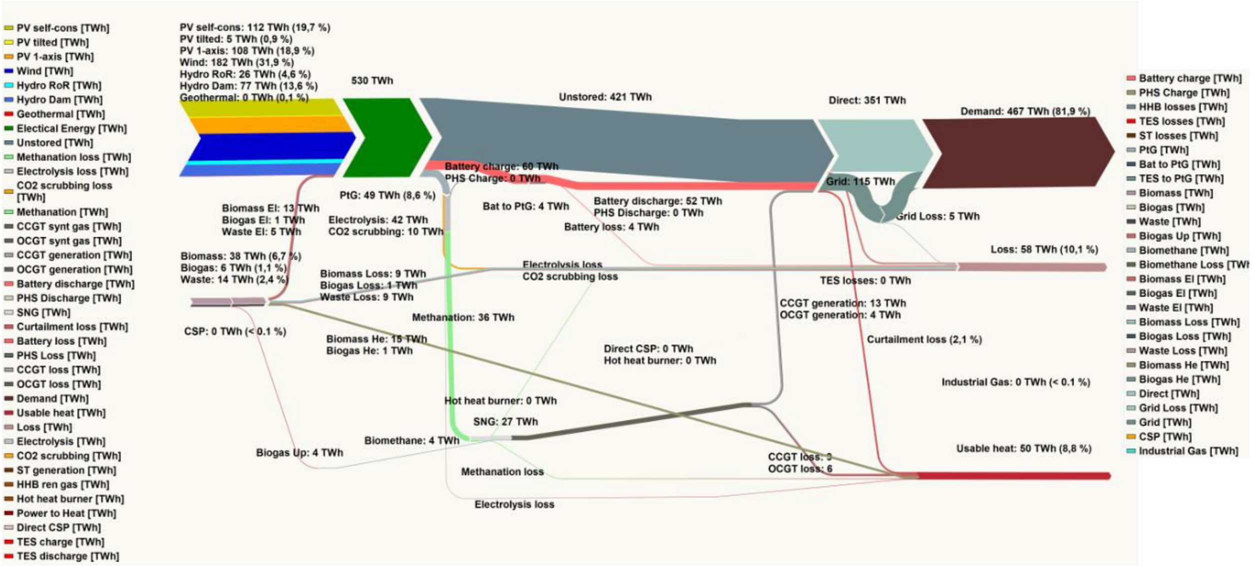


Figure 47. Energy flow of the system in TWh for the year 2030 in basic scenario.

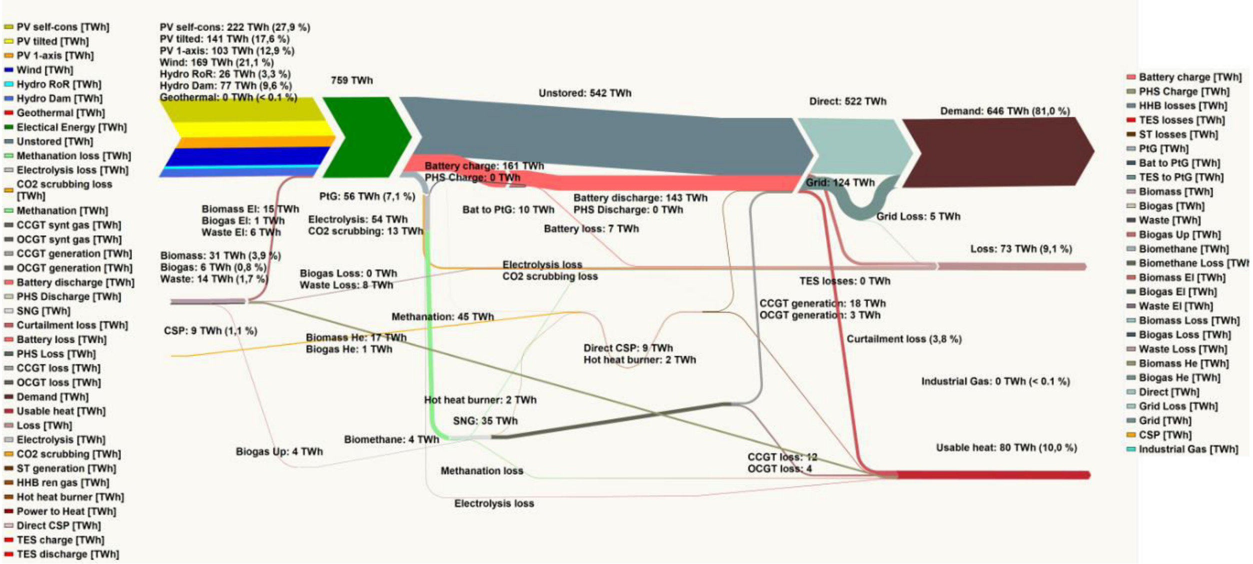


Figure 48. Energy flow of the system in TWh for the year 2050 in basic scenario.

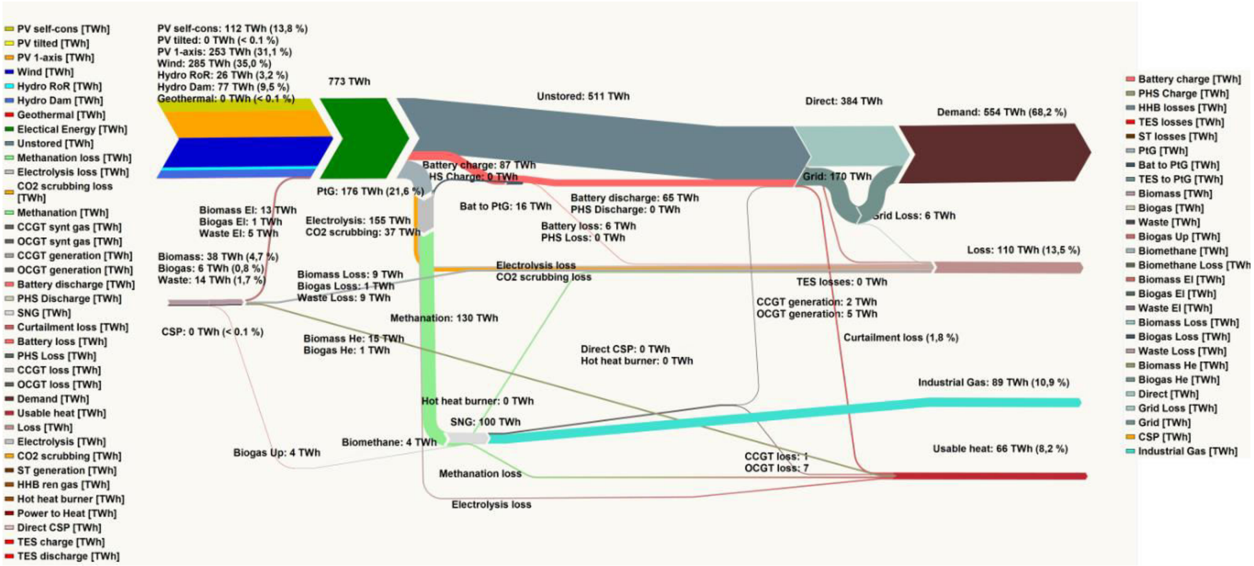


Figure 49. Energy flow of the system in TWh for the year 2030 in integrated scenario.

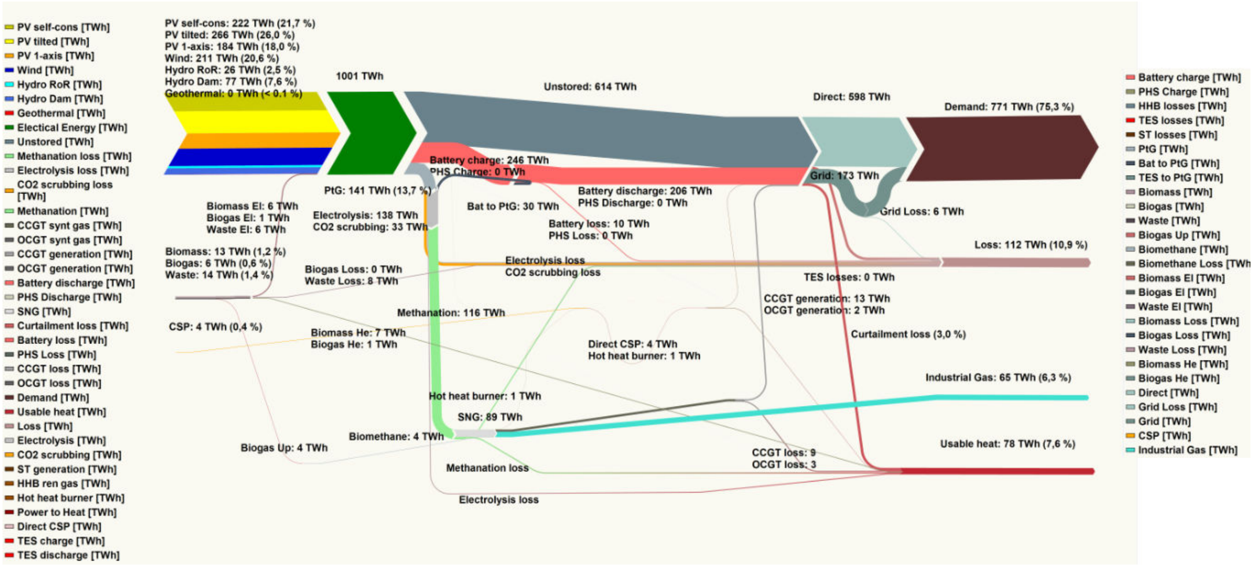


Figure 50. Energy flow of the system in TWh for the year 2050 in integrated scenario.

9 CONCLUSION

In this research the economic and technical aspect of a sustainable energy system and its feasibility for Turkey analyzed and discussed. The main goal was to build an energy frame by utilizing Turkey's huge green energy potential by employing by bioenergy technologies, solar PV, hydropower, wind energy and other RE technologies.

Currently Turkey's energy system profile heavily depends on imported fossil fuel sources. Due to the decision made during COP21 agreement, Turkey will have to modify its current situation in order to reach more sustainable energy system profile.

This research indicates that sufficient energy can be provided by existing RE technologies for the year 2030 in Turkey with a 49-54 €/MWh$_{el}$ cost. Moreover industrial gas demand and for storage purpose can be covered as well. Moreover the excess energy produced represents 5.1% for year 2030 and 9.5% for year 2050 of electricity demand for basic scenario. Where it represents 6.3% for year 2030 and 9.7% for year 2050 of electricity demand for integrated scenario. That amount of energy in the system can be used to cover heat and mobility demand.

For all regions LCOE tend to decline till year 2050 for both basic and integrated scenarios by the effect of learning curve - lower capacities costs for all technologies. In comparison to basic scenario, LCOE lower in integrated scenario due to lower storage utilisation and as a result of to flexible demand from industrial gas synthetic gas generation.

For the bioenergy usage the bottleneck is the "sustainability" criteria. Many different sources have various numbers for Turkey. Those numbers and their impact on environment discussed earlier in this research. A rigid approach is applied for the amount of Turkey's sustainable biomass potential (excluding energy crops etc.) therefore the total amount of available sustainable biomass is limited. However as a result of decreasing cost of other renewable energy alternatives (especially solar PV and batteries) the model decides to decrease biomass usage numbers from 2030 to 2050 for both scenarios.

Explicitly North West is an importing region by the reason of its denser population and demand from the industry side. On the other hand West and Central regions are clearly the exporting regions.

For both cases solar PV technologies and wind energy alone cover almost 80% of energy production expect the regions where Turkey's streams are mostly exist. For a sustainable Turkish energy systems, solar PV domination in terms of electricity generation capacity is not surprising when Turkey's geographical location is considered along with decreasing cost of batteries till year 2050. Installation of prosumers PV and batteries is also boosted by the increasing electricity prices in the distribution network till year 2050 resulting increased batteries system demand. Storage is highly significant for the model and for the energy demand. There is nearly 138% capacity increase in basic scenario and 147% capacity increase in integrated scenario from year 2030 to 2050. Almost 23% of the total energy demand is provided by storage for year 2050 in basic scenario where 25% is provided in integrated scenario.

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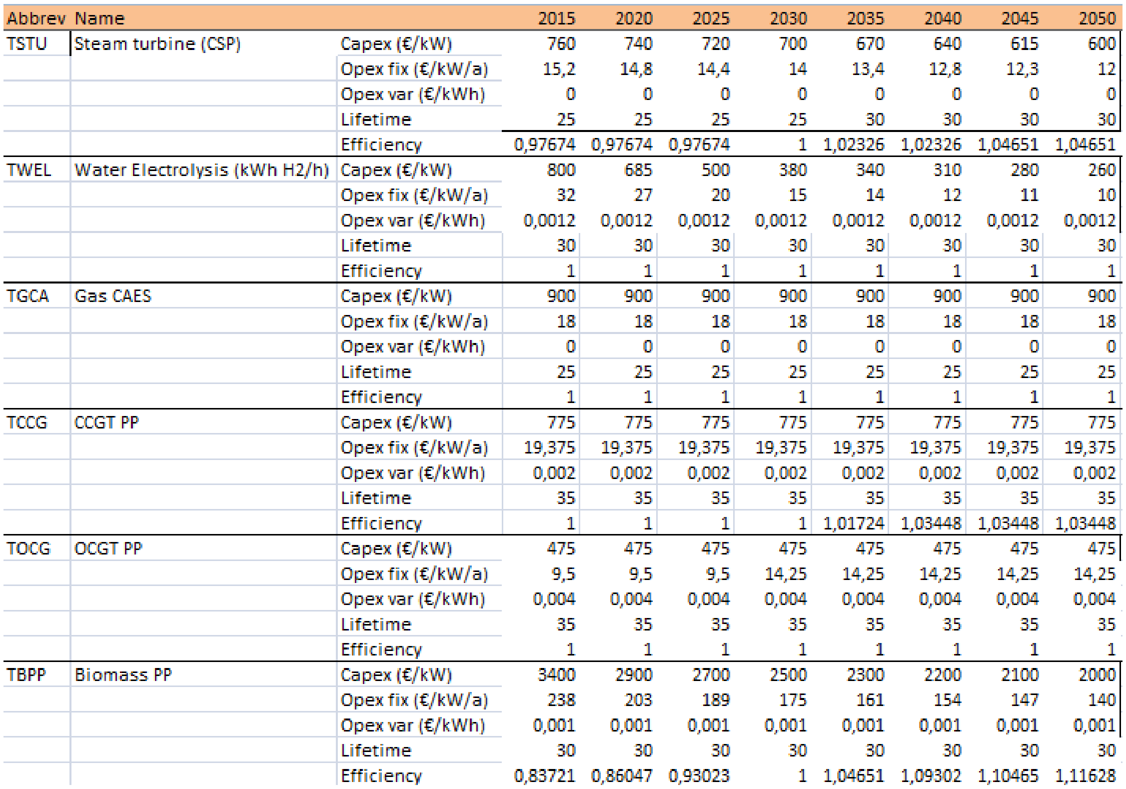
APPENDIX

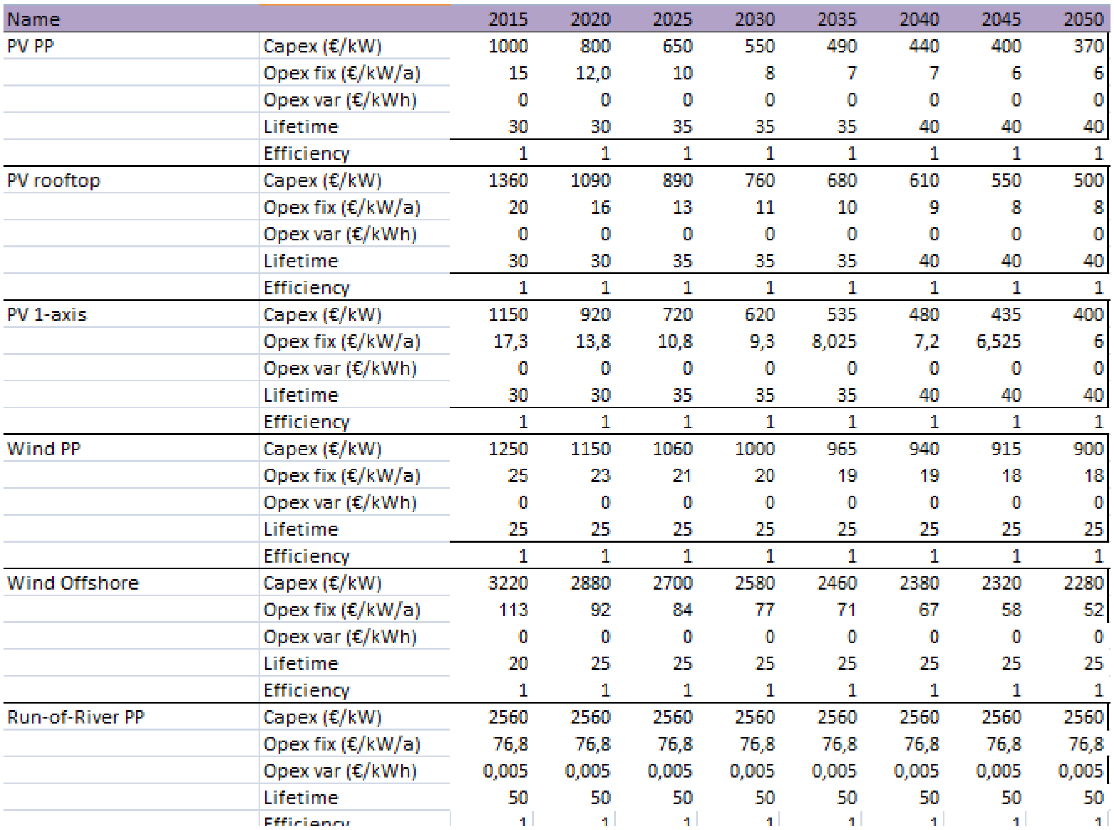
Figure 51. Technical and Financial Assumptions of the resource and transformer technologies employed by the model.



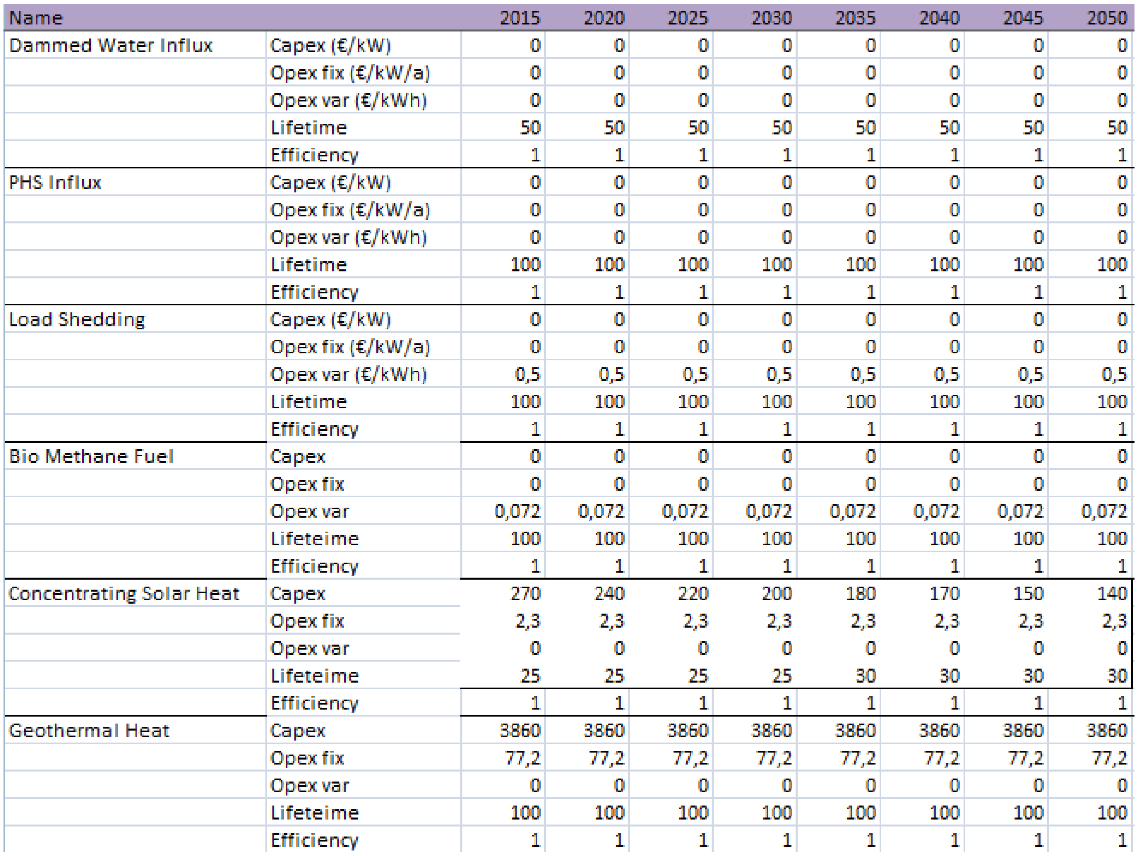
Abbrev	Name		2015	2020	2025	2030	2035	2040	2045	2050
TSTU	Steam turbine (CSP)	Capex (€/kW)	760	740	720	700	670	640	615	600
		Opex fix (€/kW/a)	15,2	14,8	14,4	14	13,4	12,8	12,3	12
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	25	25	25	25	30	30	30	30
		Efficiency	0,97674	0,97674	0,97674	1	1,02326	1,02326	1,04651	1,04651
TWEL	Water Electrolysis (kWh H2/h)	Capex (€/kW)	800	685	500	380	340	310	280	260
		Opex fix (€/kW/a)	32	27	20	15	14	12	11	10
		Opex var (€/kWh)	0,0012	0,0012	0,0012	0,0012	0,0012	0,0012	0,0012	0,0012
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	1	1	1	1	1	1	1	1
TGCA	Gas CAES	Capex (€/kW)	900	900	900	900	900	900	900	900
		Opex fix (€/kW/a)	18	18	18	18	18	18	18	18
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	25	25	25	25	25	25	25	25
		Efficiency	1	1	1	1	1	1	1	1
TCCG	CCGT PP	Capex (€/kW)	775	775	775	775	775	775	775	775
		Opex fix (€/kW/a)	19,375	19,375	19,375	19,375	19,375	19,375	19,375	19,375
		Opex var (€/kWh)	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002
		Lifetime	35	35	35	35	35	35	35	35
		Efficiency	1	1	1	1	1,01724	1,03448	1,03448	1,03448
TOCG	OCGT PP	Capex (€/kW)	475	475	475	475	475	475	475	475
		Opex fix (€/kW/a)	9,5	9,5	9,5	14,25	14,25	14,25	14,25	14,25
		Opex var (€/kWh)	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004
		Lifetime	35	35	35	35	35	35	35	35
		Efficiency	1	1	1	1	1	1	1	1
TBPP	Biomass PP	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
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	0,83721	0,86047	0,93023	1	1,04651	1,09302	1,10465	1,11628

Abbrev	Name		2015	2020	2025	2030	2035	2040	2045	2050
TMSW	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
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	0,79412	0,91176	0,95588	1	1,04412	1,08824	0,86765	1,23529
TDAM	Hydro Dam PP	Capex (€/kW)	3000	3000	3000	3000	3000	3000	3000	3000
		Opex fix (€/kW/a)	30	30	30	30	30	30	30	30
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	50	50	50	50	50	50	50	50
		Efficiency	1	1	1	1	1	1	1	1
TMET	Methanisation (kWh Me/h)	Capex (€/kW)	492	421	310	234	208	190	172	160
		Opex fix (€/kW/a)	10	8	6	5	4	4	3	3
		Opex var (€/kWh)	0,0015	0,0015	0,0015	0,0015	0,0015	0,0015	0,0015	0,0015
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	1	1	1	1	1	1	1	1
TLIQ	Liqid Fuel Syn	Capex (€/kW)	738	632	465	351	312	285	258	240
		Opex fix (€/kW/a)	15	13	9	7	6	6	5	5
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	25	25	25	25	25	25	25	25
		Efficiency	1	1	1	1	1	1	1	1
TDES	RO Desalination (m3/h)	Capex (€/kW)	25	25	25	25	25	25	25	25
		Opex fix (€/kW/a)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	20	20	20	20	20	20	20	20
		Efficiency	1	1	1	1	1	1	1	1
TCHP	BHKW biogas	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
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	0,83721	0,86047	0,93023	1	1,04651	1,09302	1,10465	1,11628

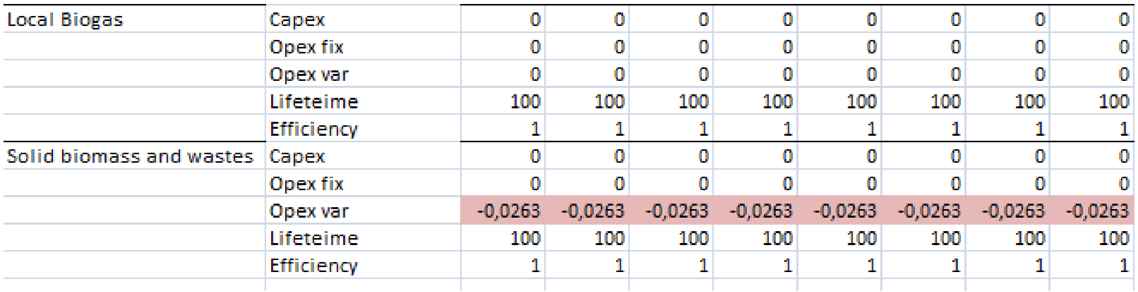
Abbrev	Name		2015	2020	2025	2030	2035	2040	2045	2050
TCOS	CO2 Scrubbing	Capex (€/kW)	749	641	470	356	314	286	258	240
		Opex fix (€/kW/a)	29,9	25,6	18,8	14,2	12,6	11,4	10,3	9,6
		Opex var (€/kWh)	0,0013	0,0013	0,0013	0,0013	0,0013	0,0013	0,0013	0,0013
		Lifetime	30	30	30	30	30	30	30	30
		Efficiency	1	1	1	1	1	1	1	1
TCSP	Concentaded solar resiever	Capex (€/kW)	279,4	218,44	187,55	167,04	153,9	134,4	122,1	104,5
		Opex fix (€/kW/a)	6,4262	5,02412	4,31365	3,84192	3,5397	3,0912	2,8083	2,4035
		Opex var (€/kWh)	0	0	0	0	0	0	0	0
		Lifetime	25	25	25	25	25	25	25	25
		Efficiency	1	1	1	1	1	1	1	1
TPTH	electricity to heat	Capex (€/kW)	20	20	20	20	20	20	20	20
		Opex fix (€/kW/a)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
		Opex var (€/kWh)	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
		Lifetime	50	50	50	50	50	50	50	50
		Efficiency	1	1	1	1	1	1	1	1
TBGD	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
		Lifetime	20	20	20	20	25	25	25	25
		Efficiency	1	1	1	1	1	1	1	1
TBGU	Biogas Upgrade	Capex (€/kW)	340	290	270	250	230	220	210	200
		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
		Lifetime	20	20	20	20	20	20	20	20
		Efficiency	1	1	1	1	1	1	1	1
TGEO	Geothermal electricity	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	40	40	40	40	40	40	40	40
		Efficiency	1	1	1	1	1	1	1	1



Name		2015	2020	2025	2030	2035	2040	2045	2050
PV PP	Capex (€/kW)	1000	800	650	550	490	440	400	370
	Opex fix (€/kW/a)	15	12,0	10	8	7	7	6	6
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	30	30	35	35	35	40	40	40
	Efficiency	1	1	1	1	1	1	1	1
PV rooftop	Capex (€/kW)	1360	1090	890	760	680	610	550	500
	Opex fix (€/kW/a)	20	16	13	11	10	9	8	8
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	30	30	35	35	35	40	40	40
	Efficiency	1	1	1	1	1	1	1	1
PV 1-axis	Capex (€/kW)	1150	920	720	620	535	480	435	400
	Opex fix (€/kW/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
	Lifetime	30	30	35	35	35	40	40	40
	Efficiency	1	1	1	1	1	1	1	1
Wind PP	Capex (€/kW)	1250	1150	1060	1000	965	940	915	900
	Opex fix (€/kW/a)	25	23	21	20	19	19	18	18
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	25	25	25	25	25	25	25	25
	Efficiency	1	1	1	1	1	1	1	1
Wind Offshore	Capex (€/kW)	3220	2880	2700	2580	2460	2380	2320	2280
	Opex fix (€/kW/a)	113	92	84	77	71	67	58	52
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	20	25	25	25	25	25	25	25
	Efficiency	1	1	1	1	1	1	1	1
Run-of-River PP	Capex (€/kW)	2560	2560	2560	2560	2560	2560	2560	2560
	Opex fix (€/kW/a)	76,8	76,8	76,8	76,8	76,8	76,8	76,8	76,8
	Opex var (€/kWh)	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005
	Lifetime	50	50	50	50	50	50	50	50
	Efficiency	1	1	1	1	1	1	1	1



Name		2015	2020	2025	2030	2035	2040	2045	2050
Dammed Water Influx	Capex (€/kW)	0	0	0	0	0	0	0	0
	Opex fix (€/kW/a)	0	0	0	0	0	0	0	0
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	50	50	50	50	50	50	50	50
	Efficiency	1	1	1	1	1	1	1	1
PHS Influx	Capex (€/kW)	0	0	0	0	0	0	0	0
	Opex fix (€/kW/a)	0	0	0	0	0	0	0	0
	Opex var (€/kWh)	0	0	0	0	0	0	0	0
	Lifetime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1
Load Shedding	Capex (€/kW)	0	0	0	0	0	0	0	0
	Opex fix (€/kW/a)	0	0	0	0	0	0	0	0
	Opex var (€/kWh)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
	Lifetime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1
Bio Methane Fuel	Capex	0	0	0	0	0	0	0	0
	Opex fix	0	0	0	0	0	0	0	0
	Opex var	0,072	0,072	0,072	0,072	0,072	0,072	0,072	0,072
	Lifeteime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1
Concentrating Solar Heat	Capex	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
	Lifeteime	25	25	25	25	30	30	30	30
	Efficiency	1	1	1	1	1	1	1	1
Geothermal Heat	Capex	3860	3860	3860	3860	3860	3860	3860	3860
	Opex fix	77,2	77,2	77,2	77,2	77,2	77,2	77,2	77,2
	Opex var	0	0	0	0	0	0	0	0
	Lifeteime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1



Local Biogas	Capex	0	0	0	0	0	0	0	0
	Opex fix	0	0	0	0	0	0	0	0
	Opex var	0	0	0	0	0	0	0	0
	Lifeteime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1
Solid biomass and wastes	Capex	0	0	0	0	0	0	0	0
	Opex fix	0	0	0	0	0	0	0	0
	Opex var	-0,0263	-0,0263	-0,0263	-0,0263	-0,0263	-0,0263	-0,0263	-0,0263
	Lifeteime	100	100	100	100	100	100	100	100
	Efficiency	1	1	1	1	1	1	1	1