MODELLING THE BIOMASS ENERGY POTENTIAL IN ELECTRICITY GENERATION TO SUPPORT TÜRKİYE'S TRANSITION TO LOW-CARBON FUTURE

TÜRKİYE'NİN DÜŞÜK KARBONLU GELECEĞE GEÇİŞİNİ DESTEKLEMEK İÇİN ELEKTRİK ÜRETİMİNDE BİYOKÜTLE ENERJİ POTANSİYELİNİN MODELLENMESİ

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ABSTRACT

MODELLING THE BIOMASS ENERGY POTENTIAL IN ELECTRICITY GENERATION TO SUPPORT TÜRKİYE'S TRANSITION TO LOW-CARBON FUTURE

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Bioenergy represents the most utilized renewable energy source globally, particularly in developing countries. These countries leverage this potential to enhance their energy security by reducing reliance on imported fossil fuels. The predominant application of this energy remains traditional cooking and heating. Nevertheless, the utilization of this potential for electricity generation has been on the rise.

The potential role of bioenergy in achieving a sustainable and secure electricity mix in Türkiye is aligned with the country's ambitious renewable energy targets. The dispatchability of bioenergy is of particular importance in complementing the intermittent nature of solar and wind power, particularly in scenarios with limited storage capacity. Bioenergy potential is considered unpredictable, and there is a lack of clarity among governments regarding the expansion of bioenergy capacity in their future renewable energy targets. Türkiye is among the countries that have increased their bioenergy capacity for electricity generation by providing support to the private sector. Nevertheless, the country has yet to establish clear capacity expansion targets for this energy source.

This study assesses the long-term potential of predictable and sustainable biomass resources for electricity generation, considering a range of bioenergy demand scenarios. The selected biomass types for this study are crop residues, firewood, animal manure, the organic fraction of municipal solid waste, and sewage sludge. To generate electricity from these resources, two distinct technologies were employed: direct combustion for solid biomass (crop residues and firewood) and biogas and landfill gas (LFG) production for wet biomass (animal manure, organic fraction of municipal solid waste, and sewage sludge). The results indicate that the total energy potential from solid biomass could reach 1200 petajoules by 2050, while the potential for biogas and LFG gas production from wet biomass could reach 11.61 billion cubic meters by the same year.

In this study, four distinct scenarios were developed using the LEAP modelling tool for the purpose of analysing electricity supply projections. The reference scenario was developed with consideration of the National Energy Plan of Türkiye, which encompasses the period from 2020 to 2035 and has been extended to 2050 for the purpose of analyzing electricity supply projections. The results of this scenario demonstrate that the proportion of renewable energy in electricity generation could reach 73%, due to the expansion of solar, wind, and nuclear energy capacity, and a reduction in total greenhouse gas emissions from electricity generation of approximately 48% relative to the base year (2020). Three bioenergy demand scenarios (low, moderate, and high) were developed as a parent scenario for use in the tool. Furthermore, the scenarios diverge in their projections of biomass utilization rates in electricity generation over the projection period. The results of the bioenergy demand scenarios indicate that the renewable energy share in total generation could reach 82% by 2050, with 17% of bioenergy contributing to the total generation in 2050. Additionally, the GHG reduction potential could reach 69% relative to the base year's value. The cost of electricity generation in scenarios involving bioenergy is higher due to the high capital costs associated with biomass power plants. In comparison to the reference scenario, the total cumulative cost could reach 783 million 2020 US$

higher over the projection period. Furthermore, the cost of one ton of GHG abatement under bioenergy demand scenarios was estimated to range between 11.1 and 11.5 US$.

The scope of this study is limited to the projection of biomass potential for electricity generation, with a focus on the most commonly utilized conversion technologies. It is possible that the potential will be higher with unpredictable biomass resources including food and drink industry wastes, domestic and imported wood chips, and wood pellets. Furthermore, as the efficiencies and costs of biomass power plants increase in the future, it is likely that more bioenergy will be included in the electricity mix of Türkiye. Nevertheless, the results of this study will provide crucial insights for policymakers, demonstrating the significant impact of sustainable bioenergy on the development of Türkiye's electricity supply mix and the achievement of long-term energy objectives. Furthermore, it will address the challenges associated with the utilization of biomass resources and encourage further investigation into additional biomass potential.

Keywords: Biomass Potential Projection; LEAP Modelling tool; Bioelectricity; Bioenergy Demand Scenarios; GHG Mitigation; Low-carbon Electricity Future

ÖZET

TÜRKİYE'NİN DÜŞÜK KARBONLU GELECEĞE GEÇİŞİNİ DESTEKLEMEK İÇİN ELEKTRİK ÜRETİMİNDE BİYOKÜTLE ENERJİ POTANSİYELİNİN MODELLENMESİ

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Biyoenerji, özellikle gelişmekte olan ülkelerde olmak üzere, dünya genelinde en çok kullanılan yenilenebilir enerji kaynağıdır. Bu ülkeler, ithal fosil yakıtlara olan bağımlılıklarını azaltarak enerji güvenliklerini artırmak için bu potansiyelden yararlanmaktadır. Bu enerjinin en yaygın kullanım alanı halen geleneksel pişirme ve ısıtma. Yine de, bu potansiyelin elektrik üretimi için kullanımı giderek artmaktadır.

Türkiye'de sürdürülebilir ve güvenli bir elektrik üretimine ulaşılmasında biyoenerjinin potansiyel rolü, ülkenin yüksek yenilenebilir enerji hedefleriyle uyumludur. Biyoenerjinin dağıtılabilirliği, özellikle depolama kapasitesinin sınırlı olduğu senaryolarda, güneş ve rüzgâr enerjisinin kesintili yapısını tamamlama konusunda özel bir öneme sahiptir. Biyoenerji potansiyelinin tahmin edilemez olduğu düşünülmekte ve devletler tarafından gelecekteki yenilenebilir enerji hedeflerinde biyoenerji kapasitesinin genişletilmesi konusunda netlik bulunmamaktadır. Türkiye, özel sektöre destek sağlayarak elektrik üretimi için biyoenerji kapasitesini artıran ülkeler arasındadır. Yine de ülke henüz bu enerji kaynağı için net kapasite genişletme hedefleri belirlememiştir.

Bu çalışma, bir dizi biyoenerji talep senaryosunu dikkate alarak, elektrik üretimi için tahmin edilebilir ve sürdürülebilir biyokütle kaynaklarının uzun vadeli potansiyelini değerlendirmektedir. Bu çalışma için seçilen biyokütle kaynakları tarımsal ürün artıkları, yakacak odun, hayvan gübresi, belediyesel katı atıkların organik kısmı ve atıksu arıtma çamurudur. Bu kaynaklardan elektrik üretmek için iki farklı teknoloji kullanılmıştır: katı biyokütle (ürün artıkları ve yakacak odun) için doğrudan yakma ve yaş biyokütle (hayvan gübresi, belediye katı atıklarının organik kısmı ve arıtma çamuru) için biyogaz ve çöp gazı üretimi. Sonuçlar, katı biyokütleden elde edilen toplam enerji potansiyelinin 2050 yılına kadar 1200 petajul'e ve yaş biyokütleden biyogaz ve LFG gazı üretim potansiyelinin ise aynı yıla kadar 11,61 milyar metreküpe ulaşabileceğini göstermektedir.

Bu çalışmada, elektrik arz projeksiyonlarını analiz etmek amacıyla LEAP modelleme aracı kullanılarak dört farklı senaryo geliştirilmiştir. Referans senaryo, 2020-2035 dönemini kapsayan Türkiye Ulusal Enerji Planını dikkate alarak geliştirilmiş ve elektrik arzı projeksiyonlarını analiz etmek amacıyla 2050 yılına kadar uzatılmıştır. Bu senaryonun sonuçları, elektrik üretiminde yenilenebilir enerji oranının güneş, rüzgar ve nükleer enerji kapasitesinin genişlemesi nedeniyle %73'e ulaşabileceğini ve projeksiyon döneminin sonunda elektrik üretiminden kaynaklanan toplam sera gazı emisyonlarının baz yıla (2020) göre yaklaşık %48 oranında azalabileceğini göstermektedir. Bu modelde kullanılmak üzere ana senaryo olarak üç biyoenerji talep senaryosu (düşük, orta ve yüksek) geliştirilmiştir. Ayrıca, senaryolar projeksiyon dönemi boyunca elektrik üretiminde biyokütle kullanım oranları açısından farklılaşmaktadır. Biyoenerji talep senaryolarının sonuçları, toplam üretimdeki yenilenebilir enerji payının 2050 yılına kadar %82'ye ulaşabileceğini ve biyoenerjinin 2050 yılında toplam üretime %17 oranında katkıda bulunacağını göstermektedir. Ayrıca, sera gazı azaltım potansiyeli baz yıl değerine göre %69'a ulaşabilir. Biyoenerji içeren senaryolarda elektrik üretim maliyeti, biyokütle enerji santralleriyle ilişkili yüksek sermaye maliyetleri nedeniyle daha yüksektir. Referans senaryo ile karşılaştırıldığında, toplam kümülatif maliyet projeksiyon dönemi boyunca 783 milyon 2020 ABD$

daha yüksek olabilir. Ayrıca, biyoenerji talep senaryoları kapsamında bir ton sera gazı azaltımının maliyetinin 11,1 ila 11,5 ABD$ arasında değişeceği tahmin edilmektedir.

Bu çalışmanın kapsamı, en yaygın olarak kullanılan dönüşüm teknolojilerine odaklanarak, elektrik üretimi için biyokütle potansiyelinin projeksiyonu ile sınırlıdır. Gıda ve içecek endüstrisi atıkları, yerel üretim ve ithal odun talaşı ve peleti gibi öngörülemeyen biyokütle kaynakları ile elektrik üretiminde biyokütle potansiyelin daha yüksek olması mümkündür. Ayrıca, gelecekte biyokütle enerji santrallerinin verimlilikleri ve maliyetleri arttıkça, Türkiye'nin elektrik enerjisi üretimine daha fazla biyoenerjinin dahil edilmesi muhtemel olacaktır. Bununla birlikte, bu çalışmanın sonuçları, sürdürülebilir biyoenerjinin Türkiye'nin elektrik arz dengesinin geliştirilmesi ve uzun vadeli enerji hedeflerine ulaşılması üzerindeki önemli etkisini göstererek politika yapıcılar için önemli bilgiler sağlayacaktır. Ayrıca, biyokütle kaynaklarının kullanımıyla ilgili zorlukları ele alacak ve ilave biyokütle potansiyelinin daha fazla araştırılmasını teşvik edecektir.

Anahtar Kelimeler: Biyokütle Potansiyeli Projeksiyonu; LEAP Modelleme Aracı; Biyoelektrik; Biyoenerji Talep Senaryoları; Sera Gazı Azaltımı; Gelecek içi Düşük Karbonlu Elektrik.

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Ali Erdinç ERSOY
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AD	Anaerobic digestion
ARIMA	Autoregressive integrated moving average
BAT	Best Available Techniques
BDSs	Bioenergy demand scenarios
BEPA	Türkiye’s Biomass Energy Potential Atlas
BioWATT	The Biogas Wastewater Assessment Technology Tool
BOD_5	Biochemical oxygen demand
CAS	Conventional activated sludge
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DS	Dry solids
EJ	Exajoule
EMRA	Türkiye’s Energy Market Regulatory Authority
EPA	The U.S. Environmental Protection Agency
EU	The European Union
EUAS	The Electricity Generation Corporation
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FOM	Fixed operation and maintenance
GDP	Gross domestic product
GEM-E3	General Equilibrium Model for Economy-Energy- Environment

GLOBIOM	Global Biosphere Management Model
GHG	Greenhouse Gas
GVA	Gross value added
GW	Gigawatt
HBDS	High Bioenergy Demand Scenario
IEA	International Energy Agency
IPPs	Independent Power Producers
kWh	Kilowatt-hour
LandGEM	The Landfill Gas Emissions Model
LBDS	Low Bioenergy Demand Scenario
LEAP	The Low Emissions Analysis Platform
LFG	Landfill gas
LFGTE	Landfill gas to electricity
LHV	Low Heating Value
MARKAL	MARKet ALlocation model
MBDS	Moderate Bioenergy Demand Scenario
MBT	Mechanical biological treatment
MENR	Ministry of Energy and Natural Resources of Türkiye
MJ	Megajoule
MSW	Municipal Solid Waste
Mt	Million ton
Mtoe	Million tons of oil equivalent
MW	Megawatt
N_2O	Nitrous oxide
NDCs	Nationally Determined Contributions
NIR	National GHG Inventory Report of Türkiye

NMOC	Non-methane Organic Compounds
OECD	The Organisation for Economic Co-operation and Development
OFMSW	Organic fraction of municipal solid waste
PJ	Petajoule
PRIMES	Price-Induced Market Equilibrium System
PST	Primary settling tank
PV	Photovoltaics
RES	Renewable Energy Support Scheme
RS	Reference scenario
SDGs	Sustainable Development Goals
TED	Technology and Environmental Database
TEIAS	The Turkish Electricity Transmission Corporation
the Plan	Türkiye's National Energy Plan
TIMES	The Integrated MARKAL-EFOM System
TSS	Total suspended solids
TURKSTAT	Turkish Statistical Institute
TWh	Terawatt-hours
UK	The United Kingdom
US$	The United States Dollar
VAROM	Variable operation and maintenance
VSS	Volatile suspended solids
WAS	Waste activated sludge
WWTPs	Wastewater treatment plants

1. INTRODUCTION

This chapter provides background information on the importance of renewable electricity, with a focus on bioenergy as a sustainable solution. It highlights the challenges of integrating renewable sources into the energy grid, but emphasizes the advantages of bioenergy, especially its versatility and potential for waste management. The chapter then defines the problem of accurately estimating a country's biomass potential and introduces the objective of this study: to analyze Türkiye's bioenergy potential from predictable biomass resources and assess its contribution to the electricity mix.

1.1. General Information

The role of electricity in economic growth and social welfare is of critical importance on a global scale. It is crucial to ensure the accessibility, reliability, and safety of electricity, while maintaining reasonable prices and minimizing environmental impact [1]. The importance of renewable electricity cannot be overstated. It offers significant benefits for the climate, health, and the environment by eliminating the emission of greenhouse gases (GHGs) during energy generation processes. This makes it the most effective and sustainable solution to prevent environmental degradation. Consequently, regulating GHG emissions can be a priority if the electricity sector is driven by renewable energy sources [2].

A growing number of countries have established carbon neutrality targets with the aim of addressing the environmental degradation caused by carbon emissions. Fossil fuels currently dominate the global energy system, contributing to a rapid increase in carbon emissions. Achieving carbon neutrality necessitates the implementation of various measures, including improvements in energy efficiency, the adoption of renewable energy sources, and investments in carbon offsets [3]. Long-term energy strategies are designed with the objective of reducing carbon emissions and enhancing energy system diversity through the utilization of renewable energy sources [4].

Bioenergy plays a crucial role in the transition to clean energy, especially for countries with low energy security. It helps reduce dependency on fossil fuels, thereby decreasing GHG emissions and enhancing energy security. Bioenergy also supports the development of local economies and provides clean energy to under-served populations, contributing to sustainable development [5].

Bioenergy represents a sustainable solution for climate change mitigation when derived from sustainable biomass growth or waste/residues that are efficiently converted into energy products. The clear advantages of bioenergy over traditional fossil fuels are due to its renewability and substantial capacity, which play a pivotal role in environmental protection. Sustainable bioenergy has the potential to facilitate the decarbonization of all energy sectors, thereby rapidly reducing dependence on fossil fuels and consequently reducing GHG emissions through substitution. The effective management and utilization of residues for energy purposes will be instrumental in achieving environmental sustainability and mitigating the adverse effects associated with conventional energy sources [6].

A number of countries have incorporated bioenergy into their Nationally Determined Contributions (NDCs) as part of their commitments to the Paris Agreement. Bioenergy presents opportunities for developing countries to implement sustainable and circular solutions for all energy uses, including electricity generation. The utilization of bioenergy in electricity generation can assist in reducing dependency on imported fossil fuels, provide clean alternatives to traditional forms of energy, and support the development of local economies [7]. The efficient use of biomass energy is a crucial element in the attainment of numerous Sustainable Development Goals (SDGs) [8], those associated with clean energy, zero hunger, industry, innovation, infrastructure, responsible production and consumption, and climate action. The efficient and sustainable use of biomass energy is a crucial element in addressing the environmental, social, and economic challenges outlined in the United Nations 2030 Agenda for Sustainable Development [9]. It is, however, of the great importance to ensure that the production and use of biomass are managed and governed in an appropriate manner in order to avoid potential sustainability challenges, such as those related to land use and resource competition.

The European Union's Renewable Energy Directive establishes criteria for ensuring the sustainable utilization of biomass for energy purposes. The Directive introduces supplementary requirements for various biomass resources. In the case of agricultural waste and residues, the Directive necessitates evidence of soil quality and carbon conservation. With regard to agricultural biomass, it requires proof that the material has not been sourced from highly biodiverse forests. In the context of forest biomass, bioenergy producers are obliged to demonstrate compliance with the relevant legislation that aims to prevent unsustainable harvesting practices and to account for emissions resulting from forest harvesting. Moreover, new biofuel facilities are required to achieve a minimum 65% reduction in direct GHG emissions relative to fossil fuel alternatives. Similarly, biomass-based heat and power facilities must achieve a minimum 70% reduction (80% by 2026). In the case of bioelectricity generated by large-scale plants (exceeding 50 MW), compliance requires the implementation of highly efficient cogeneration technology, the adoption of Best Available Techniques (BAT), the achievement of a minimum efficiency of 36% (for plants above 100 MW), or the incorporation of carbon capture and storage technology [10].

Türkiye has implemented a Renewable Energy Support Scheme (RES) to facilitate the integration of renewable energy sources into the country's electricity generation infrastructure. The RES is a financial support mechanism designed with the objective of reducing the cost of producing renewable energy and encouraging investment in the sector. The scheme provides financial support for wind and hydropower plants at a rate of 0.073 US$ per kilowatt-hour (kWh), for geothermal facilities at 0.105 US$/kWh, and for solar and biomass energy plants at 0.133 US$/kWh [11]. This scheme represents a significant component of Türkiye’s strategy to reduce its reliance on fossil fuels and to augment the proportion of renewable energy in the country’s overall electricity generation.

1.2. Problem Definition

It is of significant importance for countries to increase their energy security level by increasing the share of renewables in their electricity supply. The strategies and plans for renewable energy installations vary considerably from one country to another, and are largely contingent on a range of geographical, economic, and social factors. The expansion of solar and wind power is encouraged by many countries due to the advantages these sources offer over other renewable energy sources. This is attributed to the cost-effectiveness and reduced environmental impact of these sources. Additionally, these forms of energy are more scalable and can be seamlessly integrated into existing energy systems. According to the International Energy Agency (IEA), in 2028, renewable energy sources will account for over 42% of global electricity generation, with the share of wind and solar PV doubling to 25% [50]. The implementation of large-scale renewable energy plans must include strategies for integrating renewable sources into coherent energy systems that are influenced by energy savings and efficiency measures. The primary challenge is to integrate a significant proportion of intermittent sources into the energy system, particularly the electricity supply [51].

In contrast to solar and wind power, biomass energy is not intermittent and can be utilized in a variety of forms to meet diverse energy requirements. It can be employed as a substitute for natural gas or coal in power plants. Nevertheless, some countries have expressed reservations about the reliability, sustainability, and predictability of biomass energy in meeting long-term energy targets. Nevertheless, this energy resource has the potential to be a valuable asset if effective resource management is implemented, given its substantial potential and compatibility with existing technology. The use of biomass energy provides a sustainable solution for both energy generation and waste management, helping to reduce GHG emissions and promote energy sustainability. However, challenges related to harvesting, collection, and transportation, as well as sanitary control regulations, hinder its widespread use [52].

The production of biomass energy has the potential to compete with food production, which could result in food insecurity and higher food prices. However, strategies that focus on the utilization of agricultural residues and organic wastes for energy generation can contribute to mitigating this challenge. By implementing effective resource management and addressing related challenges, biomass energy can emerge as a valuable and sustainable component in the global energy mix. Consequently, this study focuses solely on the utilization of residues and wastes, without directly tackling issues of food insecurity within the country.

1.3. The Objective and Scope of the Study

Bioenergy sector of Türkiye has experienced significant improvement over the past decade, largely due to supportive policies implemented through the RES scheme. Capitalizing on its abundant and diverse biomass resources, the country has focused primarily on bioenergy for electricity generation. As mentioned earlier, the preferred conversion methods in Türkiye for electricity and heat generation include biogas production from wet biomass sources such as animal manure, sewage sludge, and organic fraction of municipal solid waste (OFMSW), and biomass combustion using dry biomass resources such as crop residues and forest residues. These methods offer versatility in the production of both electricity and heat.

Estimating a country's biomass potential for energy use is a complex undertaking that is often addressed at both the national and international levels. However, estimating long-term biomass potential, which is particularly important for planning a country's long-term energy goals, presents significant challenges. The inherent unpredictability of certain biomass sources, such as industrial wastes, hinders the ability to comprehensively capture all available biomass potential. However, for specific and predictable biomass resources, long-term estimates can be formulated using various assumptions. Therefore, the aim of this study is to conduct a detailed analysis of Türkiye's bioenergy potential derived from predictable biomass resources and to assess their potential contribution to the country's electricity mix. Through the identification of primary biomass resources and the application of robust statistical methods, this research endeavors to provide reliable estimates of this potential.

To achieve this objective, this study employed a comprehensive research methodology encompassing the following steps:

- **Literature Review:** A thorough analysis of relevant literature was conducted. This includes energy assessments of Türkiye, studies on energy supply and demand by government agencies and academic institutions, and exploration of existing research on bioenergy potential estimation.
- **Biomass Potential Estimation:** Tailored forecasting approaches and techniques was employed to estimate Türkiye's long-term biomass potential. These may include multiple regression, Autoregressive integrated moving average (ARIMA) models, and other trend analysis methods that account for the specific characteristics of various biomass resources.
- **Statistical Modelling of Growth:** Statistical techniques were utilized to project the growth of relevant sectors in Türkiye, including agriculture, livestock, and waste generation. This informed the development of biomass energy utilization scenarios at different ambitious levels.
- **Electricity Demand and Supply Projections:** Projections of electricity demand and supply in Türkiye was generated for a 30-year period (2020-2050). These projections considered macroeconomic, demographic, and other factors like population, GDP, and sector-specific variables.
- **LEAP Modelling and Scenario Development:** The Low Emissions Analysis Platform (LEAP) modelling tool was used to develop electricity demand and supply scenarios. This involved estimating sectoral electricity demand over the projection period and creating scenarios with varying levels of bioenergy prioritization in the electricity mix. A reference scenario (RS), aligned with Türkiye's official long-term electricity supply targets, was included for comparison.
- **GHG Mitigation Potential:** The GHG mitigation potential of different ambitious bioenergy demand scenarios (BDSs) were estimated relative to the RS. This analysis determined the maximum contribution these scenarios can make towards Türkiye's decarbonization targets in the energy sector.

- **Cost Analysis:** The total cost of electricity generation for each scenario was estimated and compared. Additionally, the GHG mitigation cost of BDSs relative to the RS was analysed.
- **Policy Implications:** The study findings can be used to inform policy decisions and guide the development and implementation of bioenergy technologies in Türkiye.

2. LITERATURE REVIEW

2.1. Bioenergy Sector in the World

Renewable energy capacity has been growing rapidly in recent years, with solar PV and wind accounting for the majority of new additions. In 2023, global renewable energy capacity reached a record high of 3,870 GW, an increase of 1,005 GW from 2020. This growth highlights the global pivot towards more sustainable energy resources. Solar energy is the fastest-growing renewable technology. In 2023, solar energy was the largest source of renewable energy capacity globally, reaching 1,419 GW. This represents a 519% increase from 2015. Bioenergy has grown more steadily than wind and solar. In 2015, 96.8 GW of bioenergy was installed. By 2020, this had grown to 133.2 GW, and by 2023, it had grown to 150.3 GW [12].

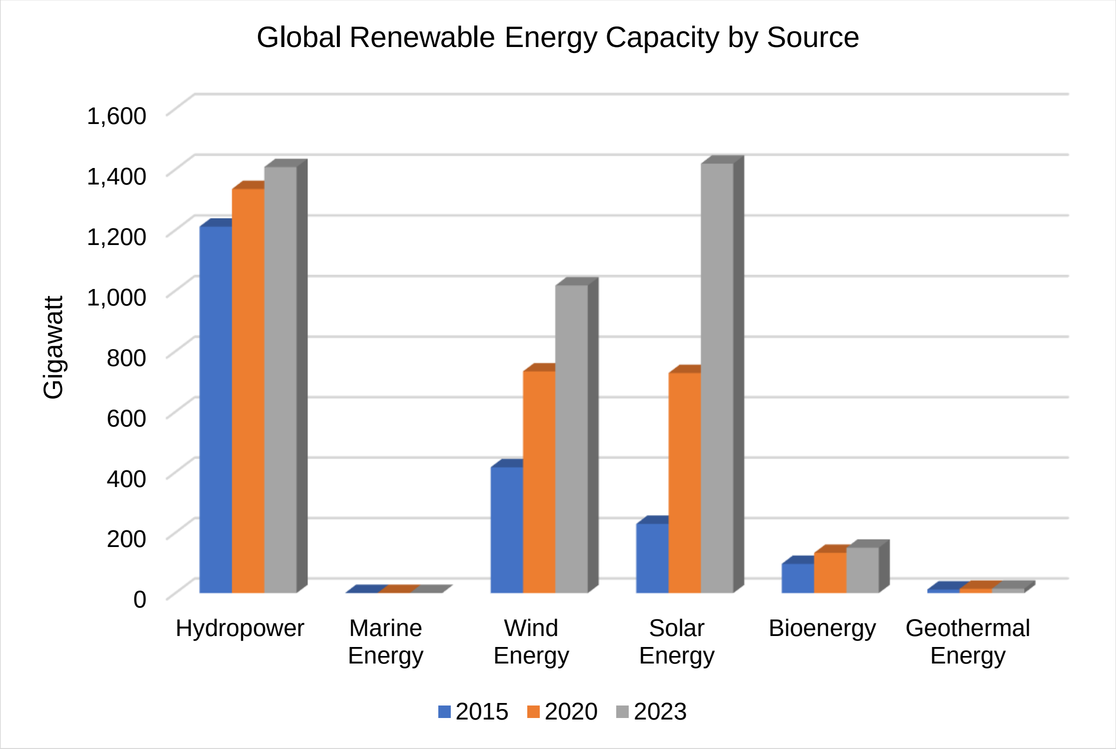


Figure 1. Global renewable energy capacity by source [12]

It is evident that bioenergy will play a pivotal role in the global energy transition. In addition to producing a diverse range of biofuels and industrial process heat that can meet the demands of sectors that are challenging to abate, bioenergy can also provide electricity on demand, which can be advantageous in periods of declining solar and wind resources. While some countries are already utilising a considerable amount of bioenergy, it is clear that others are not doing enough to facilitate the growth of the bioenergy industry [13].

Bioenergy represents the largest renewable energy source globally, accounting for approximately 12% of total final energy consumption. Bioenergy can be employed for the generation of electricity and for a variety of other applications, including heating, cooking, and transportation. Currently, over 85% of bioenergy is utilized for heating and cooking purposes (Figure 2). In 2020, bioenergy constituted approximately 20% of the total heat consumption, with modern bioenergy accounting for 8% and the traditional utilization of biomass representing 12% of that [14].

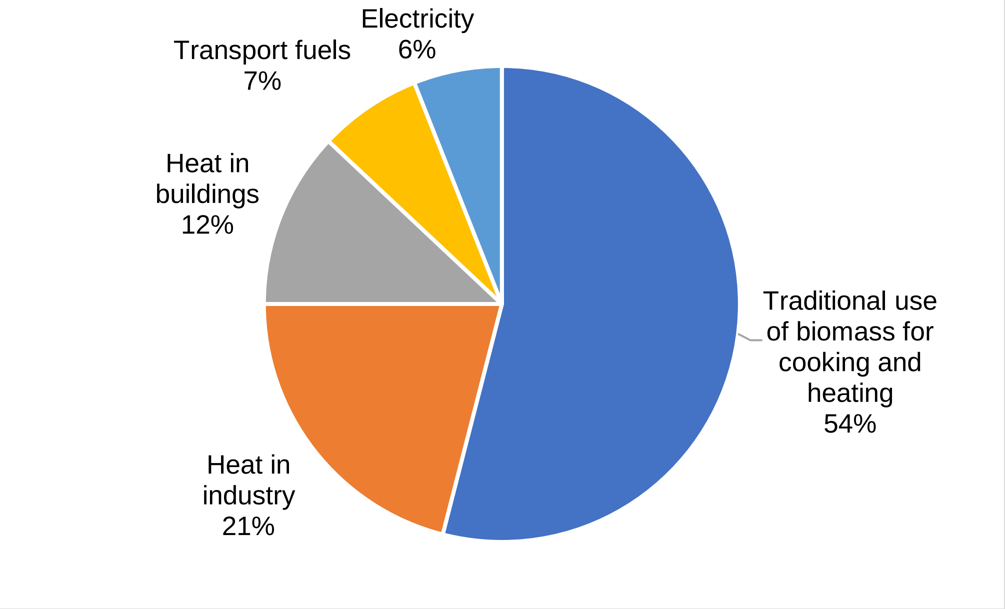


Figure 2. Share of global bioenergy consumption by end use, 2020 [14]

Bioenergy is being used more and more to produce electricity. It relies on using pellets, biogas, municipal solid waste, and agricultural and forestry residues, with wood pellets being the main biofuel used for electricity generation. In 2020, the world's bioenergy power capacity was 133.2 GW, with solid biofuels and renewable waste from combustion accounting for approximately 82.4% of this total. Biogas represented 15.2% of the total capacity. By 2023, the capacity had reached 150.3 GW, with the share of solid biofuels and renewable sources increasing to 83.9% of the total. The proportion of biogas in installed capacity declined to 14.2% [12].

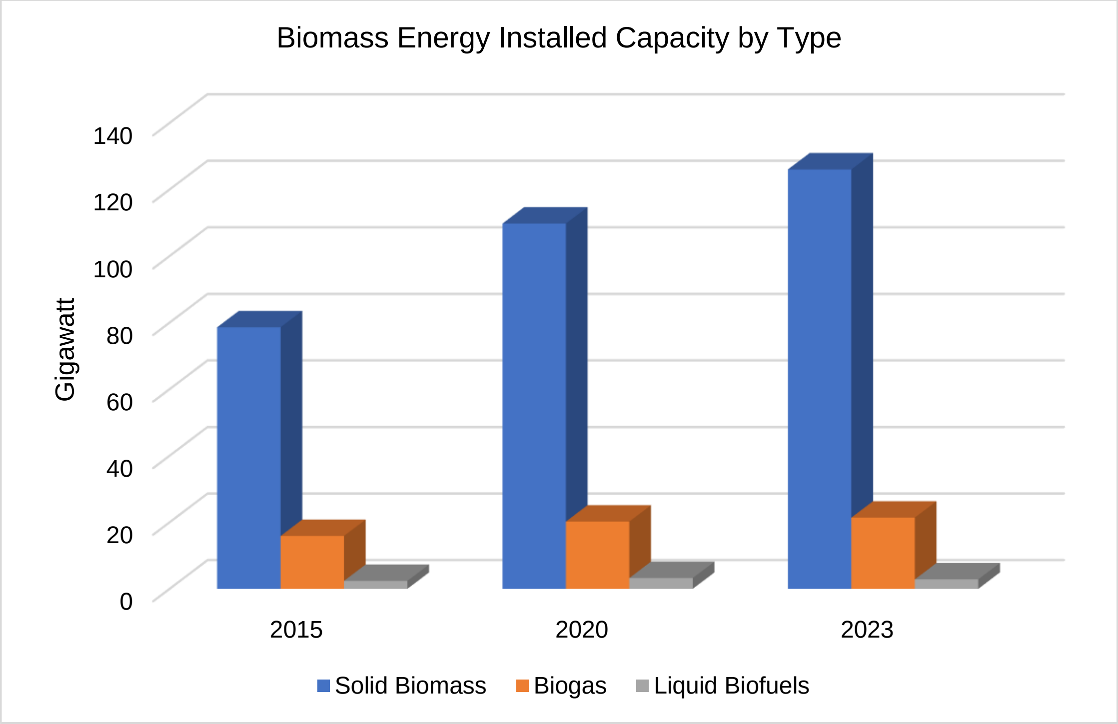


Figure 3. The installed capacity of bioenergy by type [12]

China is the global leader in total capacity, with the majority of its capacity (approximately 96%) reliant on the combustion of solid biofuels and renewable waste. Biogas can be utilized directly to provide heat or generate electricity. The generation of biogas constituted a smaller portion of the total capacity, with an installed capacity of 20 GW globally in 2020 and 21.4 GW in 2023. This represents a doubling of the capacity since 2010. The key players in biogas capacity were Brazil, China, the European Union (especially Germany), the United Kingdom, and the United States, accounting for over 86% of the total biogas capacity in 2020. Germany held the largest share at 37% of the global total with 7.5 GW, followed by the United States (11%), the United Kingdom (9%), Italy (7%), and China (4%). Two-thirds of the global biogas production was utilized for power generation, with half of that amount dedicated to electricity generation and the other half employed for combined heat and power (CHP) applications [14]. In the period between 2020 and 2023, Türkiye maintained its position as the 17th largest bioenergy producer globally, with a 6th place ranking in biogas capacity [12].

2.2. Overview of Türkiye’s Electricity Sector

The energy policy of Türkiye is formed by a number of key factors, with an emphasis on ensuring the security of energy supply, maintaining stable markets, promoting sustainability, and advancing technology. The country's objective is to enhance the security of its energy supply through diversification, with a particular emphasis on the utilization of domestic renewable energy sources, including biofuels and biomass, in order to reduce dependence on imported energy supplies and prevent an increase in GHG emissions.

Türkiye has set an objective of achieving net zero GHG emissions by 2053, which will entail a significant decarbonization of its energy sector. In order to achieve this objective, the 2030 energy strategy of Türkiye is centered on three key objectives: enhancing energy efficiency, increasing renewable energy capacity, and reducing GHG emissions. This strategy targets achieving a 16% cut in energy consumption and contributing to a 100 Mt reduction in emissions by 2030.

Türkiye has experienced the most rapid growth in energy demand among Organisation for Economic Co-operation and Development (OECD) countries over the past two decades, ranking second only to China in the world in terms of increased electricity and natural gas demand. The country is situated in a region that encompasses approximately 60% of the world's proven oil and natural gas reserves, positioning it as one of the most significant natural gas and electricity markets in the region. Nevertheless, Türkiye is reliant on imports to the tune of 74% in order to meet its energy demands. The adaptable structure of Türkiye's energy strategy and its reliance on imported energy sources have elevated international relations to a prominent position within this field. In order to enhance the security of its energy supply, the energy strategy of Türkiye is focused on the diversification of routes and resources. Furthermore, the country aspires to contribute to regional and global energy security, as well as to become a regional energy trading hub [15].

The fundamental elements that constitute the international dimension of Türkiye's energy strategy are as follows:

- To ensure the diversification of routes and resources in the supply of oil and natural gas, taking into account the increasing demand and import dependency,
- To contribute to the enhancement of energy security at the regional and global levels,
- To be a regional trading hub in energy,
- To consider the social and environmental impacts in the context of sustainable development at each stage of the energy chain,
- To enhance the proportion of domestic and renewable energy utilized in the generation of electricity,
- To integrate nuclear power into the energy mix [15].

The Eleventh Development Plan (2019-2023) [16] established ambitious targets, with the objective of reducing the natural gas share in electricity generation from 29.9% to 20.7%, increasing renewables from 32.5% to 38.8%, and raising locally sourced electricity from 150 Terawatt-hours (TWh) to 219.5 TWh. In addition to the aforementioned targets, Türkiye has made noteworthy advancements in the utilization of renewable energy sources, with a notable increase from 25% in 2000 to 42% in 2020. Furthermore, the Twelfth Development Plan (2024-2028) [17] of of Türkiye has the objective of further developing the country's energy sector and reducing its dependence on imports. The objective set forth in the plan is to achieve a 50% share of renewable energy in the generation of electricity by 2028. This objective will be accomplished by expanding the capacity of solar and wind energy sources.

In 2022, the Ministry of Energy and Natural Resources of Türkiye released the Türkiye's National Energy Plan (the Plan) [18], outlining the country's energy goals until 2035. The Plan envisions a scenario between 2020 and 2035, aiming to achieve the following targets by 2035:

- Electricity consumption: Reach 510.5 TWh.

- Share of electricity in final energy consumption: Increase to 24.9%.
- Total installed power capacity: Reach 189.7 GW.

Breakdown of installed power capacity:

- Solar energy: 52.9 GW
- Wind energy: 29.6 GW
- Nuclear energy: 7.2 GW
- Share of renewable energy sources in electricity generation: Increase to 54.7%.
- Share of renewable energy sources in installed power capacity: Increase to 64.7%.

Türkiye's demand for electricity increases annually due to a growing population and expanding industrialization. Consumption rose significantly from 128 TWh in 2000 to 306.7 TWh in 2020. The electricity sector holds the largest share of total energy demand in Türkiye. This share increased from 13.4% in 2000 to 19.7% in 2020, and remained unchanged in 2021 [19].

Looking at the overall picture of Türkiye's electricity sector in 2020, gross electricity generation reached 306.70 TWh. However, after accounting for transmission losses, internal consumption within the power sector, and oil refinery usage, the net production was determined to be 260.72 TWh. Net imports and exports had a minimal impact, totaling -0.59 TWh. Consequently, the net sectoral usage of electricity in Türkiye was 260.08 TWh. It's important to note that Independent Power Producers (IPPs) and the The Electricity Generation Corporation (EUAS) were responsible for the majority of electricity generation, contributing 91.6%. The remaining 8.4% came from autoproducers (Table 1).

Table 1. Türkiye's 2020 overall electricity supply and demand

Parameter	**2020 value**
Electricity Production in 2020 (Gross Demand), TWh	306.70
EUAS & IPP Generation, TWh	281.03 (91.6%)
Autoproducers, TWh	25.68 (8.4%)
Net imports / (exports), TWh	-0.59
Transmission Losses & Internal Consumption, TWh	-43.41
Oil refineries, TWh	-2.62
Net Electricity Demand, TWh	**260.08**

The industry sector accounts for 45.1% of total electricity demand in 2020. In 2000, its share was 48.6%. This decline can be explained by the increase in electricity consumption in the residential, commercial and service sectors in recent years. However, the industry sector has made a significant contribution to Türkiye's electricity demand. The specific demand of the transport and agriculture sectors grew in a manner comparable to the total demand growth between 2000 and 2020, maintaining the same share in the energy balance throughout this period. The breakdown of Türkiye's total electricity demand by sector over the past two decades is visualized in Figure 4. After 2020, the total electricity demand reached to 284.27 TWh in 2021 and the industry sector share was around 47% with a slight increase in 2020. The residential sector demand share decreases from 23.3% to 21.6% in one year.

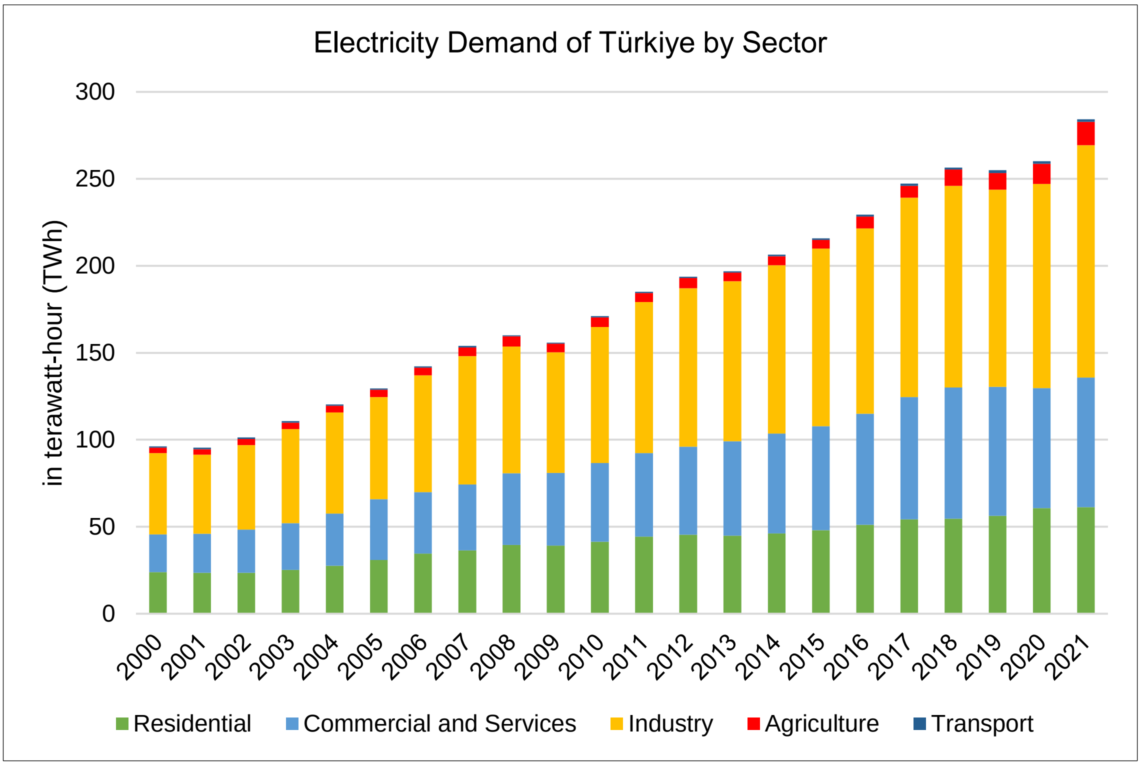


Figure 4. Electricity demand of Türkiye by sector[19]

In electricity supply side, the Turkish electricity sector has undergone significant growth and transformation in recent years. The country meets its electricity needs from a mix of energy sources including coal, natural gas, hydro, wind, solar, biomass, and geothermal.

The electricity generation in Türkiye depends mostly on natural gas and imported coal. The share of natural gas in electricity generation plants increased substantially in 2021, from 23.1% to 33.2% in comparison to 2020. When it is added imported coal that takes around 16.4% for the end of 2021, the import dependency is around 49.6%. The installed capacity increased from 95.9 GW to 99.8 GW in one year, due mainly to increase in renewable energies. Solar, wind and biomass has increased their capacity around 3.5 GW in one year.

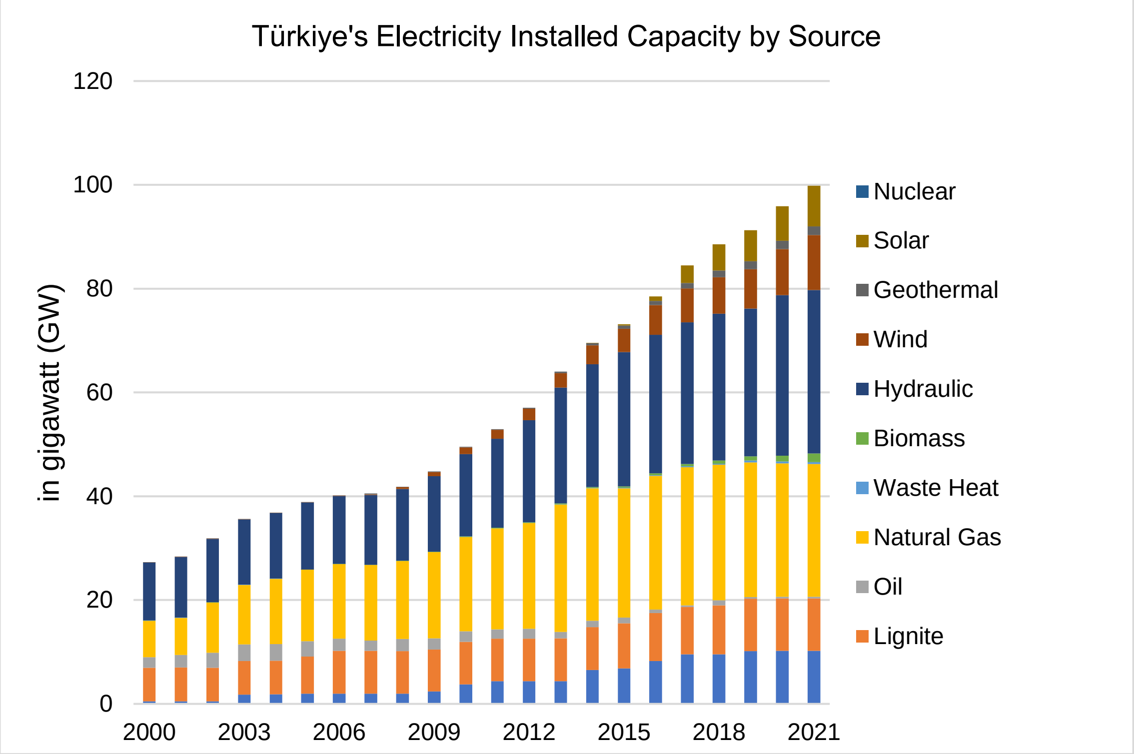


Figure 5. Electricity installed capacity of Türkiye by source [19]

In terms of resources, as of 2021, fossil fuels contributed 64.2% of the total electricity generation, while renewables 35.8%. Compared to 2019, the utilization rate from all sources except coal and hydraulic resources has increased in 2020 and 2021, including natural gas, geothermal, wind, liquid fuels, biofuels and waste heat, and solar.

Türkiye has made significant progress in increasing the use of renewable energy in its power sector over the past two decades. According to data from the Turkish Electricity Transmission Corporation (TEIAS), the share of renewables in electricity production increased from around 25% in 2000 to around 42% in 2020. In terms of installed capacity, the total capacity of renewables in Türkiye grew from 11.2 GW in 2000 to 49.2 GW in 2020. In 2020, hydropower was the dominant source of renewable energy in Türkiye, accounting for 61% of total power production from renewables. Wind energy was the second largest contributor, at 19%. These trends show that Türkiye has made significant progress in increasing the use of renewable energy and reducing its reliance on fossil fuels in the power sector. Table A. 1 and Table A. 2 in Appendix-1 provide a detailed breakdown of

Türkiye's electricity landscape over the past two decades. Table A.1 focuses on the installed capacity of power plants by fuel source, while Table A.2 dives into the electricity generation figures for each fuel source during this period.

Türkiye's domestic energy potential is considerable, with a variety of sources that can be harnessed for electricity production. According to estimates by EUAS[20], Türkiye has vast reserves of lignite and asphaltite, which can be used to generate electricity. In addition, the country has significant potential for hydroelectric power, with an estimated economic potential of 160 TWh/year. Türkiye also has significant potential for renewable energy sources, including wind power, geothermal energy, biomass and biogas, and solar power.

While there are certainly challenges to be faced in the Turkish electricity sector, such as meeting increasing demand and ensuring a reliable and sustainable supply, these energy sources offer opportunities for growth and development in the years to come. With the right investments and policies, Türkiye can harness its domestic energy potential to increase energy security, reduce dependence on imports, and promote sustainable economic growth.

Table 2. Türkiye’s domestic energy source potential [20]

Energy Source	Potential 2021	Revised Potential 2023
Lignite*	19.3 billion tons	20.2 billion tons
Hard Coal**	1.51 billion tons	1.51 billion tons
Asphaltite	82 million tons	82 million tons
Crude Oil***	411.2 million barrels	507.3 million barrels
Bituminous Coal	1.64 billion tons	1.64 billion tons
Hydro	160 TWh/year (economic potential)	160 TWh/year (economic potential)
Natural Gas	3.1 billion cubic meters	543.4 billion cubic meters
Wind Power	48,000 MW	47849 MW
Geothermal	4.99 billion tons of oil equivalent (2000 MW)	40000 MWt (4500 MWe)
Biomass and Biogas	10.6 million tons of oil equivalent	3.89 Mtep
Solar Power	1,527 kWh/m2/year	1,527 kWh/m2/year
Uranium	25,604 tons	25,604 tons
* Belong to 2019 ** As of end of 2021 *** Producible		

Coal, including hard coal, asphaltite, and lignite, has played a significant role in Türkiye's electricity generation. In 2020, coal contributed 34.5% of the country's total electricity demand, with hard coal and asphaltite contributing 22.1% and lignite contributing 12.4%, respectively. While the use of hard coal has decreased slightly in recent years, its installed capacity has continued to increase steadily since 2000, reaching 10.24 GW in 2021. Lignite, on the other hand, is a domestic energy resource, with significant reserves in Western and Central Anatolia regions. In 2020, the lignite-fired installed capacity was 10.12 GW, which corresponds to 10.55% of the total installed capacity. Despite being important energy resources, the use of coal, especially hard coal and lignite, is associated with various environmental and health concerns. The government has taken measures to mitigate their negative impacts, such as implementing emission control technologies and promoting the use of renewable energy sources. In line with Türkiye's goal of increasing the share of renewable energy sources and reducing greenhouse gas emissions, the share of lignite in electricity generation is expected to decrease in the upcoming years. However, several modernization projects are underway to increase the efficiency and capacity of existing lignite power plants. Coal is expected to continue playing a role in Türkiye's energy mix, but the government is striving to minimize its negative impacts and shift towards a cleaner and more sustainable energy system [19].

Likewise coal, natural gas plays a crucial role in electricity generation in Türkiye. In 2020, natural gas-fired power plants contributed 23.1% to the country's total electricity generation, which increased to 33.2% in 2021. This significant increase in the share of natural gas can be attributed to its lower emissions and higher efficiency compared to coal-fired plants. Despite the increase in its share in electricity production, the installed capacity of natural gas power plants slightly decreased from 25.67 GW in 2020 to 25.58 GW in 2021 [19].

Liquid fuels used in electricity generation in Türkiye include fuel oil, diesel oil, LPG (Liquified Petroleum Gas), and naphtha. However, the use of LPG and naphtha in electricity generation ended in 2009 and 2010, respectively. Currently, the contribution of diesel oil is much lower than that of fuel oil, which accounts for around 0.2% of total liquid fuels used in electricity generation as of 2021. The use of oil in electricity generation has been decreasing annually. In 2000, oil's share in total capacity was 7.5%. By 2020, this share had dropped to 0.1% with a capacity of 0.31 GW. As of 2021, the capacity of oil power plants was 0.26 GW [19].

Türkiye has made significant strides in increasing its renewable energy capacity. The country's largest source of renewable energy is hydropower, followed by wind power and solar power. The installed renewable capacity increased from 11.2 GW in 2000 to 49.2 GW in 2020, and reached 53.2 GW in 2021 with hydropower comprising the majority at 61%, followed by wind power at 19% [21].

The expansion of wind and solar power has been mainly driven by the decreasing cost of these technologies. While there have been positive developments in geothermal and bioenergy, their growth has been relatively slower than wind and solar. Nevertheless, these technologies still offer significant potential for expanding Türkiye's renewable energy capacity and reducing its dependence on fossil fuels.

Hydropower is one of the oldest and most commonly used renewable energy sources in Türkiye's electricity generation mix. The country has significant water resources, which makes it an ideal location for hydropower production. In recent years, hydropower has become an increasingly important contributor to country' electricity supply. In 2020, 25.5% of total electricity was met by hydropower plants. The government has also set ambitious targets to expand its hydropower capacity in the coming years, making it a key focus area for renewable energy development in the country. The total installed capacity was 30.98 GW in 2020 and increased to 31.49 in 2021[19].

Wind power has been growing in importance in Türkiye's electricity generation mix in recent years. According to the latest official data, wind power's share in electricity generation was 8.1% in 2020, up from 1.4% in 2010. As of 2021, the installed capacity of wind power plants in Türkiye is 10.6 GW, making up around 11% of the country's total installed capacity.

Türkiye has significant potential to expand its solar power capacity in the electricity sector. Solar power generation in Türkiye commenced in 2014 with an initial capacity of 40 MW. By 2020, this capacity had surged to 6.67 GW, and by the close of 2021, Türkiye's installed solar capacity stood at approximately 7.8 GW[19]. The country's official targets indicate a rapid expansion of photovoltaics (PV) capacity, positioning solar energy as a primary driver in decarbonizing the energy sector and reducing emissions[18].

Türkiye is located in an area with high geothermal potential due to its location on the active fault lines of the Mediterranean and the Aegean regions. The country has been utilizing geothermal resources since the 1960s, with the first geothermal power plant commissioned in 1974. Currently, Türkiye is ranked fourth in the world in terms of installed geothermal capacity, after the United States, the Philippines, and Indonesia [22]. According to EUAS, the estimated feasible geothermal capacity is calculated at 4.5 GW [20]. By 2020, Türkiye had achieved an installed geothermal capacity of around 1.6 GW, a remarkable progression from 94 MW in 2010 [19]. Geothermal energy is poised to play a pivotal role in Türkiye's decarbonization objectives leading up to 2053.

Waste heat recovery is an important issue in Türkiye's energy sector. In electricity generation, waste heat recovery systems can be used to increase the efficiency of power plants by capturing and reusing waste heat that would otherwise be lost. This can lead to significant energy savings and reduced greenhouse gas emissions. Türkiye offers a variety of waste heat recovery technologies applicable to various power plants, including steam turbines, gas turbines, and internal combustion engines. The government incentivizes the use of these systems through a feed-in tariff for electricity generated from waste heat. A report [23] on the Assessment of Waste Heat Potential in Türkiye identified the industrial sector, particularly iron and steel, cement, and textiles, as having the highest waste heat potential. The energy sector, specifically hard coal thermal power plants, natural gas combined cycle plants, and lignite plants, also holds significant potential. The report estimated that with proper utilization, this waste heat could generate 2,700 GWh/year of electricity. However, as of 2020 only 1,276 GWh of waste heat was actually utilized, which is around 47% of the total potential [19].

The bioenergy sector in Türkiye has experienced a notable expansion, with an increase in installed capacity from 86 MW in 2010 to 1,105 MW in 2020, 1,643 MW in 2021, and 1,920 MW in 2022 [21]. This signifies Türkiye's substantial progress in capitalizing on biomass as a renewable energy source. This significant rise highlights Türkiye's success in harnessing biomass as a renewable energy resource. The country's commitment is further evidenced by the substantial capacity increase between 2020 and 2022. In just two years, the total biomass energy capacity jumped from 1.1 GW to 1.9 GW, representing an impressive 73.8% growth (Figure 6).

However, Türkiye still has untapped bioenergy potential that could be utilized to further increase its renewable energy capacity. This expansion in bioenergy installed capacity reflects Türkiye's recognition of the potential benefits of bioenergy, including reduced GHG emissions, improved energy security, and increased rural development. Furthermore, the growth of bioenergy in Türkiye could also provide an important source of sustainable, locally sourced fuel for the country's growing energy needs.

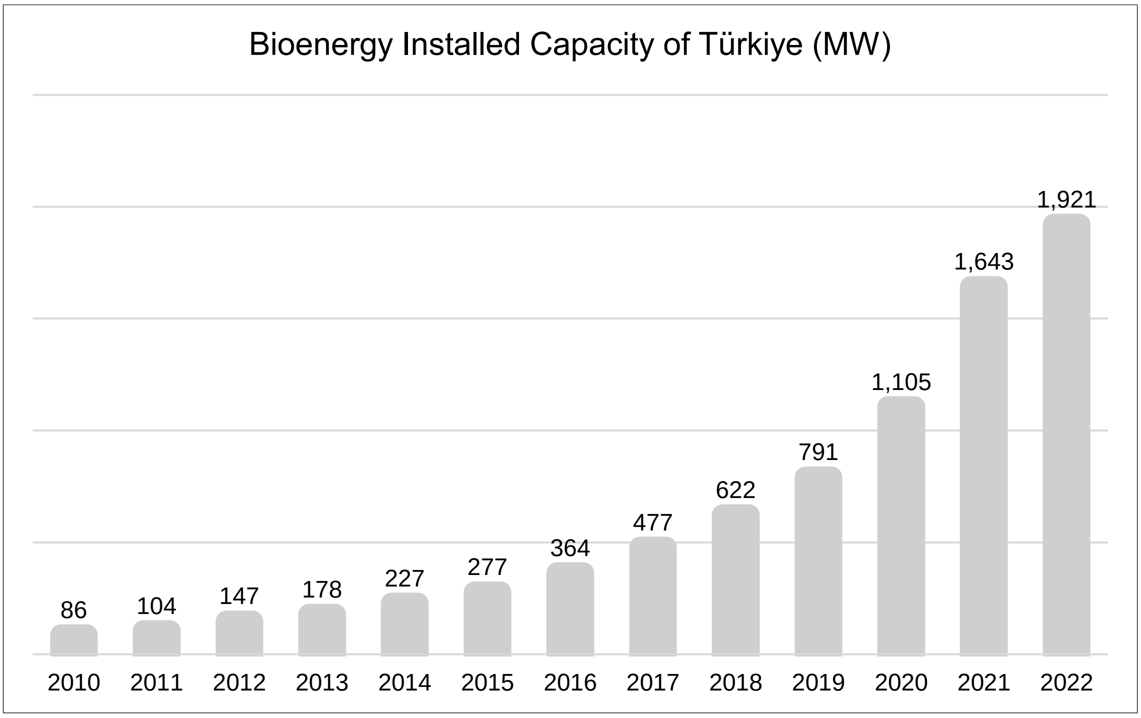


Figure 6. Türkiye’s bioenergy installed capacity between 2010-2022 [21]

In Türkiye various bioenergy technologies are employed, considering factors such as biomass type, environmental conditions, and cost. According to the Türkiye’s Energy Market Regulatory Authority’s (EMRA) 2022 RES list [24], the predominant contributors to electricity generation in the bioenergy sector are biogas and landfill gas CHP systems utilizing MSW, animal manure and sewage sludge, constituting approximately 54.5%, and direct combustion CHP systems primarily utilizing agriculture (crop) and wood industry residues, accounting for about 41.1%. Gasification and pyrolysis technologies make minor contributions, totaling 1.1% and 3.3%, respectively (Figure 6). With a total installed capacity of 1,273 MW in 2021, the remaining 1,643 MW can be attributed to unlicensed capacity. Furthermore, biomass distribution reveals that animal manure, crop residues, and forestry residues are the most utilized types in Turkish biomass plants. Plants exclusively employing animal manure typically focus on biogas production, while MSW is utilized for landfill gas (LFG), anaerobic digestion (AD), and direct combustion purposes (Table 3).

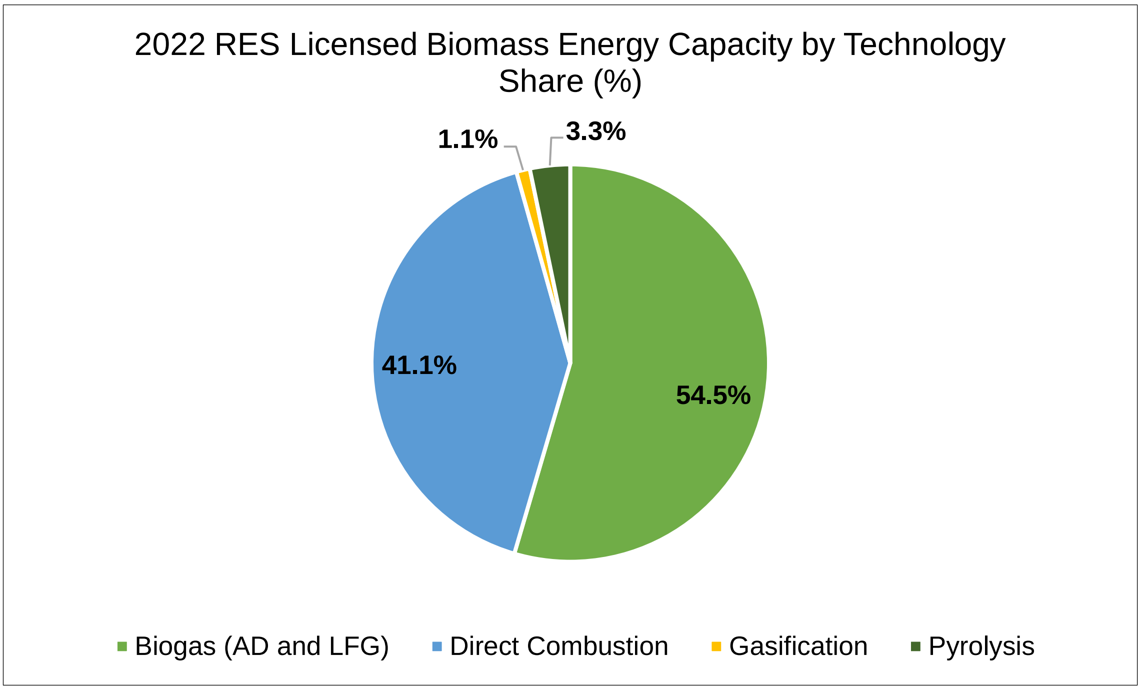


Figure 7. Türkiye's 2022 bioenergy capacity share by technology [24]

Table 3. Türkiye’s 2021 licensed bioenergy capacity by feedstock type [24]

Biomass Feedstock Groups	**Capacity (MW)**
Animal waste	150.8
Animal waste and Crop residues	146.9
Animal waste, Crop residues, Forestry waste	16.7
Animal waste and MSW	1.2
Crop residues and Energy Crops	39.2
Crop residues and Forestry waste	169.1
Forestry waste	148.6
Forestry waste and sewage sludge	8.0
Sewage sludge	16.6
MSW	527.7
Waste Tyres	38.8
Mixed wastes	9.4
Total	**1273.0**

2.3. Sustainable Biomass Resources and Biomass Conversion Technologies

Biomass, as a renewable resource, refers to organic material derived from plants and animals that can be used to produce energy. It is a versatile energy source that can be converted into transportation fuels, heat, electricity, and various products. Biomass is considered renewable because it can regrow relatively quickly, making it sustainable for long-term use. This resource captures solar energy through photosynthesis and can be utilized in various forms such as wood, crop waste, or organic municipal waste.

Three main categories exist for classifying biomass based on its origin and composition. The first is natural biomass, which encompasses organic materials like algae, wood and plant matter that occur naturally in the environment. Residual biomass, the second category, is comprised of organic waste generated by human activities. This waste can come from agriculture, industry, or urban centers and can be further classified as wet or dry depending on its moisture content. The final category, energy crops, consists of specific crops cultivated solely for the purpose of bioenergy production. These crops are planted to maximize biomass yield for energy use [25].

Bioenergy plays a significant role in reducing carbon emissions and promoting environmental sustainability by providing an alternative to fossil fuels. It is a valuable resource that contributes to a more secure, sustainable, and economically sound future by supplying clean energy sources, reducing dependence on foreign oil, generating jobs, and revitalizing rural economies.

Bioenergy sustainability presents a complex challenge. While bioenergy offers a clear alternative to fossil fuels and has the potential to reduce GHG emissions in various sectors such as electricity generation, heating, transport and industry, its environmental and socio-economic benefits depend on responsible management (Figure 8). Uncontrolled bioenergy supply chains and use can have unintended consequences beyond the energy sector, affecting critical areas such as agriculture, forestry, rural development, and waste management due to their inherent linkages.

A significant concern lies in the potential for land-use change driven by increased bioenergy demand. This may lead to the conversion of land currently used for food production or ecological services into areas dedicated to bioenergy crops. Such a scenario could pose threats to food security and biodiversity.

However, bioenergy is not without its benefits. By-products from bioenergy production can be utilized to improve soil quality. In addition, bioenergy plantations can be designed for phytoremediation purposes to help clean water. Furthermore, the integration of agroforestry practices alongside bioenergy production provides an opportunity to enhance biodiversity. The potential for increased carbon sequestration through improved land management practices associated with bioenergy production is also substantial [14].

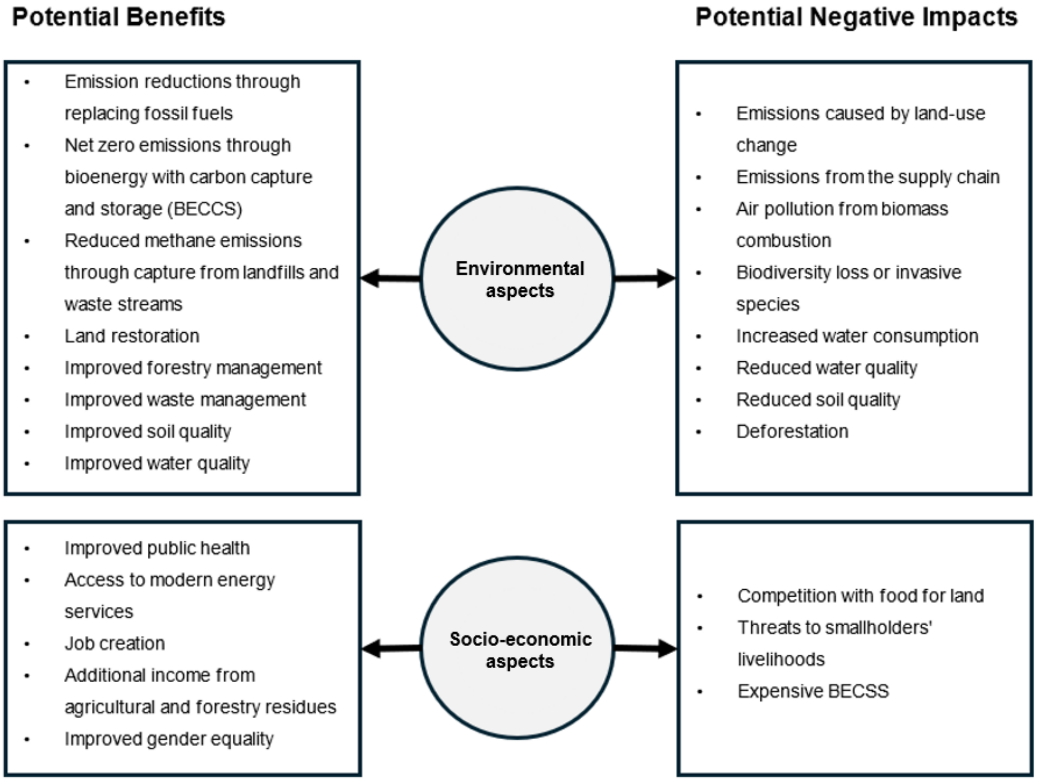


Figure 8. Potential aspects related to bioenergy sustainability [14]

Biomass conversion technologies refer to the processes that convert biomass into energy or other valuable products. These technologies can be broadly categorized into thermochemical, and biochemical conversion processes [25].

Thermochemical technologies are central to the field of biomass power generation. The main thermochemical conversion processes used for this purpose are combustion, gasification, pyrolysis and liquefaction. Combustion involves the burning of biomass to produce heat, which is then used to generate electricity. This process is the most widely used for biomass energy production, accounting for over 97% of global bioenergy production. Gasification is a process that converts biomass into a combustible gas mixture known as syngas, which consists of carbon monoxide, hydrogen, and carbon dioxide. This syngas can then be used to generate electricity either through direct combustion or through chemical processes. The introduction of biomass gasification has been instrumental in increasing the efficiency and reducing the capital costs associated with biomass power generation, particularly through the integration of gas turbine technology. Pyrolysis is a process in which biomass is thermally decomposed in the absence of oxygen, resulting in the production of bio-oil, syngas and char. Both bio-oil and syngas can be used to generate electricity. An important aspect of this process is the use of fast pyrolysis, which processes biomass to produce a product that serves as both an energy source and a feedstock for chemical production. Liquefaction can be direct or indirect; direct liquefaction includes methods such as hydrothermal liquefaction and fast pyrolysis to produce liquid tars, oils, and/or condensable organic vapors. Indirect liquefaction involves the use of catalysts to convert non-condensable, gaseous by-products of pyrolysis or gasification into liquid forms [26]. A variety of biomass feedstocks are integral to thermochemical power generation technologies. Agricultural residues such as rice straw, wheat straw, corn stover, sugar cane bagasse, and rice hulls are commonly used. Forestry residues such as wood chips, sawmill waste, bark and black liquor also play an important role. Energy crops such as miscanthus, switchgrass, willow, poplar, and eucalyptus are grown specifically for energy production. Another source is MSW, which includes food waste, yard trimmings, paper, cardboard, plastics, and textiles. In addition, industrial by-products such as food industry waste, pulp and paper mill sludge, and wastewater treatment plant solids are used. Algae and macrophytes, such as microalgae, algae and aquatic plants, are also used for their energy potential [27].

Biochemical power generation technologies primarily use microorganisms or enzymes to convert biomass into energy or valuable products. AD is a process in which microorganisms break down organic matter in an oxygen-free environment to produce biogas for power generation. Fermentation uses microorganisms or enzymes to convert sugars into ethanol or other biofuels for power generation. Enzymatic hydrolysis uses enzymes to break down complex carbohydrates in biomass into sugars, which are then fermented into biofuels or used to generate electricity. Microbial fuel cells convert organic matter directly to electricity through electrogenesis. These technologies offer high conversion efficiencies, low emissions, and the flexibility to use a variety of biomass feedstocks, but they also face challenges such as high costs and the need for specialized equipment and expertise [28].

Biochemical conversion processes can utilize both wet and dry biomass feedstocks for electricity generation. Wet biomass feedstocks are particularly suitable for biochemical conversion processes such as AD and fermentation. These processes can convert wet biomass feedstocks into biogas, which can be used to generate electricity or upgraded to biomethane for injection into natural gas pipelines. AD is a common biochemical conversion process that can utilize wet biomass feedstocks to produce biogas. The process is particularly suitable for wet biomass feedstocks, such as food waste, animal manure, and wastewater treatment plant sludge, which have high moisture content and are difficult to handle and transport [29].

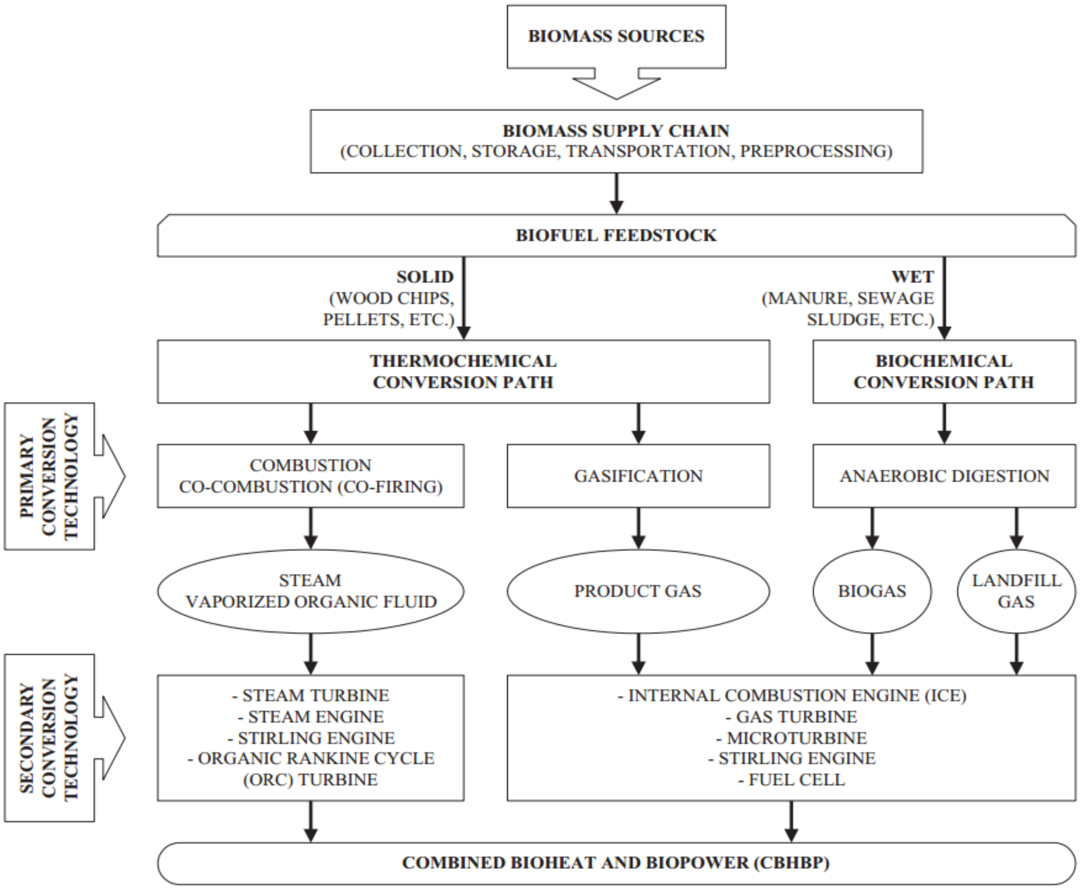


Figure 9. The major conversion pathways for bioelectricity generation [30]

2.4. Biomass and Bioenergy Potential Assessments: A Global and Turkish Review

The introduction of biomass energy has been a central topic of investigation in numerous studies within the existing body of literature. A significant number of these studies are devoted to assessing the long-term potential of biomass energy.

For example, M.R. Errera et al. [31] conducted a study for projecting the global potential of bioenergy supply for 2050. Their research considered critical factors such as land availability, global demands, yield improvements, and waste recovery. They explored three scenarios: business as usual, optimistic trends, and full adaptation response. Notably, the full adaptation response scenario showed the potential to significantly increase bioenergy supply, potentially meeting the global primary energy demand by 2050, with a primary reliance on energy crops. The study suggests that bioenergy could contribute between 64 and 313 Exajoule (EJ) to the global energy matrix in 2050, marking a substantial shift from firewood to energy crops and biowastes in the supply composition.

Lauri, P., et al [32] employed the Global Biosphere Management Model (GLOBIOM) to project the potential for woody biomass energy up to the year 2050. Their findings indicate that woody biomass could account for up to 18% of the world's primary energy consumption by that time.

A study was conducted by Ruiz et al. [33] with the objective of developing a long-term forecast of the biomass potential of the EU28 countries by 2050. In this study, a range of biomass resources were considered in terms of their energy potential, including not only domestic biomass resources in each EU28 country but also imported biomass from other countries. A variety of sector-specific models were employed for the analysis. The results indicate that in the low scenario, the bioenergy potential could reach 9 EJ/year by 2050, while in the high scenario, this potential could reach 25 EJ/year.

Jablonski, S. et al. [34] explored the potential for bioenergy to contribute to a sustainable the United Kingdom (UK) energy system. The study evaluated the prospects and policy implications of bioenergy for heat, electricity, and transport services. The different scenarios were developed in which heat generation represents more than 50% of the bioenergy use in the long-term. The share of bioelectricity in all developed scenarios is limited and biogas is the main bioenergy source for the production of electricity in all developed scenarios.

In their studies, Allen and Hammond [35] emphasized that bioenergy has the potential to play a significant role in the UK's low-carbon future, provided that sustainable biomass resources are available and supportive policies and technologies were developed. They projected that by 2050, bioenergy's contribution to UK primary energy supply could reach up to 1062 TWh and this corresponds to the 5% of total electricity generation.

Panos and Kannan [36] explored in their studies the role of biomass energy in electricity and heat in long-term for Switzerland by using the The Integrated MARKAL-EFOM System (TIMES) tool. The analysis showed that domestic biomass could contribute 5-7% of electricity and 14-21% of heat production by 2050, depending on natural gas prices and climate policy. Bioelectricity scenario results showed that up to 8.7% (6.2 TWh) of total generation could be met with bioelectricity in 2050. Bioenergy technologies, such as biogenic CHP plants, complement other assets in the electricity, heat, and ancillary services markets, providing about 22-44% of the total secondary control power in 2050. Biogas and biomethane offer a cost-effective and efficient use of biomass for stationary applications. However, the penetration of biomass in the energy system depends on factors such as energy policies, biomass resources, and technology costs.

The study carried out by Li, M. et al. [37] discussed the potential for biomass usage in the Australian electricity grid as a transition pathway towards renewable energy, utilizing the CleanGrid model to simulate electricity dispatch. Findings showed that as carbon prices increase, bioelectricity becomes a most cost-effective and flexible option, with its generation share reaching around 9-12% in higher carbon price scenarios. Biomass power plants can provide flexible power generation for grid stability and load balancing.

Meryem, S.S., et al. [38] used the LEAP modelling tool to track the production and consumption of non-woody waste biomass and predict its future demand and availability as renewable energy in Pakistan. The results showed that the activity level of biomass would increase with alternative scenarios for both animal and crop waste. The share for biogas production also showed an increasing trend. The article emphasized the importance of utilizing indigenous biomass potential to address the country's energy needs and suggests that investment in research, infrastructure, and policies can improve the socio-economic status of Pakistan.

Ru Fang, Y., et al. [39] investigated the potential for region-specific bioenergy production and its capacity for CO_2 reduction through the utilization of crop straw (wheat, rice, and corn straw) by 2030, comparing it to the utilization of these resources in 2018. The results demonstrated that by 2030, approximately 75.1 million tons of coal equivalent (Mtce) for electricity, 151.5 Mtce for bioethanol, 182.1 Mtce for biomethane, and 329.1 Mtce for briquette fuel could be utilized, resulting in a total CO_2 reduction of 563 Mt.

By employing the LEAP modeling tool, Rehan, M., et al. [40] projected the bioelectricity capacity of Pakistan by 2050, considering diverse biomass types and bioelectricity generation technologies. The researchers' findings indicate that the bioelectricity share in total electricity generation could reach 265 TWh by 2050.

Table 4 provides a summary of selected bioenergy potential estimation studies conducted in various regions and countries.

Table 4. Bioenergy potential estimation studies from various countries

Region/ Country	Biomass Type	Bioenergy Potential	The Modelling tool Used	Projection Period	Reference
World	Energy Crops and biowaste	64-313 EJ	LEAP	By 2050	[31]
World	Woody Biomass	358 EJ/year	GLOBIOM	2000-2050	[32]
European Union (EU28)	Crop residues, animal manure, energy crops, roundwood and municipal solid waste, imported pellet, imported bioethanol and imported EMHV	9–25 EJ/year	CAPRI, EFISCEN	By 2050	[33]
United Kingdom	Dry biomass (crop and residues, woody biomass), Wet biomass (OFMSW, food and drink industry wastes, sewage sludge) Imported dry biomass (pellets and chips), imported bio-oil, bio-ethanol, bio-diesel	More than 1600 PJ	MARKAL	2000-2050	[34]
United Kingdom	Energy crops, crop residues, woody biomass, organic municipal waste, waste fats and oils	1062 TWh/year	DECC 2050 Calculator	By 2050	[35]
Switzerland	Domestic biomass resources (woody biomass, food waste, green waste, industrial bio-waste, sewage sludge, animal manure)	6.2 TWh/year for electricity generation	TIMES	By 2050	[36]
Australia	Crop straw, woody biomass and bagasse	4.9 GW	CleanGrid	2018	[37]
China	Crop straw	75.1 Mtce for electricity generation	-	2018-2030	[39]
Pakistan	Agriculture residue, animal manure, municipal waste and forest residue	265 TWh/year for electricity generation	LEAP	2022-2050	[40]

In Türkiye, a number of studies have been conducted with the objective of estimating the potential for biomass and bioenergy production. However, the majority of these studies were conducted without considering the potential for future growth in biomass production.

The Ministry of Energy and Natural Resources of Türkiye (MENR) has established a platform, titled Türkiye’s Biomass Energy Potential Atlas (BEPA) [41], which provides data on the potential biomass energy sources in different regions of the country. The platform's objective is to facilitate the promotion of biomass energy utilization for sustainable development. The platform includes interactive maps, data on the types and amounts of biomass resources, and information on existing and potential biomass energy facilities. It is a valuable tool for researchers, investors, and policymakers interested in the development of biomass energy in Türkiye. According to data from the BEPA platform, Türkiye's theoretical biomass energy potential was estimated 33.54 million tons of oil equivalent (Mtoe). This capacity is distributed among different types of biomass, with animal/crop biomass accounting for 29.77 Mtoe, forest biomass for 0.86 Mtoe, and municipal wastes for 2.91 Mtoe.

In the study, conducted by Toklu, E. [42], the theoretical and feasible biomass potential of Türkiye from a variety of sources, including wood, animal, and plant waste, was estimated at 33 Mtoe and 17 Mtoe, respectively. These estimates were based on data from the 2008 production period. Ozturk and Bascetincelik [43] focused on the agricultural sector and determined the biomass potential and its energy potential for the period 2002-2003. Their results showed a total agricultural biomass potential of 363.1 Petajoule (PJ). Ozcan, M. et al. [44] examined the electricity potential from various biomass sources such as municipal solid waste, energy crops, animal manure, and wastewater treatment sludge, utilizing 2011 production data. Their research suggests a total electricity potential of 188.21 TWh/year from biogas and 278.40 TWh/year from all biomass sources combined. Ozturk, M. et al. [45] estimated biomass production of Türkiye is expected to reach a level of 52.5 Mtoe by 2030. In their study, Ersoy and Ugurlu [46] estimated the potential for biogas production from animal manure in the year 2015. The researchers determined that the theoretical potential of biogas was

8.41 billion m³, which represented 5.25% of Türkiye’s electricity demand for that year. Ozdil and Caliskan [47] investigated the biomass potential from agricultural crops in Türkiye and calculated the corresponding electricity generation potential for the decade between 2008 and 2018. Their analysis estimated the electricity generation potential from biomass to be 997 TWh for this period, representing 36% of the country's total electricity generation during the same timeframe. Cekinir, S. et al. [48] conducted a study on Türkiye's long-term energy projections until 2050. Their research forecasted bioelectricity production to reach 390 TWh by 2050. However, this study relied on biomass potential estimations from various sources that may not have specifically focused on long-term assessments. Şenol, H., et al. [49] made a forecast of the potential for biogas production in Türkiye by region until 2035, based on the use of animal manure. The findings revealed that the potential for electricity generation from biogas reached 19.9 TWh by 2035. Table 5 presents the results of several studies conducted to assess the long-term bioenergy potential of Türkiye.

Table 5. Long-term bioenergy potential estimates for Türkiye

Biomass Type	**Bioenergy Potential**	**The Projection Period**	**Reference**
All available resources	52.5 Mtoe by 2030	2010-2030	[45]
All available resources	390 TWh by 2050	2020-2050	[48]
Animal Manure	19.9 TWh from biogas production by 2035	2022-2035	[49]

This research differentiates itself from previous studies by its comprehensive approach. It evaluates the diverse sustainable biomass resources across various sectors in Türkiye, including agriculture, forestry, livestock, and waste. Furthermore, it provides long-term potential projections for bioenergy development. In contrast, prior studies in Türkiye have primarily concentrated on estimating current biomass potential for short-term energy production. This study, however, shifts the focus to exploring long-term sustainable bioenergy potential of Türkiye, particularly its role in achieving net-zero carbon emissions and meeting future electricity demands.

The findings of this study extend beyond Türkiye's borders and offer valuable insights for other countries facing energy security challenges due to dependence on imported fossil fuels. These nations can utilize the study's framework to assess their own indigenous biomass resources and bolster the viability of biomass for electricity generation.

3. METHODOLOGY AND DATA COLLECTION

Forecasting the long-term potential of biomass and bioenergy production requires the use of diverse data from a variety of sectors. This chapter provides a detailed description of the specific statistical methods and tools used to estimate long-term biomass and bioenergy potential for the selected biomass resources.

Furthermore, this chapter provides an overview of the methodology employed for long-term electricity demand and supply projections, outlining the key assumptions used in the long-term analysis.

3.1. Selected Biomass Resources and Bioenergy Technologies

Türkiye's bioenergy sector relies on different types of biomass for various conversion processes. The choice of technology depends on the form of the biomass feedstock. Dry or solid biomass is typically converted through direct combustion, while wet feedstock is better suited for biogas and LFG production.

According to the extrapolating data from RES licensed plant list [24] , animal manure dominates the feedstock for biogas plants, accounting for a substantial 93% in licensed capacity in 2020. This process often utilizes a co-feedstock approach, with a significant 78% combining animal manure with crop residues. In contrast, combustion technology relies heavily on crop residues (56%) and woody biomass (almost all, at 99%). Municipal solid waste also plays a role in combustion, while waste tires are uniquely suited for pyrolysis. Sewage sludge finds its use split between AD plants (74%) and combustion after dewatering. When forestry waste enters the mix with animal manure and crop residues, direct combustion becomes the only viable technology [24].

This study focuses on two distinct biomass categories for bioelectricity generation in Türkiye, chosen based on their inherent properties and suitability for conversion technologies. Dry biomass, encompassing crop residues (such as straws from arable crops, tree pruning from horticulture) and forest product (firewood), is prioritized due to its advantageous combustion characteristics in biomass power plants. Conversely, wet biomass resources, including animal manure, OFMSW, and sludge from wastewater treatment plants (WWTPs), are well-suited for AD and LFG processes. These conversion pathways yield biogas/biomethane, which can be subsequently utilized in CHP units for electricity generation (Figure 10). This targeted selection of biomass feedstocks optimizes conversion efficiency and leverages the inherent advantages of each biomass type for specific technologies, ultimately maximizing bioelectricity production within the Turkish context.

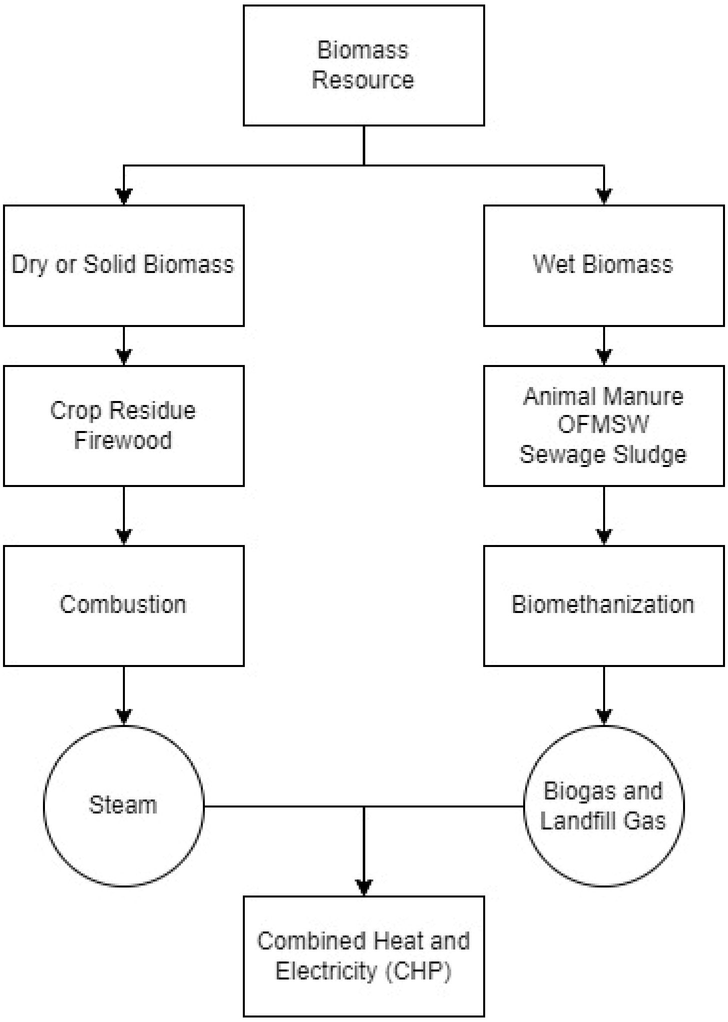


Figure 10. The selected biomass and bioelectricity generation pathways

3.1.1. Crop Residues

Crop residues are biomass leftover in fields after crops have been harvested, such as straw, stems, and leaves. Primary crop residues are what remains in the field after the main portion of the crop has been harvested, while secondary crop residues are the by-products of processing primary residues, such as husks, shells, and kernels. Both types of residues can be used for bioenergy production, as well as for improving soil quality and reducing waste. Additionally, tree pruning can also be used as a feedstock for bioenergy production. Utilizing these residues helps reducing reliance on non-renewable energy sources and promotes the use of sustainable and renewable energy sources [53].

Collection of primary residues is influenced by factors like the type of harvesting machinery, timing of residue production, farm size, and transportation costs. Access to residues at the site is crucial for accurately predicting bioenergy potential from agricultural residues. Tree pruning, which includes branches and twigs removed from trees for various reasons, can be processed into wood chips or pellets for heating or electricity generation [54] .

Türkiye is known for its suitable climate and soil conditions that allow the cultivation of a wide range of arable and horticultural crops. Thus, various crops haven been cultivated in different parts of the country. Consequently, crop residues can be considered as valuable biomass resources for bioenergy production.

Between 1990 and 2020, the agricultural land area excluding meadows and pastures decreased from 27.8 million hectares to 23.14 million hectares. The decline in agricultural land in Türkiye is primarily due to urbanization, industrialization, and changing land use patterns. However, Türkiye still has a large agricultural land area, and the sector remains crucial to the country's economy and employment [55].

Table 6 provide a breakdown of Türkiye's agricultural land use in 2020, showing that field crops were the dominant crops, covering over two-thirds of the total agricultural area. Fallow land and permanent crops like fruits and spices made up most of the remaining area, while vegetables and ornamental plants occupied only a small fraction of the land. Within the field crop category, a select group including wheat, barley, sugar beet, cotton, sunflower, and maize held a dominant position, collectively accounting for 78% of the total sown area. Fruits, with a cultivation area of 3.56 million hectares, were another significant contributor. Notably, olive, hazelnut, pistachio, and grape cultivation played a key role within the fruit sector, representing a substantial 66% of the total fruit-growing area [55].

Table 6. Türkiye's 2020 Agricultural Land Use [55]

Agricultural Land Use	**Million Hectares**	**Share**
Field crop	15.63	67.5%
Fallow land	3.17	13.7%
Vegetable Growing	0.78	3.4%
Fruits and the beverage-spice crops	3.56	15.4%
Ornamental plants	0.005	0.02%
Total	**23.14**	**100%**

3.1.1.1. Selection of crops and their residues for estimating biomass and bioenergy potential

In previous years, several studies [56], [57], [58], [59] have been conducted to estimate the energy potential of various crops. These studies were guided by a detailed literature review and an analysis of current production profiles in Türkiye. The initial selection of crops and related crop residues to be analyzed in this assessment was based on the following criteria:

- the scale of production of the specific crop in Türkiye,
- the availability of residue collection, and
- the suitability of their residues to be used as feedstock for energy production.

Table 7 presents a summary of the selected crops, their residues, and the associated collection methods. Some residues are collected directly from the fields in which they are produced following the harvest, while others are obtained as by-products during the processing of crops at facilities dedicated to this purpose. For example, wheat straw is collected directly from the field, whereas corn cobs are obtained from processing facilities.

Table 7. Selected crops and their residues for bioenergy production

Crop Type	Residue Type	Collection Type
Cereals		
Wheat	Straw	In field
Barley	Straw	In field
Rye	Straw	In field
Oat	Straw	In field
Maize	Stover	In field
	Cob	Processing facility
Rice	Straw	In field
	Husk	Processing facility
Oilseeds		
Sunflower	Stalk	In field
	Head	Processing facility
Soybean	Stalk	In field
Legumes		
Dry bean	Leaves	In field
Chickpea	Husk	Processing facility
Groundnut	Straw	In field
Roots and Pulses		
Sugar beat	Top (leaves)	In field
Cash Crops		
Cotton	Stalk	In field
Tree Fruits		
Hazelnut	Shell	Processing facility
	Tree Pruning	In field
Olive	Pomace	Processing facility
	Tree Pruning	In field
Grapes	Tree Pruning	In field
Apples	Tree Pruning	In field

Crop Type	Residue Type	Collection Type
Mandarin	Tree Pruning	In field
Orange	Tree Pruning	In field
Lemon	Tree Pruning	In field
Peach	Tree Pruning	In field
Apricot	Tree Pruning	In field
Cherry	Tree Pruning	In field
Pear	Tree Pruning	In field

3.1.1.2. Forecasting crop production potential for each selected crop

This study employs a multifaceted approach to forecasting future crop demand and production. Initially, data on crop production were obtained from the Turkish Statistical Institute (TURKSTAT) [60] and the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) [61]. To predict future crop demand, the study employs a multiple regression analysis using STATGRAPHICS software.

Multiple regression analysis is a statistical technique used to predict the value of a dependent variable based on the values of two or more independent variables. The multiple regression equation takes the form [62]:

$$Y = B_0 + B_1X_1 + B_2X_2 + \cdots + B_kX_k + \in$$

[1]

Where:

- Y is the dependent variable
- $X_1, X_2, ..., X_k$ are the independent variables
- $B_0, B_1, B_2, ..., B_k$ are the regression coefficients
- ε is the error term

This analysis relies on population and gross domestic product (GDP) per capita projections as the key independent variables. The regression model is applied if only a statistically significant relationship (at a 95% confidence interval) exists between domestic crop demand and these independent variables. Crops with weaker relationships are excluded from the analysis. In addition, the projection of future imports and exports for each crop is based on the application of the ARIMA method.

Autoregressive Integrated Moving Average (ARIMA) is a statistical model used for time series forecasting. It leverages past values of the data series (AR terms), past forecast errors (MA terms), and potential non-seasonal or seasonal patterns (I term) to predict future values [63].

3.1.1.3. Calculation of energy potentials of residues from each selected crop

To determine the energy potential of crops, parameters such as crop/residue ratio, moisture content, availability of residues for energy production and energy content of residues are used and the values for each was taken from the referenced studies [56], [57], [58], [59]. Table 8 provides a list of selected crops and residues and their specific characteristics for energy potential estimation.

The crop to residue ratio refers to the amount of crop residues generated per unit of crop produced. Higher ratios mean there are more residues available for energy production. The Low Heating Value (LHV) of crop residues represents the amount of energy that can be extracted from them through combustion. Moisture content impacts the LHV, as higher moisture levels reduce the energy potential. Availability of crop residues depends on various factors like storage conditions, transportation, and other logistics, which can influence the feasibility of using the material for energy production. The energy potential of crop residues was determined using the Equation [2].

$$TEP = \sum_{z=1}^{n} CP_z \times RCR_z \times \left(\frac{100 - MC_z}{100}\right) \times A_z \times LHV_z$$

[2]

Where, TEP is the total energy potential of crop residues as megajoule, CPz is the agricultural crop production in tons per year, RCRz is the residue to crop ratio, MCz is the moisture content of each crop residue as a percentage, Az is the availability rate of each crop residue for energy production, LHVz is the low heating value of each crop residue as MJ/kg, n is the total number of crop residue type *and z is the crop residue type.*

Table 8. Crop/residue properties for energy potential [56], [57], [58], [59]

Crop	**Residue Type**	**Residue to crop ratio (RCR)**	**Calorific value (LHV) (MJ/kg)**	**Availability (A) (%)**	**Moisture Content (MC) %**
Wheat	Straw	1.1 - 1.13	15.9-16.7	15	12.5
Barley	Straw	1.1 - 1.22	18.5	15	13
Oat	Straw	0.37 – 1.1	18.5	15	11.5
Rye	Straw	0.99 – 1.1	17.4	15	15
Maize	Stover (stalk)	1.41 - 1.8	16.4	60-100	9
Maize	Cob	0.18 - 0.57	15.5-17.7	60-100	8
Rice	Straw	1.0 - 1.1	14.9	100	17.5
Rice	Husk (Hull)	0.24 – 0.25	13.5-16.4	80-100	11.5
Sunflower	Stalk	1.29	13.6	100	10.4
Sunflower	Head	1.17	14.5	100	11.7
Soybean	Stalk (Straw)	0.76-3.5	14.9-19.4	60	15
Dry bean	Stem and leaves	1.45	14.7	15	5

Crop	**Residue Type**	**Residue to crop ratio (RCR)**	**Calorific value (LHV) (MJ/kg)**	**Availability (A) (%)**	**Moisture Content (MC) %**
Chickpea	Straw (Stalk)	0.3 – 1.3	14.3	75	5
Groundnut	Straw (Haulm)	2.2	14.8	80	15
Sugar beets	Top (Leaves)	0.13	16.6	15	75
Cotton	Stalk	7.18	18.1	75	16
Hazelnut	Shell	0.48	19.9	20	7.64
Olive	Pomace	0.55	20.69	90	65
Grapes	Pruning	0.42	18	80	45
Apples	Pruning	0.19	17.8	80	40
Mandarin	Pruning	0.29	17.6	80	40
Orange	Pruning	0.35	18.05	80	40
Olive	Pruning	1.2	18.45	80	40
Lemon	Pruning	0.3	17.6	80	40
Peach	Pruning	0.4	18.2	80	40
Apricot	Pruning	0.19	20.05	80	40
Cherry	Pruning	0.19	21.7	80	40
Hazelnut	Pruning	3.34	19	80	40
Pear	Pruning	0.22	18.2	80	37.5

3.1.2. Firewood

Woody biomass is essential for rural areas in Türkiye and globally, as it is a major and important energy source. Around 50% of the world's population depend on woody biomass or other biomass for domestic purposes such as heating and cooking. Informal harvesting of State forests and other woody biomass resources in farming areas supplies about 50% of the total fuelwood demand.

Forests have great potential as a source of biomass, comprise forest residues, categorised in the literature as primary residues (by-products of conventional forestry), secondary residues (by-products of industrial processes), and tertiary residues (by-products of construction, demolition, and packaging processes) [64] Unlike other wood fuels such as logs, chips, pellets, and briquettes, which are categorized as secondary residues, the potential for energy wood production can be directly associated with a country's productive forest wealth and wood production trend for long-term estimations.

Türkiye has significant forest resources with approximately 23.1 million hectares of forest land in 2021, which was 20.2 million hectares in 1973 and 20.8 in 1999, covering around 29% of the country's land area [65]. The wood wealth in forests increased from 0.9 billion m^3 in 1973 to 1.7 billion m^3 in 2021. In respect to this, between 1973 and 2021, there has been an increase of 0.8 billion m^3 in the tree wealth of the country's forests [66].

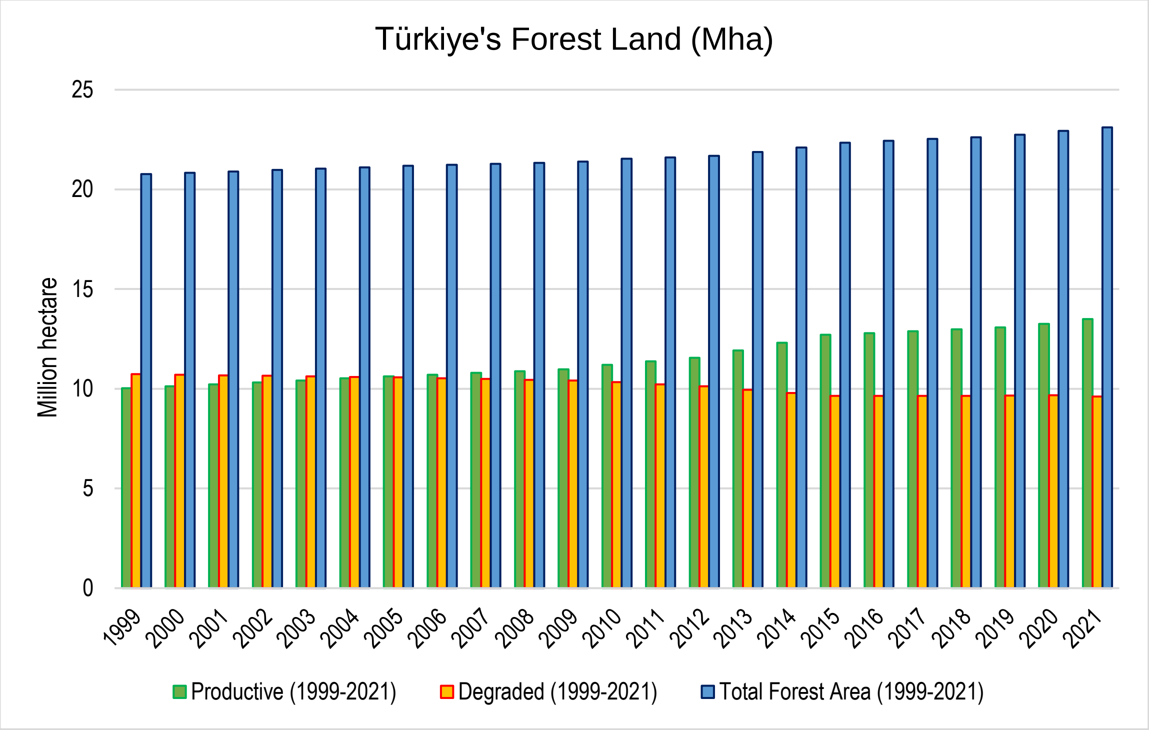


Figure 11. Distribution of forest land of Türkiye [65]

Firewood is the most traditional and widespread form of wood fuel in Türkiye, particularly in rural areas. It is typically sourced from small-scale forestry operations, such as thinning and pruning, and from wood waste generated from construction and other activities. The potential for firewood production and use would depend on factors such as forest management practices, availability of raw materials, transportation infrastructure, and the development of efficient and sustainable wood fuel technologies. Despite these high potentials, these energy resources are not utilized efficiently by modern methods. Most of the produced firewood is used in rural parts of the country for household heating and cooking purposes.

The roundwood production in Türkiye is carried out by both the government and the private sector. The government owns and manages 99% of the forests in Türkiye, and the General Directorate of Forestry is responsible for the management and operation of these forests. The ongoing production in the forests of the Turkish government is run by forest villagers. The private sector also plays a significant role in the roundwood production in Türkiye [66].

Türkiye's forests are about 48% coniferous, 33% broadleaved, and 19% mixed, which is reflected in roundwood production [67]. In 2021, industrial wood dominated production with 27.74 million cubic meters (m^3), with coniferous wood leading with 20.92 million m^3. Firewood consumption, totaling 4.67 million m^3, is split almost evenly between coniferous and broadleaved sources (2.32 million m^3 and 2.35 million m^3, respectively). Notably, coniferous firewood consumption has been decreasing since 2010, while industrial coniferous wood consumption has been increasing steadily, reaching a peak of 20.92 million m^3 in 2021. Broad-leaved wood consumption for industrial purposes has also increased, reaching 6.8 million m^3 in 2021, but at a slower pace than coniferous wood [65]. This shift in consumption patterns is reflected in the overall increase in roundwood production in Türkiye, which increases from 14 million m^3 in 2000 to a record 32.4 million m^3 in 2021, with industrial use leading the way (Table 9).

Table 9. Roundwood production in Türkiye by usage purpose [65]

Year	Firewood			Industry		
	Coniferous	Broad-leaved	Total	Coniferous	Broad-leaved	Total
	m^3	m^3	m^3	m^3	m^3	m^3
2000	2,143,580	4,538,646	6,682,226	5,755,064	1,574,205	7,329,269
2001	2,149,224	4,290,956	6,440,181	5,158,114	1,619,557	6,777,671
2002	2,188,197	4,260,520	6,448,716	6,307,449	1,697,689	8,005,138
2003	2,322,237	4,321,306	6,643,542	5,622,925	1,697,573	7,320,498
2004	2,421,310	4,480,312	6,901,622	6,342,103	1,911,174	8,253,277
2005	2,431,414	4,085,558	6,516,972	6,258,109	1,842,175	8,100,284
2006	2,253,331	3,699,241	5,952,572	7,047,543	2,251,153	9,298,696
2007	2,195,132	3,613,789	5,808,920	7,724,281	2,328,696	10,052,977
2008	2,375,710	3,832,596	6,208,306	9,019,893	2,521,101	11,540,994
2009	2,535,863	3,777,593	6,313,456	8,787,324	2,676,664	11,463,988
2010	2,460,335	3,654,881	6,115,216	9,501,980	3,066,539	12,568,520
2011	2,436,685	3,324,701	5,761,386	10,390,865	3,141,597	13,532,462
2012	2,191,341	3,276,432	5,467,773	10,744,778	3,679,587	14,424,365
2013	2,121,895	2,962,553	5,084,448	10,848,147	2,819,840	13,667,987
2014	1,802,537	2,666,758	4,469,295	11,307,865	3,615,344	14,923,209
2015	1,850,302	2,419,236	4,269,538	12,807,215	3,830,383	16,637,598
2016	1,872,877	2,272,630	4,145,507	12,715,352	4,294,646	17,009,998
2017	1,637,635	2,068,064	3,705,699	11,486,044	4,035,578	15,521,622
2018	2,076,292	2,080,595	4,156,887	13,918,115	5,162,022	19,080,137
2019	2,367,712	2,383,617	4,751,328	16,252,761	5,860,487	22,113,248
2020	2,342,942	2,244,236	4,587,178	18,087,054	6,664,012	24,751,066
2021	2,317,462	2,346,801	4,664,263	20,917,243	6,818,025	27,735,268

As seen in Table 9 industrial wood production is somewhat higher than the firewood production due to the development in the forest products industry in the late years. Firewood remains a significant tradable commodity in Türkiye, particularly as a primary fuel source for rural populations and low-income urban residents. Traditionally used for heating, cooking, and cleaning in the residential sector, firewood's share of total household energy consumption has steadily declined. While it held a substantial 26% share in 2000, this figure had significantly decreased to 4.6% by 2021 (Figure 12). This trend reflects a growing shift towards alternative energy sources within Turkish households.

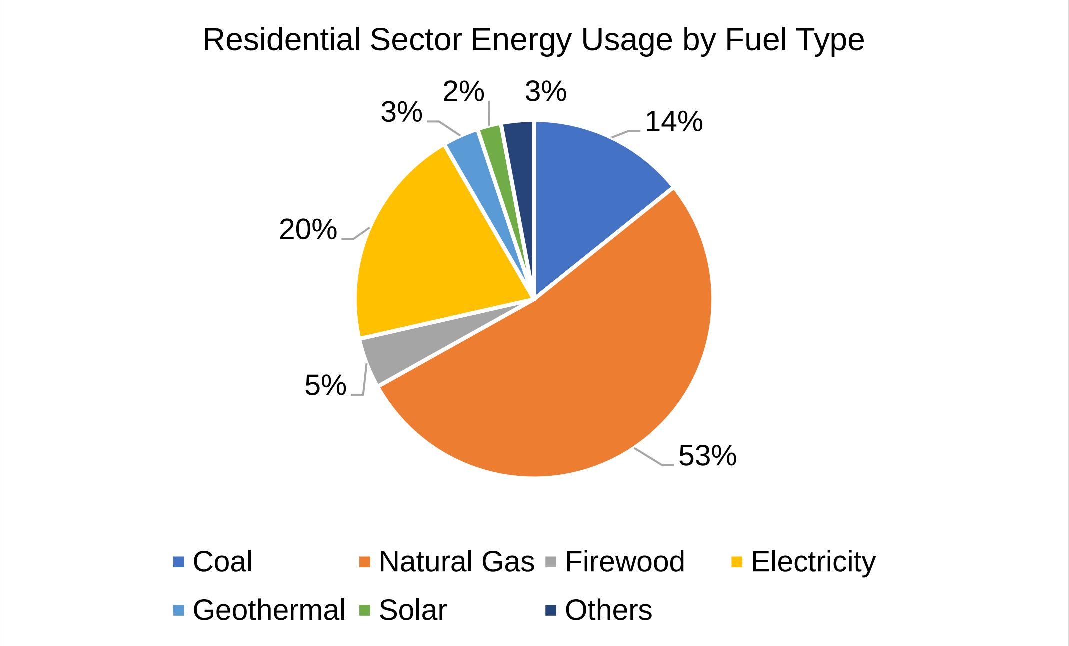


Figure 12. Firewood usage in energy consumption in Türkiye, 2021 [19]

3.1.2.1. Forecasting roundwood production potential

In order to forecast the future roundwood production in Türkiye, the productive forest land area needs to be predicted first. This can be achieved by analyzing the forest land data of the last two decades, provided by the Türkiye’s General Directorate of Forestry [65], and applying a statistical method, ARIMA to forecast the forest area for the projected period. Next, a multiple regression analysis was used to estimate the production of both coniferous and broad-leaved roundwood. This analysis uses two variables to make its prediction: time and the projected productive forest area. The validity of this approach was confirmed by a statistically significant relationship between these factors and roundwood production at a 95% confidence interval [37]. The distribution of the projected roundwood production potential by tree species for industrial purposes and firewood use was determined by their average over the last 5 years. And these averages were applied to the projection period. The reason why the average of the last 20 years was not used is that in the early 2000s the share of firewood was about 72% for broadleaf production and 28% for coniferous production. In parallel with increasing needs of industry their share decreased to 26% for broad-leaved, 10% for coniferous as of 2021. As the trends observed over recent years provide a more realistic indication of future roundwood use, the average of the last five years was taken as the basis for the analysis. Please refer to Table 10 for a comparison of roundwood use between the years 2000 and 2021. Finally, the projected firewood production is estimated for use in direct combustion CHP plants for electricity generation.

Table 10. Roundwood use distribution in 2000 and 2021 in Türkiye [65]

Roundwood	2000		2021	
	Industry	Firewood	Industry	Firewood
Coniferous (m^3)	5,755,064	2,143,580	20,917,243	2,317,462
Broad-Leaved (m^3)	1,574,205	4,538,646	6,818,025	2,346,801
Total (m3)	7,329,269	6,682,226	27,735,268	4,664,263
Share in total	52%	48%	86%	14%

3.1.2.2. Calculation of energy potential of roundwood by tree type

The energy content of wood from these two tree species is different. According to the FAO guideline [68], assuming a water content of the wood of 20%, broad-leaved trees have a higher standard energy value of 10,158 megajoules per cubic meter (MJ/m³) compared to 7,350 MJ/m³ for coniferous trees. To estimate the total energy potential of wood from these two tree species Equation [3] was used.

$$TEP = \sum_{w=1}^{n} FP_w \times \left(\frac{100 - MC_w}{100}\right) \times LHV_w$$

[3]

Where, TEP is the total energy potential of firewood as megajoule, FPw is the firewood production in m^3 *per year, MCw is the moisture content of each wood type as a percentage, LHVw is the low heating value of each wood type as MJ/m*^{3}*, n is the total number of wood types, and w is the wood type.*

3.1.3. Animal Manure

Manure is a by-product of livestock production. Unlike crop residues, manure production is not categorised as primary or secondary residue and can be used for energy production with minimal pre-treatment. Manure is a valuable material that can be used as a source of organic matter and fertilizer for crop and pasture production. Manure can also be used as a source of energy on the farm through AD to produce biogas to then produce heat and/or electricity.

Livestock production in Türkiye is a pivotal component of the country's agriculture sector and economy, encompassing cattle, sheep, goat, and poultry production. Small-scale farms and domestic breeds characterize the Turkish livestock sector, which is better adapted to the harsh climate of eastern Türkiye but less productive. The majority of farms are small-scale, with low-yielding local breeds grazing on pastures and meadows in the east, and more mechanized farms exist in the west. Many farmers and rural households rely heavily on livestock products for a portion of their income. Small farmers rely on livestock products such as cattle, sheep, and goat to generate income and ensure food security because animal and milk sales account for a significant portion of their income.

The cattle farming in Türkiye has steadily increased over time. Although there was a slight decline in production from 1991 to 2003, this was mainly due to the decrease in domestic cattle. The decline in domestic cattle breed population is influenced by several factors, including economic challenges, high input costs, and poor animal health conditions. The conservation of domestic cattle breeds in Türkiye is considered important for maintaining biodiversity and ensuring sustainable livestock production. From 2004 until 2020, total cattle population has continued to rise steadily and has reached 18.16 million head including buffalo (Table 11). In recent years, the number of modern dairy cattle farms has increased with animal support. The Ministry of Agriculture and Forestry (MoAF) provides subsidies, and investment supports to farmers for the establishment of modern animal farms, renovation works and construction of processing plants. With these supports, the capacity of dairy farms has also increased. However, small size farms in Türkiye (with a 1-4 head of cattle) are still dominant, representing 60% total of 1.38 million registered cattle farms as of 2018 according to MoAF.

Türkiye has been a major producer of sheep and goat in Europe, West Asia, and North Africa. These animals contribute significantly to the country's meat and milk output, with sheep and goats together accounting for a substantial portion of the annual meat and milk production. Additionally, sheep, goat, and their products have been traditional export items, with a significant share in the country's export earnings. The natural pastures and grasslands in various regions of Türkiye are more suitable for sheep and goat rearing than for crop and dairy farming. In addition, sheep and goat are well adapted to the climatic conditions of the country, making them an important source of meat, milk, fibre, and skins. Sheep have consistently been the most raised livestock in the country, with 42.13 million in 2020. This highlights the economic significance of the sheep farming in the country. Similar to sheep, the population of goat in the country has been significant, totalling 11.99 million in 2020 (Table 11).

Poultry production holds significant importance in Türkiye's economy, with a notable upward trend in chicken population over the past three decades. Broiler chicken population, however, has exhibited a fluctuating pattern from 1991 to 2020. The numbers steadily increased in the early years, reaching a peaking at 258.05 million head in 2020. This variability could be attributed to diverse factors, including shifts in consumer demand, market dynamics, or adjustments in poultry farming practices. On the other hand, the chicken-layer population in Türkiye has consistently grown, achieving a peak of 121.3 million head in 2020 (Table 11).

Table 11. Livestock population trend by animal species (1991-2020) [69]

Year	Cattle, Culture	Cattle, Crossbred	Cattle, Domestic	Sheep	Goat	Chicken-Layer	Chicken-Broiler
	Million head						
1991	1.25	4.03	6.69	40.43	10.76	50.83	88.38
1992	1.34	4.13	6.48	39.42	10.45	52.22	100.31
1993	1.44	4.34	6.13	37.54	10.13	58.18	120.08
1994	1.51	4.54	5.85	35.65	9.56	57.84	125.84
1995	1.70	4.78	5.31	33.79	9.11	57.32	71.69
1996	1.80	4.91	5.18	33.07	8.95	53.88	99.07
1997	1.72	4.69	4.78	30.24	8.38	61.40	104.87
1998	1.73	4.70	4.60	29.44	8.06	69.72	167.28
1999	1.78	4.83	4.45	30.26	7.77	71.89	167.86
2000	1.81	4.74	4.22	28.49	7.20	64.71	193.46
2001	1.85	4.62	4.07	26.97	7.02	55.68	161.90
2002	1.86	4.36	3.59	25.17	6.78	57.14	188.64
2003	1.94	4.28	3.56	25.43	6.77	60.40	217.13
2004	2.11	4.40	3.56	25.20	6.61	58.77	238.10
2005	2.35	4.54	3.63	25.30	6.52	60.28	257.22
2006	2.77	4.69	3.41	25.62	6.64	58.70	286.12
2007	3.30	4.47	3.28	25.46	6.29	64.29	205.08
2008	3.55	4.45	2.85	23.97	5.59	63.36	180.92
2009	3.72	4.41	2.59	21.75	5.13	66.50	163.47
2010	4.20	4.71	2.46	23.09	6.29	70.93	163.98
2011	4.84	5.12	2.43	25.03	7.28	78.96	158.92
2012	5.68	5.78	2.46	27.43	8.36	84.68	169.03
2013	5.95	6.11	2.35	29.28	9.23	88.72	177.43
2014	6.18	6.06	1.98	31.14	10.34	93.75	199.98
2015	6.39	5.73	1.87	31.51	10.42	98.60	213.66
2016	6.59	5.76	1.73	30.98	10.35	108.69	220.32
2017	7.80	6.54	1.60	33.68	10.63	121.56	221.25
2018	8.42	7.03	1.59	35.19	10.92	124.05	229.51
2019	8.56	7.55	1.57	37.28	11.21	120.73	221.84
2020	8.84	7.59	1.53	42.13	11.99	121.30	258.05

Türkiye produces a substantial amount of animal manure annually, and since the 1960s, many studies have been conducted in the area of bioenergy research and development projects using animal-based biomass. The main types of animal manure used for bioenergy production in the country are from cattle and chickens. Currently, various technologies, including AD, direct-combustion, and pyrolysis, are employed for bioenergy production from animal manure. Additionally, other byproducts from the food industry, such as animal remains, can also be utilized as a biomass feedstock.

While anaerobic digesters are prevalent, there is a rising trend in direct combustion technology for bioenergy production in Türkiye. Additionally, pyrolysis technology is gaining traction, with one plant certified under the RES scheme using chicken manure as feedstock. To optimize biogas production and make anaerobic digesters more feasible, operational conditions need to be fine-tuned, and pre-treatment techniques should be integrated. Strategies like ensiling and co-digestion can enhance biomethane potential yields. As Türkiye focuses on sustainable energy sources and waste valorization, the utilization of agricultural residues for biogas production becomes increasingly important.

As stated before, the bioenergy production sector in Türkiye utilizes various feedstocks beyond animal manure, including agricultural (crop) residues, forestry residues, and municipal solid waste. While animal waste remains a common feedstock for bioenergy plants, the diversification of feedstocks contributes to a more sustainable and efficient energy production system. The share of animal waste used in bioenergy plants varies by technology [24]. AD, pyrolysis, and direct combustion are among the technologies employed for bioenergy production from animal waste in Türkiye.

Table 12. Animal waste use in bioenergy technologies in Türkiye [24]

Biomass type/ Technology	AD	Combustion	Pyrolysis
Animal waste	93%	6%	1%
Animal waste and crop residues	78%	22%	0%
Animal waste, crop residues and forestry residues	0%	100%	0%
Animal waste and MSW	100%	0%	0%

As shown in Table 12, the predominant utilization of animal waste (predominantly manure) is in biogas production, representing 93% of the total capacity when employed as the sole feedstock. The combined use of animal waste and crop residues allows for a 78% capacity for co-digestion processes and a 22% capacity for co-combustion processes. In cases where animal waste is employed in combination with crop and forestry residues, the capacity is limited exclusively to co-combustion technology, with no capacity for biogas production. Ultimately, when animal waste is employed in the context of municipal solid waste (MSW), the entirety of the capacity is allocated to biogas production.

As can be observed, Türkiye has considerable potential for the production of biogas, which is derived primarily from animal manure. The most prevalent animal species in Türkiye are cattle, sheep, goat, and chickens. This study focuses on forecasting manure production from these animals and utilizing it for biogas production and subsequent electricity generation via CHP units. The inability to collect manure from sheep and goat presents a challenge to the wider use of these animals, yet their potential was included in the calculations. Animal species such as horses, camels, and pigs were excluded due to their minimal contribution to the overall energy potential. The analysis of essential parameters is crucial for estimating manure characteristics for biogas production from different animal types.

Estimation of daily manure production, the key parameter is the live animal's weights. Türkiye has distinct cattle breeds—culture, crossbred, and domestic—with varying manure production potentials. Other factors influencing production include gender and physical attributes, such as dairy cows having higher potentials than non-dairy cattle (other cattle). Chickens' manure characteristics depend on gender and purpose—layers for egg production and broilers for meat—with variations in live weight. The manure production potential for sheep and goat depends on factors like live animal weight, but the differences in daily manure production between different breeds of sheep and goat are relatively small (please see Table 14 which provides data on the average live weight of livestock breeds in Türkiye and their corresponding manure characteristics for biogas production, sourced from various sources).

The availability of manure for energy production depends on several factors, including the type and number of animals, the management practices of the farms, and the amount of manure produced. Generally, larger animal operations tend to produce more manure, making it more readily available for biogas production. However, even small farms can contribute to the availability of manure for biogas production. Additionally, it is essential to consider the logistics of manure collection and transportation to a biogas plant for processing. Manure from confined animal feeding operations is typically more recoverable than manure from grazing animals, as it is generally easier to collect and transport from the site. Cattle manure is generally more suitable for biogas production compared to sheep and goat manure due to its greater availability and collectability. This is because cattle produce a larger amount of manure and are often confined in feedlots or barns, making their manure highly collectiable. On the other hand, sheep and goat are typically raised on extensive pasture systems, which can make it more difficult to collect and transport their manure to biogas plants. Additionally, sheep and goat farming in Türkiye is usually on a smaller scale, resulting in a lower total amount of manure produced. This can make it more challenging to achieve economies of scale in the production of biogas from sheep and goat manure. Chickens are usually raised in confined housing systems, such as battery cages, which makes the collection and handling of manure more straightforward than for animals that are free-range. In Türkiye, commercial poultry operations are huge and can produce large quantities of chicken manure, which makes it a readily available and reliable source of feedstock for biogas production.

The specific manure characteristics of each type of livestock can vary depending on a variety of factors. By understanding these characteristics and managing manure carefully, it is possible to optimize biogas production and promote sustainable agriculture. Cattle manure is typically high in total solids and volatile solids, which can make it an ideal feedstock for biogas production. However, the composition of cattle manure can vary depending on factors such as diet, age, and breed. For example, manure from dairy cows may have a higher nutrient content than non-dairy cattle's manure. Manure of sheep and goat generally contain higher levels of total solids and volatile solids due to their unique digestive system, which allows them to extract more nutrients from their feed. This means that sheep and goat manure may have a higher potential for biogas production per unit of manure than cattle manure. Chicken manure is typically high in nitrogen and phosphorus, which can make it a valuable feedstock for biogas production. However, chicken manure can also be high in ammonia, which can be toxic to the microorganisms used in the biogas production process. Therefore, it is important to manage chicken manure carefully and take steps to reduce ammonia levels before using it as a feedstock for biogas production.

3.1.3.1. Forecasting animal manure production potential

The projection of animal populations is a fundamental data set for forecasting future manure production potential. In this study, the forecasting of animal population was conducted in consideration of the forecasting of public demand for their products, including meat, milk, and eggs.

In order to forecast the population of dairy cattle, it is essential to forecast milk demand. Therefore, the analysis was conducted using multiple regression analysis with population growth and GDP per capita as independent variables to forecast milk demand. Other cattle populations were estimated based on historical trends. On average over the past two decades, the split between dairy and other cattle has been around 40–60%. Similarly, sheep and goat populations were calculated based on combined demand for their meat and milk, while chicken populations were calculated based on demand for both eggs and meat. This comprehensive approach, which considers both demand and historical trends, provides a reliable foundation for forecasting future manure production.

Table 13. Animal by-product demand by type and species [69]

Year	Per capita milk demand			Per capita meat demand			Per capita egg demand
	Cow	Sheep	Goat	Sheep	Goat	Chicken	Chicken
	kg/ person	kg/ person	kg/ person	kg/ person	kg/ person	kg/ person	number/person
2000	134.9	12.0	3.4	3.4	0.3	9.9	208.1
2001	129.4	11.0	3.4	3.4	0.9	9.1	157.0
2002	112.8	9.9	3.2	3.3	0.9	10.2	174.2
2003	141.6	11.5	4.1	3.0	0.8	12.6	187.3
2004	141.3	11.3	3.8	2.8	0.8	12.5	160.6
2005	145.6	11.5	3.7	2.8	0.7	13.0	172.8
2006	155.8	11.4	3.6	2.7	0.7	12.6	165.7
2007	159.8	11.1	3.4	2.7	0.7	14.4	169.9
2008	157.4	10.4	2.9	2.7	0.7	14.1	167.3
2009	159.6	10.1	2.6	2.6	0.6	16.3	171.0
2010	168.4	11.1	3.7	2.5	0.6	17.7	132.2
2011	184.6	11.9	4.3	2.8	0.6	18.5	129.4
2012	211.2	13.3	4.9	2.9	0.7	18.8	145.6
2013	217.1	14.4	5.4	3.1	0.8	18.3	156.7
2014	218.6	14.3	6.0	3.1	0.8	19.3	161.5
2015	214.9	15.0	6.1	3.2	0.9	20.0	168.5
2016	210.2	14.5	6.0	3.3	0.9	19.6	169.1
2017	231.8	16.6	6.5	3.3	1.0	21.5	170.0
2018	243.9	17.6	6.9	3.6	1.0	20.8	169.7
2019	249.6	18.3	6.9	3.8	1.0	20.5	187.2
2020	259.9	13.2	6.6	4.1	1.1	19.8	195.4

As stated, multiple regression analysis was employed to estimate future demand for various animal products, including milk from cattle, sheep, and goat, meat from chicken, sheep and goat, and eggs from chickens. This analysis considered population and GDP per capita as independent variables. The weaker statistical relationship between animal products and independent variables was also taken into account in the calculations. Furthermore, to project future imports and exports for each animal product, the ARIMA method was employed. This method analyzed data on import and export percentages from the past two decades for each product to predict future trends. This comprehensive approach ensures precise projections for animal-based food production in Türkiye.

3.1.3.2. Calculation of biogas production potential from animal manure

In this study, the specific methane yield of each animal's manure is taken into consideration. The specific methane yield of animal manure can vary depending on the type of manure and the conditions of the AD process. The specific methane yield is defined as the quantity of methane produced per unit mass of volatile solids (VS) present in the manure. The theoretical potential for biogas/biomethane production from animal manure is typically estimated by incorporating a number of coefficient factors into the following Equation [4]:

$$TBP = \sum_{m=1}^{n} MP_m \times AC_m \times TS_m \times VS_m \times SMY_m \tag{4}$$

Where TBP is the theoretical potential of biomethane production (m^3/year), MP is the total amount of the manure (kg/year), AC represents the availability coefficient (%), TS denotes the ratio of total solid animal manure (%), and VS is the ratio of volatile solids in total solids (% of TS), SMY is the specific methane yield (m3 /kgVS), n is the total number of animal type and m is the animal type.

Table 14 presents data on the average live weight of animal breeds in Türkiye and their corresponding manure characteristics for biogas production, derived from a range sources [46], [47], [48].

Table 14. Manure characteristics and methane yield [46], [47], [48]

Animal Type	Animal Live Weight, kg	Average Manure Production, kg/head/day	Manure Availability Coefficient %	Total Solids (% of manure intake	Volatile Solids (% of TS)	Specific Methane yield (m3/ kg VS)
Dairy Cow	476.42	38.11	65	13.95	83.36	0.18
Other Cattle	300.11	16.51	50	14.66	84.65	0.33
Sheep	50-60	2.1-2.5	13	27.50	83.63	0.30
Goats	45	2.4	13	31.71	73.06	0.30
Chicken-Layer	1.5-2.0	0.09	99	25.00	75.00	0.35
Chicken-Broiler	1.5-2.0	0.17	99	25.88	77.28	0.35

Equation [5] and Equation [6] were used to determine the total electrical energy potential and installed capacity of biogas CHP plants.

$$E_{P\,(AD)} = \frac{\left(CH4_{(AD)} \times E_{ff} \times LHV_{CH4} \times \mathrm{CF}\right)}{3.6}$$

[5]

$$P_{S\,(AD)} = \frac{E_{P\,(AD)}}{8760}$$

[6]

Where the variable "$E_{P(AD)}$ " represents the amount of possible electrical energy from the AD technology, "$CH4_{(AD)}$" is the actual volume of methane produced from the AD plant, E_{ff} electricity efficiency of AD-CHP system, which is taken 35%, "LHV_{CH4}" is the lower heating value of methane, which is taken 37.2 MJ/m3, "CF" stands for capacity factor, which is taken 85% and "$PS_{(AD)}$" is the installed capacity (size) of the AD.

3.1.4. Municipal Solid Waste

Municipal Solid Waste (MSW) is indeed a valuable energy resource that can be effectively managed through proper waste management techniques. Direct landfilling without prior separation leads to various environmental issues, making it one of the least favorable methods of waste management. The EU Waste Framework Directive promotes waste prevention as a priority, with landfilling as the last resort. MSW comprises a diverse mix of waste from households, industries, hospitals, and businesses, containing valuable components that can be reused, recycled, and recovered. Energy recovery plays a crucial role in minimizing the amount of waste sent to landfills, highlighting the importance of sustainable waste management practices in our current era.

The EU has indeed adopted a progressive transition strategy from landfill-based MSW management to integrated waste management techniques, such as recycling, mechanical biological treatment (MBT), and incineration with energy recovery, known as the modern waste hierarchy [70]. This modern waste management hierarchy aims to reduce the final disposal (landfilling) of waste and promote the minimization of waste generation. This shift is part of the EU's broader efforts to move towards a more sustainable model, emphasizing the circular economy and environmentally friendly waste management practices.

Figure 13. Waste hierarchy [70]

MBT processes play a crucial role in waste management, particularly in reducing the environmental burdens associated with waste disposal. In MBT, the waste undergoes mechanical and biological stages to stabilize it and recover valuable materials. One significant aspect is the reduction of LFG production through controlled decomposition of organic substances, which minimizes the environmental impact of landfill gas emissions. By diverting waste from landfills to MBT facilities, the volume of waste requiring disposal decreases, leading to a reduction in GHG emissions and the need for LFG management. In addition, the popularity of MBT has increased with the implementation of the Landfill Directive, which requires Member States to reduce the amount of biodegradable waste sent to landfills. MBT has the ability to reduce waste volumes and methane emissions, and its modular nature offers flexibility while being less expensive and faster to construct than other large-scale, centralized alternatives [71]. Waste undergoes a preliminary sorting stage in MBT facilities, employing either dry or wet methods based on the intended final product. This separation aims to concentrate the organic materials, leaving behind a fraction rich in biodegradable components ideal for subsequent biological processes. MBT offers a variety of biological treatment options, including aerobic composting and AD, or even a combination of both. Notably, AD of the organic fraction can generate biogas, a valuable source of energy. Additionally, MBT can be employed to produce soil amendments and refuse derived fuel (RDF), further diverting waste from landfills [72].

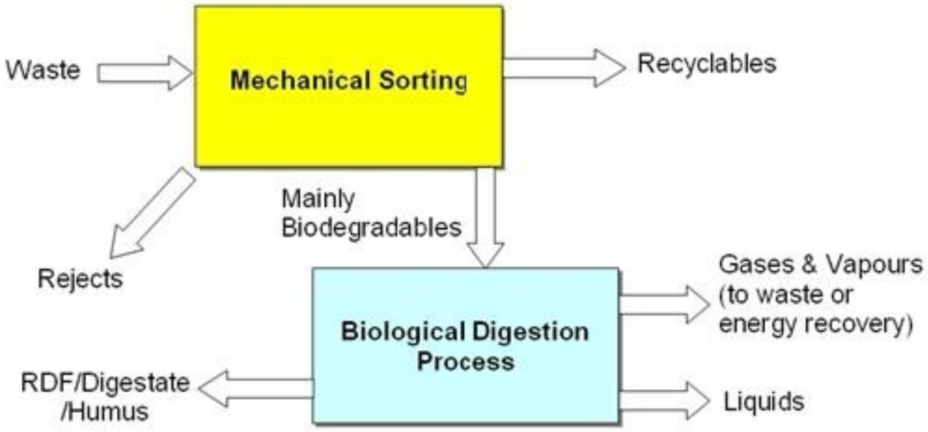


Figure 14. Biodegradable waste seperation in MBT facilities [72]

MSW is a growing concern in Türkiye due to the increasing population and urbanization, as well as the changing consumption patterns and lifestyles. MSW not only poses significant environmental and health risks, but also represents a valuable resource that can be used for energy production and resource recovery. The management of MSW and landfill sites in Türkiye faces several challenges that impact the environment and public health. One significant challenge is the inadequate separation and collection of waste at the source, leading to a high proportion of organic waste being disposed of in landfills. This improper disposal results in the production of methane, a potent GHG that contributes to climate change. Additionally, there is a lack of resources and investment in the management and operation of landfill sites, including monitoring and maintenance activities. This deficiency can lead to environmental risks such as soil and water contamination, as well as health hazards like the spread of diseases.

In parallel with the increase in the population of Türkiye, the municipal waste production has also risen. As of 2020, the total waste production has reached 34.76 Mt, an increase from 31.66 Mt in 2000. It is encouraging to note that waste management is improving year by year. The waste collection rate in 2000, as reported by municipalities, was 79.2%. This has increased to 93% as of 2020. The per capita waste production exhibited fluctuations in 2000, with a value of approximately 490 kg. This declined to 398 kg in 2008 but subsequently increased slightly, reaching a value of 415 kg in 2020 (Table 15).

Table 15. Municipal solid waste production and collection trends [73]

Year	MSW, generated, ton	MSW, collected, ton	% of collected MSW in total MSW	Per capita waste production, kg/year
2000	31,665,157	25,070,841	79.2%	489.19
2001	31,030,870	25,134,000	81.0%	473.01
2002	30,999,260	25,373,000	81.9%	466.84
2003	31,081,370	26,118,000	84.0%	462.61
2004	29,736,100	25,014,000	84.1%	437.23
2005	29,908,960	25,147,068	84.1%	434.34
2006	30,081,820	25,280,000	84.0%	431.40
2007	29,267,910	24,825,848	84.8%	414.64
2008	28,454,000	24,361,000	85.6%	397.86
2009	29,093,500	24,820,771	85.3%	400.95
2010	29,733,000	25,277,000	85.0%	403.31
2011	30,259,500	25,563,292	84.5%	404.95
2012	30,786,000	25,845,000	84.0%	407.07
2013	31,008,000	26,906,903	86.8%	404.45
2014	31,230,000	28,011,000	89.7%	401.95
2015	32,496,729	29,766,310	91.6%	412.70
2016	33,763,457	31,583,553	93.5%	423.02
2017	34,148,052	31,896,876	93.4%	422.57
2018	34,532,646	32,209,222	93.3%	421.11
2019	34,645,203	32,266,966	93.1%	416.63
2020	34,757,760	32,324,472	93.0%	415.69

Waste composition in Turkish provinces is variable and influenced by economic and geographical factors [74], [75], [76]. However, organic part of MSW makes up a significant portion, ranging from 40 to 60 percent. For example, according to the National GHG Inventory Report of Türkiye (NIR) [77] the average OFMSW of

Türkiye was reported as 54.5% in 2020. This high percentage highlights the substantial amount of biodegradable waste generated annually.

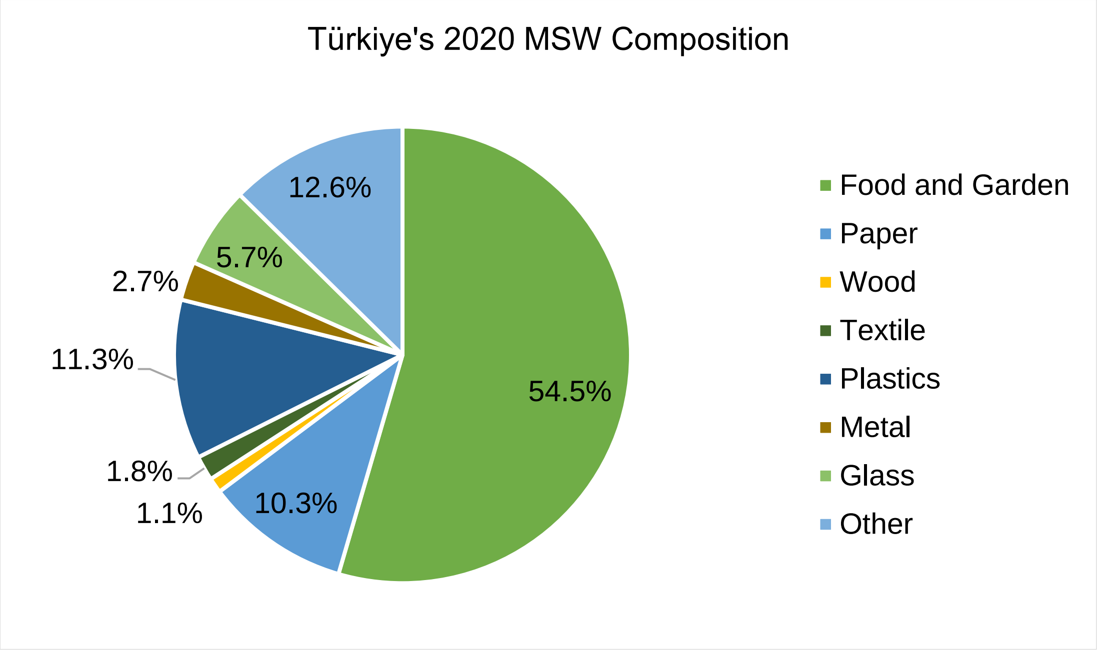


Figure 15. Türkiye’s 2020 average municipal solid waste composition [77]

Türkiye employs various waste disposal methods, with sanitary landfills dominating (69.4% in 2020). However, the rise in recovery facilities and composting plants since 2015 (13.2% in 2020) signals a shift to sustainable waste management [73]. In 2020, a total of 32.3 million tons (Mt) of municipal waste was collected by 1,387 municipalities in Türkiye. Approximately 0.4% of this waste was disposed of through other undesired methods such as open burning, burial, lake and river disposal, and dumping onto land [78]. Figure 16 presents the MSW management trend of Türkiye.

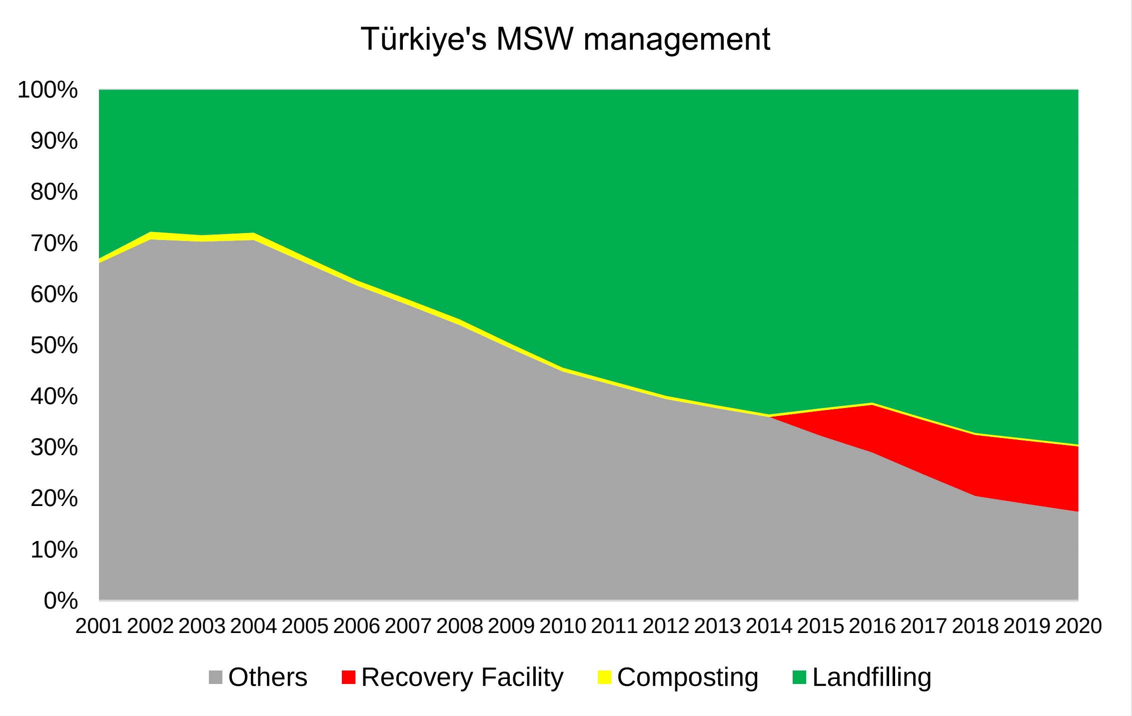


Figure 16. Türkiye's MSW management [78]

There has been a significant increase in sanitary landfills in Türkiye, with the number of sites going from 15 in 2003 to 93 in 2022 [79]. This expansion helps manage waste for over 65 million people across roughly 1,200 municipalities. However, there are still regions lacking proper infrastructure. Six provinces (Adıyaman, Bartın, Batman, Hakkari, Rize, Şırnak and Hakkari) have no landfills at all, and nine others (Ardahan, Artvin, Bayburt, Çankırı, Gümüşhane, Kars, Siirt, Sinop, Tunceli) have landfill sites but lack LFGTE and AD plants that could improve methane production from waste.

Landfill gas to electricity (LFGTE) plants are important in Türkiye as they allow for the recovery of methane gas produced from organic waste in landfills. The methane can be captured and used as a source of energy, reducing the environmental impact of landfill sites and providing a renewable source of energy. LFG is a significant source of methane emissions, which is a potent greenhouse gas. While the methane production from landfill areas can last for around 50 years, the efficiency of LFGTE plants can decrease over time as the methane production decreases, making them less efficient in energy production. After the methane production decreases to a low level, the landfill is considered "closed" and is typically covered with a final soil layer and monitored for potential environmental impacts. There are several reasons why municipalities may choose to convert LFGTE systems to AD systems. One of the main reasons is that LFG systems have a limited lifespan, as the amount of methane produced decreases over time. Additionally, LFGTE systems are often inefficient at capturing all of the methane produced, resulting in greenhouse gas emissions that contribute to climate change. The first LFG production in Türkiye started in 2006 at the Ankara Mamak landfill site, and since then the production of electricity from landfill waste through LFG production has been increasing rapidly. By 2020, almost all landfill waste in Türkiye was used for biomethanization (Figure 17).

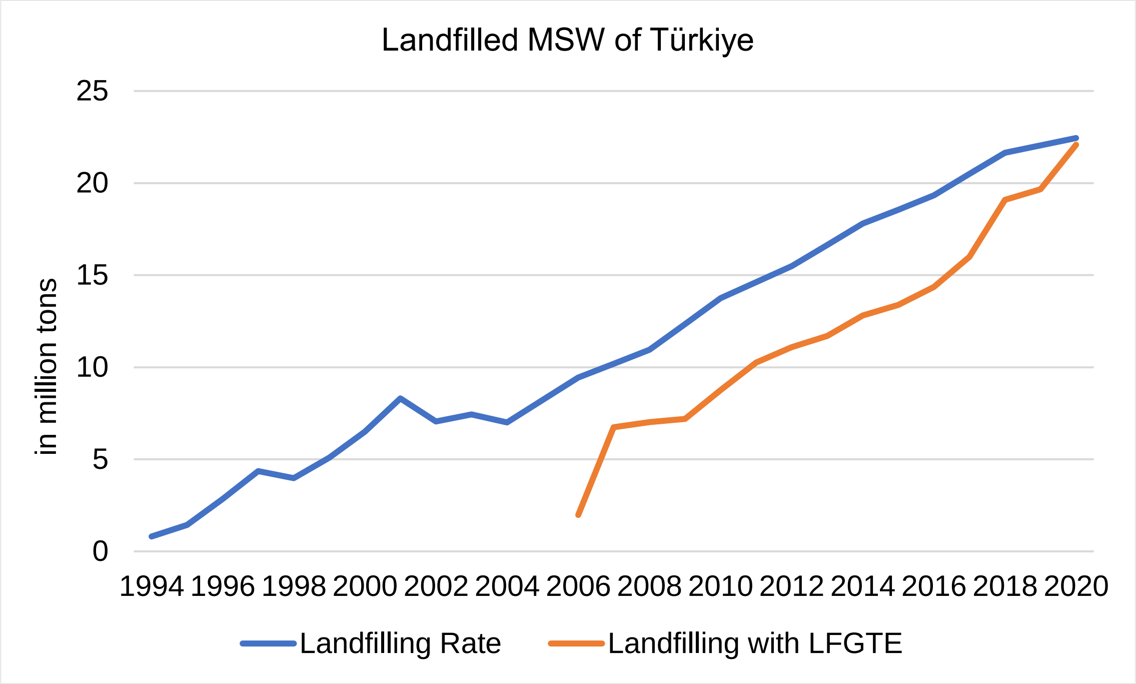


Figure 17. MSW sent to landfills and utilized for LFG production [78], [80]

Organic fractions, recyclable materials, and non-recyclables are the main components of MSW. Organic fractions can be composted or processed in AD plants to produce energy, while recyclable materials can be reused to save natural resources. Non-recyclables can be incinerated as a source of fuel. Incineration and AD are both alternatives to landfilling. Incineration involves heating waste at least 900°C, generating energy through a steam turbine, and removing hazardous organic compounds and toxic metals with a filter. AD, on the other hand, only handles biodegradable organic waste to generate biogas. Both methods can avoid landfilling and support a circular economy by using organic waste and non-recyclables to create energy [81].

Unlike LFG, AD plants can continue to produce biogas for a longer period of time and are generally more efficient at capturing methane. AD plants also have the potential to produce higher-quality biogas, as the composition of the gas can be controlled more effectively than with LFG systems. Another reason for the lower methane production in LFG systems is the oxidation of methane as it travels through the landfill cover and soil. Furthermore, the organic waste feedstocks used in AD systems are often diverted from landfills, which can help to reduce methane emissions from the waste. Overall, the conversion from LFG to AD systems can provide several benefits in terms of both energy production and environmental sustainability.

In recent years, the Turkish government has taken steps to support the development of AD plants, including the introduction of feed-in tariffs for biogas production and various incentive programs. As a result, the number of AD plants in Türkiye has been increasing steadily, and this trend is expected to continue in the future.

The 2022 RES list [24] shows that the total capacity of licensed LFG and AD plants is approximately 402 MWe. The combined capacity of other technologies, including gasification, and direct combustion, for generating biomass energy from MSW is 528 MWe. Unlicensed LFG capacity is estimated at 113 MWe for the end of 2019 [80].

The study suggests that the non-organic and non-hazardous fraction of MSW is not considered sustainable for energy production. This is because recycling and reusing these materials, such as plastics and glass, is a more environmentally friendly and resource-efficient approach compared to using them for bioenergy generation.

In advanced waste treatment plants, non-hazardous waste that is not suitable for recycling or reuse is used to produce Refuse Derived Fuel (RDF). RDF is a form of MSW that has been sorted and subject to basic processing treatment. It consists largely of combustible components of non-hazardous municipal waste and has more consistent combustion characteristics than unsorted MSW. However, while RDF utilization can contribute to energy recovery from waste, it is not a fully carbon-free process due to the presence of non-organic, fossil-fuel-derived components in MSW.

3.1.4.1. Forecasting OFMSW production potential to be used in landfill gas and biogas production

To forecast the potential for biogas and LFG production from OFMSW, a two-step analysis was conducted. First, future MSW production is projected using multiple regression analysis. This considered how population growth and increasing GDP per capita would impact waste generation. Next, historical trends were analyzed to predict future MSW collection efficiency. These combined forecasts provide the foundation for predicting the future potential of biomethane generation from MSW.

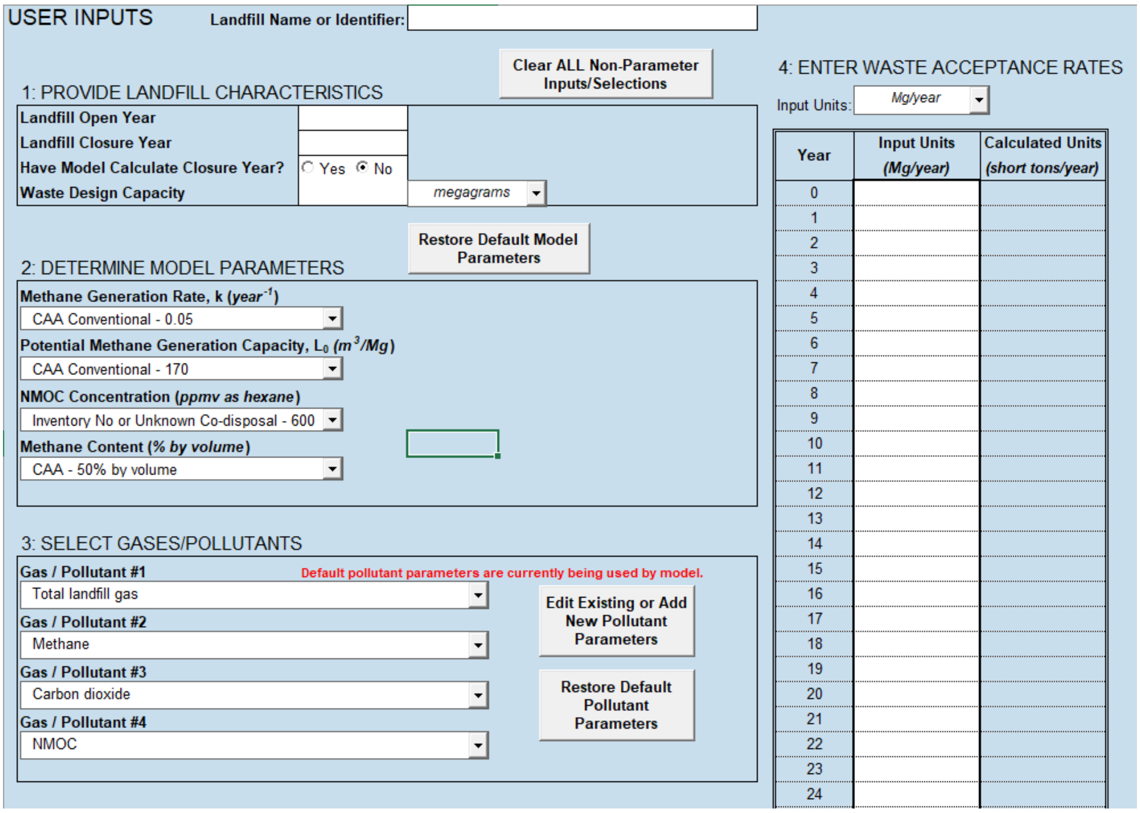
The two main approaches to assess the potential of biogas and LFG as renewable resources are:

1. *Direct collection of methane gas from existing landfills.* This involves capturing the methane gas that is naturally produced from the decomposition of organic waste in landfills and using it as a renewable energy source.
2. *Using a MBT system to divert biodegradable waste from landfills and instead send it AD plants.* This allows the biogas produced from the AD process to be captured and utilized as a renewable energy source, rather than the methane being released from the landfill.

3.1.4.2. Landfill Gas Emissions Model for calculating landfill gas production potential

This study employed the Landfill Gas Emissions Model (LandGEM) [82], a software program developed by the U.S. Environmental Protection Agency (EPA), to estimate the future potential of landfill gas (LFG).

LandGEM serves as an automated estimation tool for various gas and pollutant emissions from municipal solid waste (MSW) landfills. These emissions include total landfill gas, methane, carbon dioxide, nonmethane organic compounds (NMOCs), and individual air pollutants. It is an excel-based model that allows users to input landfill characteristics, determine model parameters, select gases or pollutants, and enter waste acceptance rates to estimate landfill gas emissions. LandGEM can be employed with site-specific data or default parameters when specific data are unavailable.



Have Model Calculate Closure Year? ○ Yes ● No

Waste Design Capacity: megagrams

Methane Generation Rate, k ($year^{-1}$): CAA Conventional - 0.05

Potential Methane Generation Capacity, L_0 (m^3/Mg): CAA Conventional - 170

NMOC Concentration (ppmv as hexane): Inventory No or Unknown Co-disposal - 600

Methane Content (% by volume): CAA - 50% by volume

Default pollutant parameters are currently being used by model.

Gas / Pollutant #1: Total landfill gas

Gas / Pollutant #2: Methane

Gas / Pollutant #3: Carbon dioxide

Gas / Pollutant #4: NMOC

Input Units: Mg/year

Year	Input Units (Mg/year)	Calculated Units (short tons/year)
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		

Figure 18. The interface of LandGEM software program

This study uses existing research (literature review) to determine the values of the required parameters used to estimate LFG production potential in Türkiye.

These parameter values are presented in Table 16 and are consistent with those used in similar studies conducted in the country.

Table 16. Parameters used in the LandGEM program [82]

Model Parameters	**Unit**	**Value**
Methane Generation Rate	k (year^{-1})	0.05
Potential methane generation capacity	Lo (m^3/ Mg)	100
NMOC Concentration	ppmv as hexane	600
Methane content	% by volume	50%

The LandGEM model utilizes a first-order decomposition rate equation (Equation [7]) to quantify methane production potential from the decomposition of landfilled waste [83].

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{J=0.1}^{1} kLo \left(\frac{Mi}{10}\right) e^{-ktij}$$

[7]

Where,

- Q_{CH4} = annual methane generation from landfill area in the year of the calculation (m3/year)
- i = 1 year time increment
- n = (year of the calculation) - (initial year of waste acceptance)
- j= 0.1-year time increment
- k= methane generation rate from landfill area (year^{-1})
- Lo = potential methane generation capacity from landfill area (m^3/Mg)
- Mi = mass of waste accepted by landfill area in the i_{th} year (Mg)

- t_{ij}= age of the jth section of waste mass Mi accepted in the i_{th} year (decimal years, e.g., 3.2 years)

As 2006 was the first year of LFG production in Türkiye (Ankara-Mamak Landfill Area), the collected waste data between 2006 and 2020 is entered into the LandGEM model. The quantity of mixed waste for the 2021-2050 period sent to LFG plants without biodegradable separation varies according to scenario structures. Electricity generation amount from LFG plant is calculated by using Equation [8].

$$EP_{(LFG)} = \frac{(\mathrm{CH4}_{(LFG)} \times \mathrm{E_{ff}} \times \mathrm{LHV_{CH4}} \times \lambda \times (1 - \mathrm{f_{ox}}) \times \mathrm{CF})}{3.6}$$

[8]

Where; E_{ff}" represents the electricity generation efficiency of the specific conversion device used in the process. "LHV_{CH4}" stands for the lower heating value of methane, while "CF" refers to the capacity factor. "λ" signifies landfill gas collection efficiency, and "f_{ox}" represents the oxidation factor in the landfill.

3.1.4.3. Calculation of biogas production potential from separated and sorted OFMSW

The remaining portion of OFMSW, which would have otherwise been sent to landfills for LFG production, will be diverted to AD and/or composting plants at varying quantities based on the different scenarios outlined in the study. Consequently, the methane production yield is expected to increase significantly due to the implementation of MBT units. Table 17 provides the biogas characteristics of diverted OFMSW [84].

Table 17. Biogas production characteristic from diverted OFMSW [84]

Parameters	Value	Unit
Total Solids (TS)	35.6%	at wet basis
Volatile Solids (VS)	94.9 %	of TS
Methane Yield	415	m^3 / Mg of VS

The theoretical potential biogas/biomethane production from OFMSW was estimated by taking into account several coefficient factors using the Equation [9]:

$$TBP = OFMSW \times TS \times VS \times SMY \tag{9}$$

Where TBP is the theoretical potential of biomethane production (m3/year), OFMSW is the total amount of the organic waste (ton/year), TS is the ratio of total solid of diverted OFMSW (%), and VS is the ratio of volatile solids in total solids (% of TS), SMY is the specific methane yield (m3 /MgVS).

Equation [5] and Equation [6] were used to directly calculate the electrical energy potential and installed capacity of biogas CHP plants fueled by OFMSW.

3.1.5. Municipal Wastewater Treatment Sludge

Sewage sludge is a byproduct of municipal wastewater treatment that can pose health risks due to the presence of pathogens, but it also has potential as a renewable energy resource. AD is the most extensively used sludge resource recovery method, as it can generate energy-rich biogas while reducing the sludge volume. Co-digestion with food waste can further boost biomethane production. Incineration can recover energy from the sludge's high calorific content, which is comparable to lignite or biomass. The energy can be used to generate heat or electricity. Sludge can be co-incinerated with coal or organic waste to recover energy, though the sludge composition can impact the process efficiency and product purity. Pyrolysis and gasification processes can potentially offer improved energy capture efficiencies and reduced environmental impact compared to conventional methods, though they face challenges related to sludge composition. Other options like supercritical oxidation, hydrothermal treatment, and microbial fuel cells are also being explored for energy recovery from sewage sludge [85]. The selection of the most appropriate sludge-to-energy recovery method depends on factors like sludge composition, energy efficiency, environmental impact, and overall cost-effectiveness.

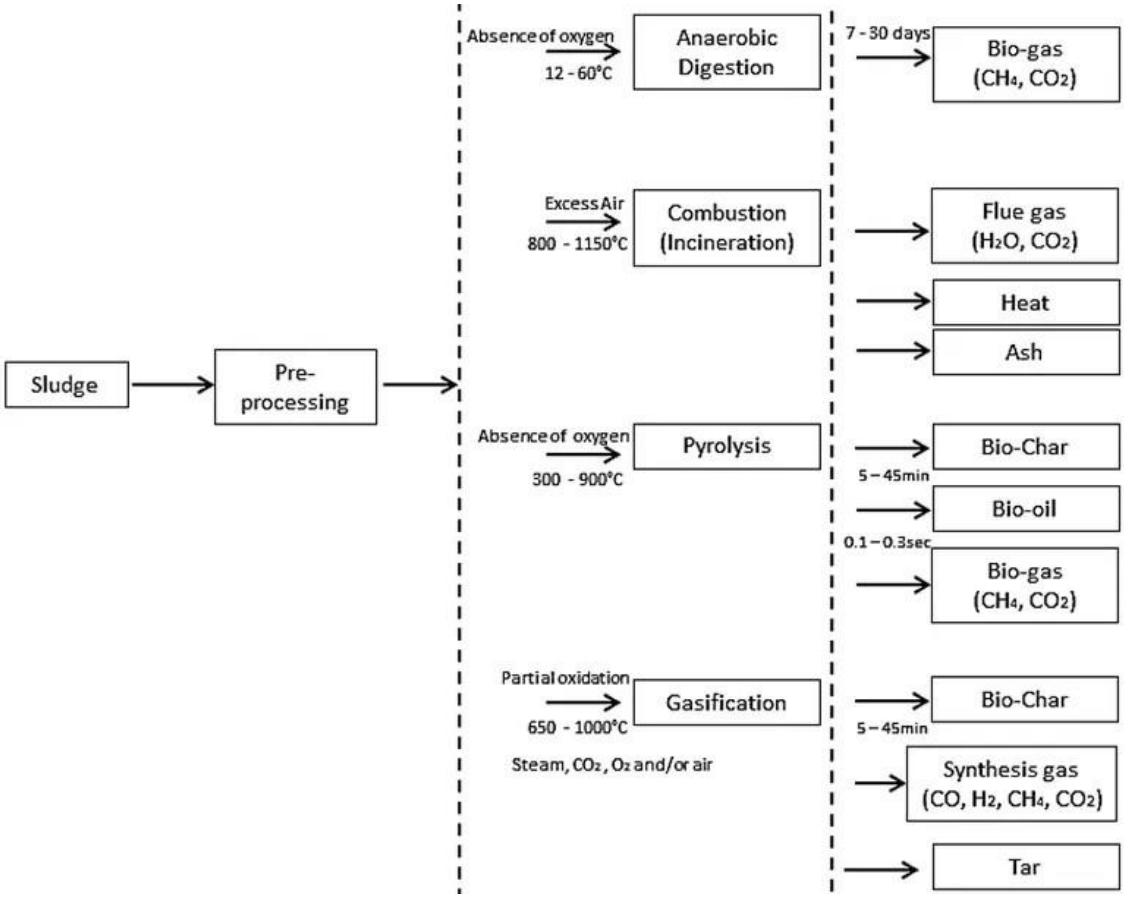


Figure 19. Potential sludge-to-energy routes [85]

Sludge stabilization is the key process for energy recovery in a WWTP. It involves different biological, chemical, and physical methods that can change the sludge's physical and chemical properties to make it easier to dewater [86]. Sewage sludge is divided into primary and secondary types. Primary sludge results from sedimentation processes, while secondary or activated sludge contains high levels of active microorganisms from biological treatment. Managing sewage sludge accounts for half the cost of wastewater treatment, necessitating effective strategies due to the significant volume generated [87].

The capacity of municipal wastewater treatment plants in Türkiye has indeed been increasing over the years. In 2016, these treatment plants had a capacity of approximately 5.94 billion m^3 per year. Moreover, the total number of wastewater treatment plants in Türkiye increased significantly, from 145 in 2002 to 1,068 with an approximate capacity of 6.4 billion m^3 per year [88]. The annual amount of wastewater treated in these plants was reported approximately as

4,358 million m^3. This growth in capacity reflects Türkiye's efforts to enhance its wastewater treatment capabilities to meet the increasing demands and environmental challenges associated with wastewater management.

These 1,068 WWTPs are categorized by their treatment methods: 60 physical, 593 biological, 223 advanced, and 192 natural. This diverse network serves the needs of 711 municipalities. The advanced treatment methods handle the majority of wastewater in Türkiye, processing 50.7% of the total volume. Biological treatment follows at 27.1%, with physical treatment at 21.9%, and natural methods contributing a minimal 0.3% (Figure 20).

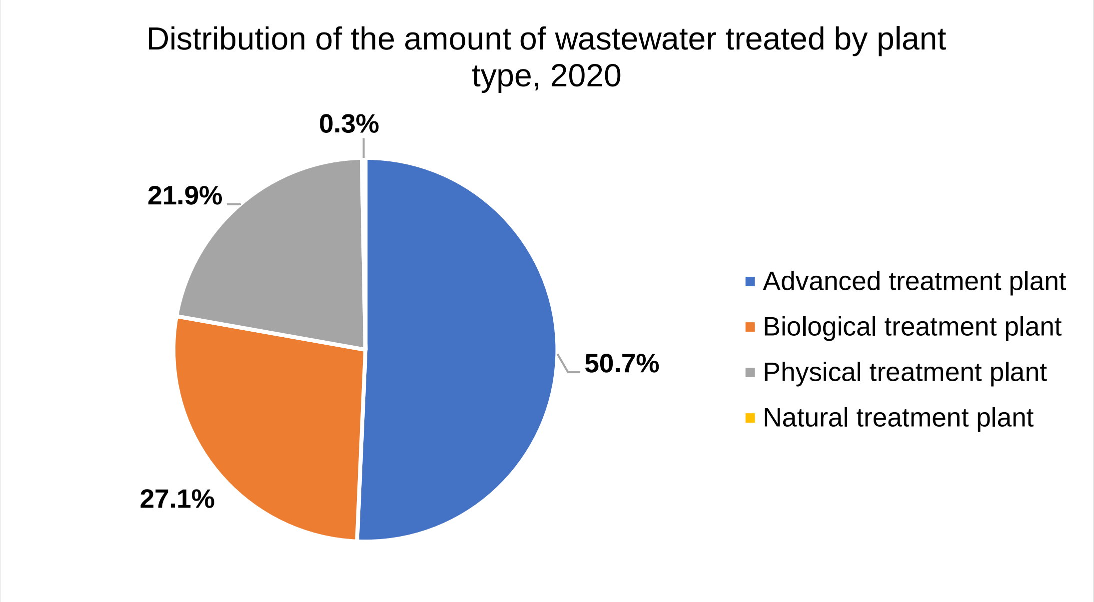


Figure 20. Wastewater Treatment by Plant Type in Türkiye (2020) [89]

By 2020, an impressive 91% of Türkiye's population had access to a municipal sewerage network. In addition, 73.3% of the population was served by a municipality with a WWTP. This means that 77.7% of the total population living in municipalities had access to wastewater treatment [89]. Moreover, the average daily wastewater discharge per person connected to the urban wastewater network was determined as 189 L per day in 2020 (Table 18).

Table 18. Data on municipal wastewater treatment of Türkiye [89]

Indicator	2001	2006	2010	2016	2020
Population (million people)	65.60	69.73	73.72	79.81	83.61
Municipal Population (million people)	53.41	58.58	61.57	74.91	78.92
Municipal population served by sewerage system (million people)	43.03	50.86	54.08	67.28	71.91
Municipal population served by WWTPs (million people)	18.46	29.64	38.06	56.02	61.29
Overall Municipal wastewater, billion m3	2.30	3.37	3.58	4.50	4.96
Per capita municipal wastewater, liters/capita-day	146.5	181.4	181.7	183.4	189.0
Rate of Treated Wastewater in Municipal Sewerage System	51.89%	63.57%	75.91%	85.40%	87.87%
Treated Municipal Wastewater, billion m^3	1.19	2.14	2.72	3.84	4.36

3.1.5.1. Forecasting municipal wastewater treatment sludge potential

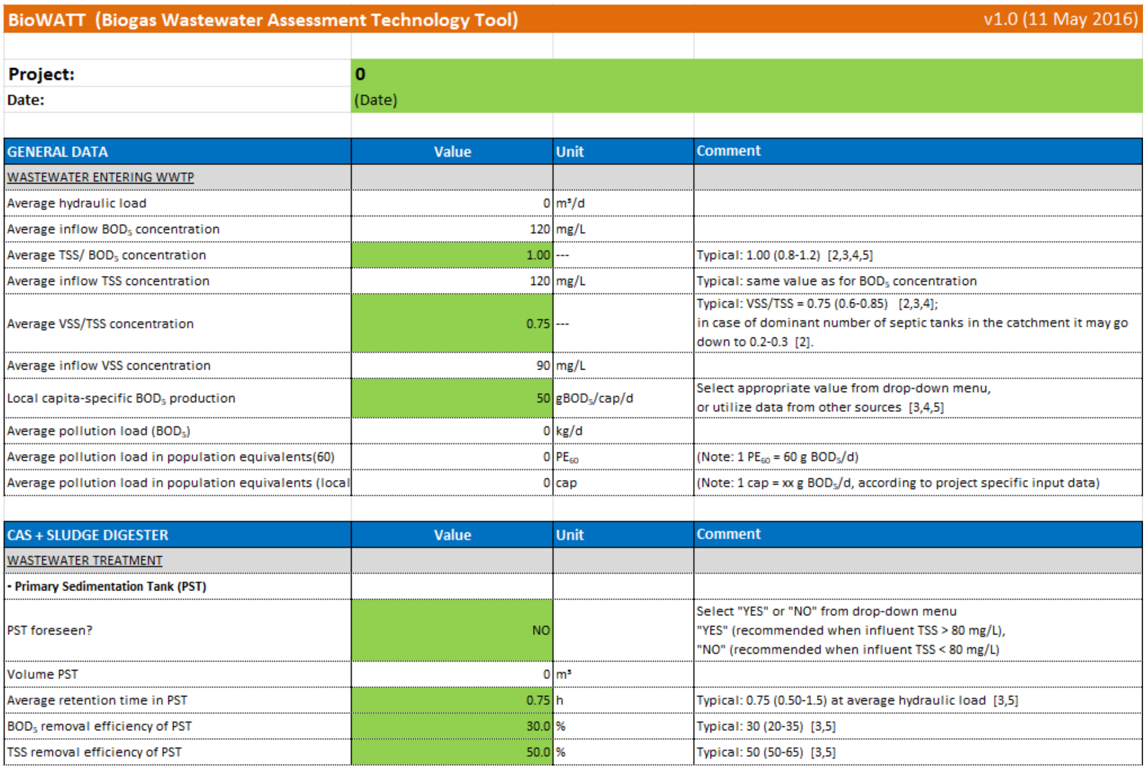
This study explores the potential for generating biogas from sewage sludge using AD plants. In recent years, there have been efforts to increase the utilization of wastewater treatment sludge for bioenergy production in Türkiye. Some municipalities have installed AD systems at their WWTPs to convert sludge into biogas. Despite these initiatives, the utilization of sludge for bioenergy production is not yet widespread in Türkiye, indicating untapped potential in this area.

The methodology for estimating biogas production potential from sewage sludge over the projection period involves several steps.

- Initially, population forecasts and municipal population proportions were used to project the country's total wastewater production, considering data from TURKSTAT [89] and growth trends. By combining these forecasts with data on the population, served by municipal sewerage systems and WWTPs, the population expected to benefit from these services in the projection period was determined.
- A regression analysis was then employed to estimate per capita wastewater production, using the projected population served by sewerage systems. This allowed for the calculation of wastewater production for the municipal population.
- Next, the volume of treated wastewater was estimated through multiple regression analysis, considering both the population served by WWTPs and the municipal wastewater volume as independent variables. Additionally, data on WWTP technology distribution from TURKSTAT [89] played a crucial role in estimating the future distribution, particularly for plants collecting sludge for biogas production.
- The proportion of biological treatment in the total treated wastewater was estimated through trend analysis.
- Following the estimating the amount of wastewater that will be treated by biological treatment plants, these annual wastewater volumes were then entered into the Biogas Wastewater Assessment Technology Tool (BioWATT) [90]. This software tool is used to estimate the biogas production potential from the sewage sludge generated during the treatment process.

3.1.5.2. Biogas Wastewater Assessment Technology Tool for calculating biogas production potential from sewage sludge

The BioWATT is a excel-based tool, was developed by the Global Methane Initiative and the WorldBank Group [90]. For municipalities and organizations seeking to explore the potential of converting wastewater into a renewable energy source, BioWATT offers a valuable and efficient tool. The tool is designed to provide a quick and preliminary assessment of wastewater-to-energy projects, empowering decision-makers with key insights before committing to a full-scale feasibility study.



BioWATT (Biogas Wastewater Assessment Technology Tool) v1.0 (11 May 2016)

Project:	**0**
Date:	(Date)

GENERAL DATA	Value	Unit	Comment
WASTEWATER ENTERING WWTP			
Average hydraulic load	0	m^3/d	
Average inflow BOD_5 concentration	120	mg/L	
Average TSS/ BOD_5 concentration	1.00	---	Typical: 1.00 (0.8-1.2) [2,3,4,5]
Average inflow TSS concentration	120	mg/L	Typical: same value as for BOD_5 concentration
Average VSS/TSS concentration	0.75	---	Typical: VSS/TSS = 0.75 (0.6-0.85) [2,3,4]; in case of dominant number of septic tanks in the catchment it may go down to 0.2-0.3 [2].
Average inflow VSS concentration	90	mg/L	
Local capita-specific BOD_5 production	50	$gBOD_5/cap/d$	Select appropriate value from drop-down menu, or utilize data from other sources [3,4,5]
Average pollution load (BOD_5)	0	kg/d	
Average pollution load in population equivalents(60)	0	PE_{60}	(Note: 1 PE_{60} = 60 g BOD_5/d)
Average pollution load in population equivalents (local	0	cap	(Note: 1 cap = xx g BOD_5/d, according to project specific input data)

CAS + SLUDGE DIGESTER	Value	Unit	Comment
WASTEWATER TREATMENT			
• Primary Sedimentation Tank (PST)			
PST foreseen?	NO		Select "YES" or "NO" from drop-down menu "YES" (recommended when influent TSS > 80 mg/L), "NO" (recommended when influent TSS < 80 mg/L)
Volume PST	0	m^3	
Average retention time in PST	0.75	h	Typical: 0.75 (0.50-1.5) at average hydraulic load [3,5]
BOD_5 removal efficiency of PST	30.0	%	Typical: 30 (20-35) [3,5]
TSS removal efficiency of PST	50.0	%	Typical: 50 (50-65) [3,5]

Figure 21. The interface of BioWATT tool [90]

One of the wastewater treatment technologies evaluated in the tool to estimate biogas production is conventional activated sludge (CAS) with anaerobic digester, which is most used technology in Türkiye. In a typical CAS plant with anaerobic digestion, wastewater influent first goes through a primary settling tank to remove suspended and floating solids. Sludge removed from the primary settling tank (primary sludge) is diverted to the anaerobic digester. After leaving the primary settling tank, the wastewater enters the activated sludge process (secondary treatment). First, the wastewater goes through a series of aeration tanks to remove biodegradable organics. In these tanks, microorganisms cultivated in the treatment process are kept in suspension, aerated, and in contact with the waste they are treating it. The result is a breakdown of organic matter into carbon dioxide, water, and other inorganic compounds. After the aeration tanks, the wastewater is sent to a secondary clarifier to settle out sludge (secondary sludge or waste activated sludge). Some of the secondary sludge is recycled to the beginning of the activated sludge process to provide the microorganisms that drive the treatment process, and the rest (excess sludge) is sent to the anaerobic digester. The anaerobic digester produces biogas from the primary sludge, and secondary sludge.

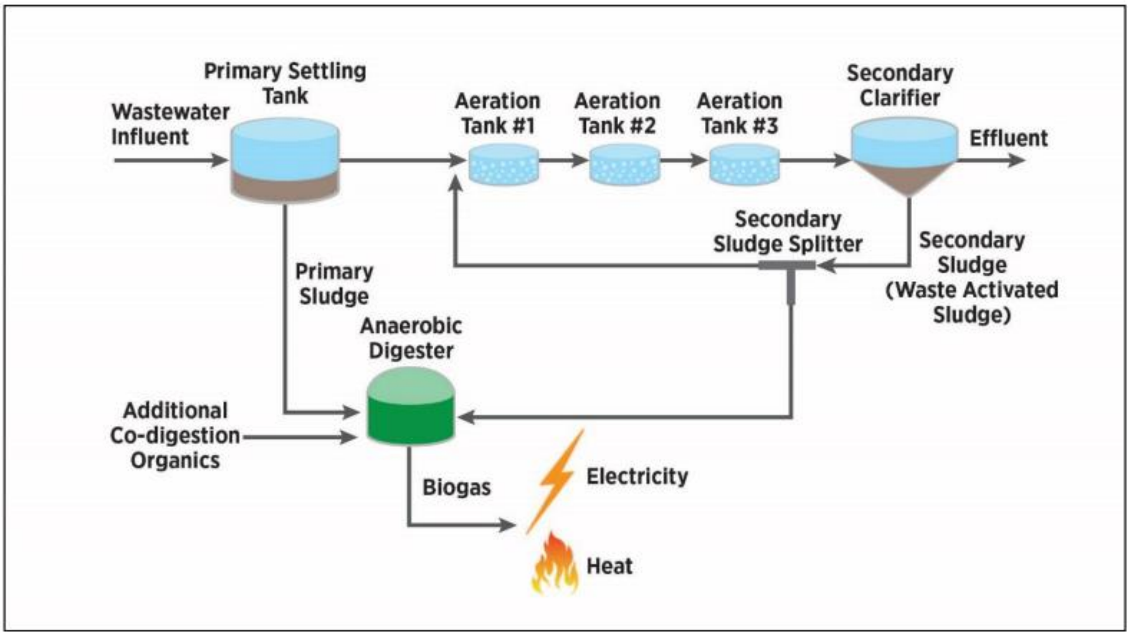


Figure 22. Conventional activated sludge plant with anaerobic digester [90]

In Table 19, a comprehensive set of parameters is presented for the estimation of biogas production from sewage sludge. The data encompasses influent characteristics, operational efficiencies, and sludge properties, all of which contribute to the modeling process.

Influent characteristics include the influent Biochemical oxygen demand (BOD_5) concentration (mg/L), which serves as an indicator of the biodegradable organic content. Additionally, the ratios of total suspended solids (TSS) to BOD_5 and volatile suspended solids (VSS) to TSS provide insights into the composition of solids within the wastewater.

Key operational efficiencies are incorporated, including the BOD_5 and TSS removal efficiencies of the primary settling tank (PST). These values quantify the efficacy of the initial treatment stages in eliminating organic matter and solids.

Sludge characteristics and handling are also represented. Table 19 includes the percentage of dry solids (DS) in both primary sludge and waste activated sludge (WAS), along with the daily WAS production per unit of BOD_5 removed.

Furthermore, parameters specific to the anaerobic digestion process are included. The digester retention time and the percentage of VS destruction for both primary and waste activated sludge are presented. These factors directly influence the degree of organic matter biodegradation and the subsequent generation of biogas. Finally, the percentage of DS after sludge dewatering reflects the solids concentration achieved following treatment.

Table 19. Biogas production parameters from wastewater sludge [90]

Parameter	**Unit**	**Value**
Average inflow BOD_5 concentration	mg/L	300
Average TSS/ BOD_5 ratio	---	1
Average VSS/TSS ratio	%	0.75
BOD_5 removal efficiency of PST	%	30
TSS removal efficiency of PST	%	50
DS of primary sludge and WAS after thickening	%DS	3.5
Daily raw Waste Activated Sludge (WAS) production (DS)	$gDS/gBOD_5$	0.75
Digester retention time	days	20
Average primary sludge VS/VS ratio	% of VS	60
Average waste activated sludge VS/VS ratio	% of VS	40
DS after sludge dewatering	%DS	23

The methodology of forecasting biomass and bioenergy potential of each selected resource is summarized in Table 20.

Table 20. Methodology for forecasting biomass and bioenergy Potential

Biomass Resource	Statistical Method Used	Data/ Variable	Target
Crop residue			
Step 1. Forecasting Crop Demand	Multiple Regression	Population and GDP per capita growth	Crop production potential
Step 2. Forecasting Crop import/export	ARIMA	Last 20 years	
Step 3. Forecasting Crop Amount	Proportioning	Residue to Crop Ratio (RCR)	Crop residue production potential
Step 4. Calculating Energy Production Potential	Equation [2]	Crop residue production potential, RCR, Moisture content, Availability and Calorific value by crop type	Overall Energy potential crop residues
Firewood			
Step 1. Forecasting Productive Forest Land Area	ARIMA	Last 20 years forestland area	Roundwood production potential by tree type
Step 2. Forecasting Roundwood Production	Simple Regression	Productive forestland area	
Step 3. Forecasting roundwood usage purpose share	Last 5 year's Average share	Roundwood production	Share of firewood in overall production
Step 4. Calculating Energy Production Potential	Equation [3]	Firewood production potential, calorific value and moisture content by tree type	Overall energy potential of roundwood
Animal Manure			

Biomass Resource	**Statistical Method Used**	**Data/ Variable**	**Target**
Step 1. Forecasting Animal by-product demand	Multiple Regression	Population and GDP per capita growth	Animal by-product production potential
Step 2. Forecasting by-product import/export	ARIMA	Last 20 years	
Step 3. Forecasting Animal population	Multiplication	By-product production and by-product yield	Animal Manure Production Potential
Step 4. Forecasting Animal manure Amount	Proportioning	Average animal live Weight and average Manure Production by animal species	
Step 5. Forecasting Biogas Production Potential	Equation [4]	Table 14	Biogas Production Potential
Organic Fraction of Municipal Solid Waste			
Step 1. Forecasting total MSW production	Multiple Regression	Population and GDP per capita growth	Collected MSW production potential
Step 2. Forecasting collected MSW	ARIMA	Last 20 years collection rate	
Step 3. Forecasting collected OFMSW	Average share of organic waste	Collected MSW production potential	Collected OFMSW production potential
Step 4. Forecasting OFMSW management	Proportioning management type with specified end year rates by scenario	Collected OFMSW production potential	Landfilling rate for LFG production and MBT rate for biogas production

Biomass Resource	**Statistical Method Used**	**Data/ Variable**	**Target**
Step 5. Forecasting LFG production potential	LandGEM tool	Landfilling rate of the Collected MSW by scenario	Biogas&LFG Production Potential
Step 6. Forecasting Biogas Production Potential	Equation [9]	Rate of OFMSW sent AD plants by scenario	
Step 7. Calculating Electricity Potential of LFG	Equation [8]	Methane production potential via LFG	Electricity potential of LFG
Municipal Wastewater Treatment Sludge			
Step 1. Forecasting Türkiye's municipal population	ARIMA	Population projection	Biologically treated wastewater production potential
Step 2. Forecasting Türkiye's municipal population served by sewage system	Simple Regression	Municipal Population projection	
Step 3. Forecasting Türkiye's municipal population served by sewage and WWTP system	Simple Regression	Municipal Population served by sewage system projection	
Step 4. Forecasting per capita municipal wastewater amount	Simple Regression	Municipal Population served by sewage system projection	
Step.5 Forecasting municipal wastewater production potential	Multiplication	Municipal Population served by sewage system and per capita municipal wastewater amount	

Biomass Resource	Statistical Method Used	Data/ Variable	Target
Step 6. Forecasting treated wastewater production amount	Multiple Regression	Municipal population served by WWTPs and municipal wastewater production	
Step 7. Forecasting biologically treated wastewater amount	Lineer Trend (1994-2020)	Treated wastewater production	
Step 8. Forecasting sludge production potential	BioWATT tool	Biologically treated wastewater amount	Sludge production potential for biogas production
Step 9. Forecasting biogas production potential	BioWATT tool	Sludge production from Conventional Activated Sludge Technology	Biogas Production Potential

3.2. LEAP Modelling Structure

This study employs the LEAP, the Low Emissions Analysis Platform, tool [91] to develop the model. The LEAP tool is a scenario-based energy-environment modelling tool that enables comprehensive energy system analysis. LEAP's structure includes key components such as demand, transformation, and resources, organized hierarchically using a tree structure with different branches representing different types of data. The tool includes a Technology and Environmental Database (TED) that provides detailed information on energy technologies. LEAP facilitates scenario analysis, allowing the creation of self-consistent storylines of future energy system evolution under specific demographic, socio-economic, and policy conditions. It supports the modeling of energy production units, energy consumption sectors, and the calculation of greenhouse gas emissions and other pollutants. The tool allows the creation of alternative scenarios, policy assessments, and the evaluation of energy demand, social costs, benefits, and environmental impacts. LEAP is designed to analyze the interactions between different policies and measures, providing a comprehensive platform for energy policy, climate change mitigation and air pollution planning.

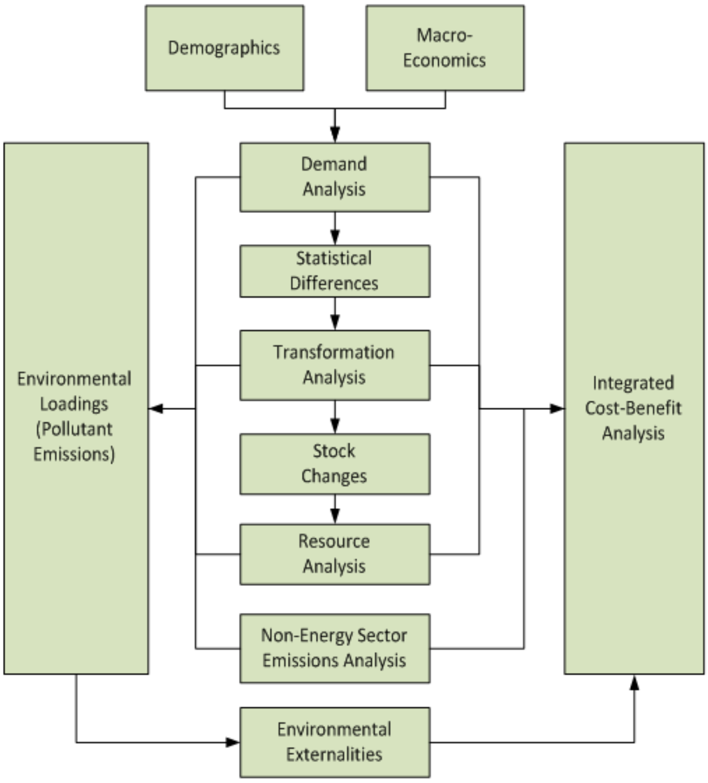


Figure 23. The structure of the LEAP's calculations [91]

3.2.1. Other Energy Modelling Tools

Energy modeling tools are essential for estimating future energy supply and demand at national or regional levels. These tools are used exploratorily, assuming changes in boundary conditions like economic growth, demography, or energy prices. They simulate technology investments and policy adoptions, influencing future supply and demand. Energy models serve four main purposes: power system analysis, operation decision support, investment decision support, and scenario identification. Two main approaches are used in energy modeling: bottom-up models, based on detailed technological explanations, and top-down models, which consider macroeconomic relations and long-term developments.

Energy and electricity models can be broadly categorized into three main types: simulation, optimization, and equilibrium models. Simulation models simulate an energy system according to certain equations and properties. They are generally bottom-up models that involve technical details of energy systems. These models allow assessing various system topologies and outcomes under different situations. Some of the models in this category are EnergyPlan and LEAP. Optimization models optimize a given quantity, typically related to system operation or expenditure. Most use linear programming with an objective function to maximize or minimize under constraints like balancing supply and demand. Mixed-integer linear programming can be used to optimize factors like the number of power plants or wind turbines. MARKet ALlocation model (MARKAL) and The Integrated MARKAL-EFOM System (TIMES) models are examples of optimization models. Equilibrium models consider the energy market as part of the overall economy and examine its interactions. They are used to evaluate the impact of economic policies. General equilibrium models consider the entire economy, endogenously assessing the balance of all sectors and describing economic indicators like GDP. Partial equilibrium models focus on balancing a single market, like electricity or energy, while ignoring the rest of the economy. Examples include General Equilibrium Model for Economy-Energy- Environment (GEM-E3) and Price-Induced Market Equilibrium System (PRIMES) [92].

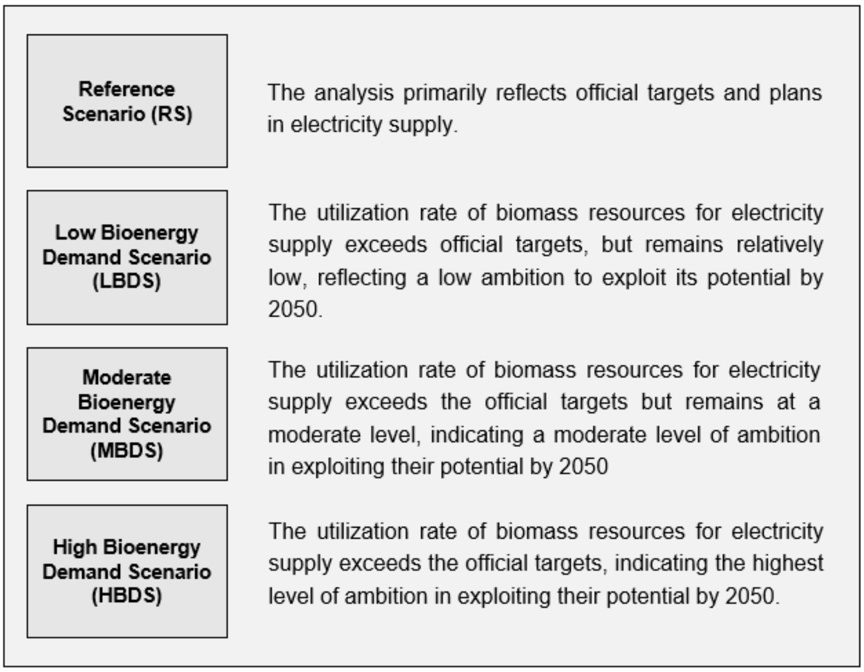
This study focuses on simulating electricity systems using defined equations and properties. This approach makes it possible to explore how the system behaves under different conditions. Fortunately, the LEAP modeling tool aligns perfectly with this objective.

3.2.2. Scenario Development

This study thoroughly explores Türkiye's electricity generation and usage, analysing factors like supply, demand, availability of resources, costs, and environmental impacts. The model encompassed a 30-year projection period divided into yearly timesteps, with a base year set in 2020 and a projection period spanning from 2021 to 2050, aiming to achieve complete electrification by 2050. Exogenous capacity data, representing the installed capacity of each electricity source (e.g., coal, solar, wind) for each year, was entered into the model. To prioritize renewables, dispatch rules were established. These rules assigned the lowest merit order value to renewable sources, signifying their preferential utilization in meeting electricity demand. Conversely, non-renewable sources like coal or gas plants received higher merit order values, positioning them as backup options to be activated only when renewable generation falls short of demand. Running the model provided critical outputs for this analysis. LEAP calculated the electricity demand for each sector within the 30-year timeframe. This analysis took into account sector-specific activity data, such as the projected number of households for the residential sector. In addition, electricity generation by source was determined for each year, showing the changing contribution of each source (coal, solar, wind, etc.) to the overall electricity mix. Capacity utilization data also provided valuable insights. By analyzing this data, it was possible to understand how often each power plant operated based on established dispatch rules that prioritized renewables. In essence, this methodology, supported by LEAP's capabilities, facilitated the estimation of long-term generation share while prioritizing renewable sources within a holistic energy system model.

The model incorporates various scenarios. A reference scenario (RS) that reflects Türkiye's official energy targets, encompassing long-term goals for electricity supply and three parent bioenergy demand scenarios (BDSs) that represent different levels of ambition for bioenergy use in electricity supply compared to the RS. In essence, the model provides alternative pathways for Türkiye's electricity future, with varying degrees of emphasis on bioenergy.

Each scenario was assessed in detail to ensure an accurate assessment of its potential. It is anticipated that there will be a gradual increase in biomass utilization over time, with the peak potential expected to be realized by 2050. The end-year utilization rates for each biomass resource were determined by considering current utilization rates and historical trends. The high BDS (HBDS) is the most optimistic, aiming to maximize the use of biomass. The low BDS (LBDS) takes a more cautious approach, predicting a lower overall utilization rate. The moderate BDS (MBDS) sits between the two, aiming for a balanced level of biomass use.



Reference Scenario (RS)	The analysis primarily reflects official targets and plans in electricity supply.
Low Bioenergy Demand Scenario (LBDS)	The utilization rate of biomass resources for electricity supply exceeds official targets, but remains relatively low, reflecting a low ambition to exploit its potential by 2050.
Moderate Bioenergy Demand Scenario (MBDS)	The utilization rate of biomass resources for electricity supply exceeds the official targets but remains at a moderate level, indicating a moderate level of ambition in exploiting their potential by 2050
High Bioenergy Demand Scenario (HBDS)	The utilization rate of biomass resources for electricity supply exceeds the official targets, indicating the highest level of ambition in exploiting their potential by 2050.

Figure 24. Definition of each developed scenario

3.2.3. Electricity Demand

In the model, the analysis of electricity demand was conducted through a sectoral approach. The energy balance sheets [19] of the Ministry of Energy and Natural Resources (MENR) of Türkiye, which provide annual sectoral electricity supply and demand figures, were used as the data source. The model introduced five distinct sectors for demand estimations, namely residential, services, industry, agriculture, and transport.

Among these sectors, the industry sector exhibited the highest electricity demand, accounting for approximately 45% of the total demand in 2020, followed by the services, residential, agriculture, and transport sectors, respectively. To project their future demand, the sectoral approach is employed. This involved defining different activity levels for each sector in the model, which, in turn, is utilized to estimate the energy intensity of each sector and, ultimately, the corresponding electricity demand.

Each sector uses specific data and assumptions to project future electricity demand. Using the trend analysis method, the annual final electricity/energy intensity is estimated to determine the final energy consumption per unit of activity for each sector throughout the projection period. In the residential sector, the LEAP model integrates population projections and data on the average number of households and family sizes to calculate electricity demand per household. For the sectors of services, industry, and agriculture, a common methodology is used to estimate electricity demand. This is based on each sector's contribution to GDP and its correlation with electricity consumption, using the GDP growth rate as a reference. The transport sector exhibits relatively low electricity demand compared to other sectors. To predict its future electricity needs, the GDP forecast of the country is used as an indicator of the level of activity.

3.2.3.1. Forecasting electricity demand for the residential sector

In the residential sector, the model also incorporates population forecasts and average household number and family size data to determine per-household electricity demand. Through the Equation [10], the electricity demand of the sector is estimated over the projection period.

$$ED_{Re} = \sum_{t=2021}^{2050} (EI_{Ret} \times HN_t)$$

[10]

Where, ED_{Re} is the electricity demand of the residential sector, EI is the electricity intensity of the sector, HN_t is the household number and t is the time (year).

3.2.3.2. Forecasting electricity demand for the services, industry and agriculture sectors

The electricity demand for each of the three sectors, which are services, industry, and agriculture (Se,In,Ag) is estimated using a common methodology. This methodology is based on the sector's contribution to GDP and how it relates to the sector's electricity consumption, using the GDP growth rate as an indicator. Through the Equation [11], the electricity demand of these sectors is estimated over the projection period.

$$ED_{Se,In,Ag} = \sum_{t=2021}^{2050} \left(EI_{Se,In,Ag} \times GVA_{Se,In,Ag}\right)$$

[11]

Where, $ED_{Se,In,Ag}$ represents the electricity demand for a specific sector (Se, In, or Ag) from 2021 to 2050. $EI_{Se,In,Ag}$ denotes the electricity intensity of the specific sector (Se, In, or Ag), measuring how much electricity is consumed per unit of economic output. $GVA_{Se,In,Ag}$ represents the gross value added of the sector (Se, In, or Ag), indicating the sector's contribution to the overall GDP.

3.2.3.3. Forecasting electricity demand for the transport sector

The transport sector has relatively low electricity demand compared to the other sectors. Its future electricity demand is estimated using the country's GDP forecast as an activity level. A model is developed to link the sector's electricity demand to GDP. Through the Equation [12], the electricity demand of these sectors is estimated over the projection period.

$$ED_{Tr} = \sum_{t=2021}^{2050} (EI_{Trt} \times GDP_{Trt})$$

[12]

Where ED_{Tr} is the electricity demand of the transport sector, EI is the electricity intensity of the sector, GDP is the country's gross domestic product and t is the time (year).

3.2.4. Electricity Supply

The electricity of Türkiye has undergone significant expansion in parallel with economic growth and population increase. In order to maintain a reliable and sustainable energy supply, ambitious targets have been set with the objective of enhancing installed capacity and diversifying the energy mix.

The RS is formulated in alignment with the official targets set forth by the government of Türkiye and through the application of trend analysis, which is used to forecast the composition of the electricity supply. The primary reference for shaping the RS, particularly in terms of electricity supply projections, is the National Energy Plan (the Plan) [18] by the Türkiye’s MENR.

The objective of the Plan is to achieve a 65% share of renewable energy in the electricity capacity and 55% in electricity generation by 2035. As the Plan covers the period from 2020 to 2035, the capacity of each source in the RS is extended to 2050 by means of an analysis of trends and a focus on specific fuel sources. Furthermore, the BDSs are modified to give priority to bioenergy and to reduce reliance on coal and natural gas in the generation of electricity.

3.2.4.1. Exogenous Capacity

In LEAP’s electricity generation module, there are two capacity variable types for power plants: exogenous and endogenous. Exogenous capacity, which users manually input, outlines the additional future capacity planned for the model. Users define both the timeline and the quantity of this future capacity for their scenarios. Conversely, endogenous capacity is generated by LEAP to fulfill the Planning Reserve Margin requirements when reserves fall short during a specific time period. This capacity type is calculated by the model, influenced by the user’s inputs and assumptions, rather than being directly chosen by the user. For this analysis, the exogenous capacities of each power plant are inputted into the model according to the scenario type over the forecast period. Table 21 presents the base year’s exogenous capacities for each power plant, as sourced from the TEİAS [21]. Please see Table A. 1 for last two decades electricity installed capacity of Türkiye by fuel type.

Table 21. Türkiye's 2020 installed power capacity by sources (MW) [21]

Fuel Type	**Installed Capacity**
Hard coal + Asphaltite +Imported coal	10,203
Lignite	10,120
Oil	312
Natural Gas	25,675
Waste Heat Recovery	380
Biomass	1,105
Hydraulic	30,984
Wind	8,832
Geothermal	1,613
Solar	6,667
Nuclear	-

3.2.4.2. Process Efficiency and Maximum Availability

Process Efficiency refers to the ratio of the useful output of a process to the input, measured in percentage. In electricity generation, it's the measure of how effectively a power plant converts fuel into electrical energy. The efficiency can vary greatly depending on the technology and fuel used. Maximum Availability is the measure of a power plant's ability to produce electricity when needed. It's defined as the amount of time a plant can operate at full or partial capacity over a certain period, expressed as a percentage. High availability is crucial for ensuring a reliable power supply. The default efficiencies power plants were obtained from various sources, and the sectoral experience was taken into account, as given in Table 22.

Table 22. Process efficiency of power plants and maximum availability

Power Plant	Process Efficiency %	Maximum Availability %
Hard Coal	42.1 [93]	80 [93]
Lignite	26.6 [93]	75 [93]
Natural Gas	54 [94]	60 [93]
Oil	48.74 [94]	80 [93]
Hydro	100 [93]	42 [93]
Wind	100 [93]	35 [93]
Geothermal	10.24 [94]	96,2 [94]
Solar	100 [93]	26,4 [94]
Nuclear	34.5 [94]	91 [94]
Solid Biomass CHP	35 [93]	85 [93]
Gas Biomass (Biogas) CHP	34 [93]	85 [93]
Waste Heat Recovery	23.82 [93]	90 [93]

3.2.4.3. Dispatch of Electricity Process

In the LEAP modeling tool, dispatch rules determine how energy processes are allocated to meet demand. In this study MeritOrderDispatch is used in order to promote renewable energy sources in a low-carbon electricity generation target. The Merit Order Dispatch Rule is used to simulate the dispatch of power plants to meet both annual demand and instantaneous demand for power in time slices of the year. Processes with the lowest merit order are dispatched first (base load) and those with the highest merit order are dispatched last (peak load). Merit order is defined for each time slice in a year, allowing processes to be dispatched differently in different seasons. Processes with equal merit order are dispatched together in proportion to their available capacity. In the context of promoting renewable energy sources in electricity generation, a merit order selection in a LEAP model could prioritize renewable energy sources by assigning them the lowest merit order value. This prioritization reflects the intention to promote the use of renewables over conventional fossil fuel-based generation.

Table 23. Applied merit order dispatch for electricity generation

Power Plant	Merit Order
Coal (Hard Coal and Lignite)	3
Natural Gas	2
Oil	3
Hydro	1
Wind	1
Geothermal	1
Solar	1
Nuclear	1
Biomass	1
Waste Heat Recovery	1

3.2.4.4. Environmental Assessment of Electricity Generation

This study employed the TED integrated within the LEAP modeling framework to assess the environmental impacts associated with electricity generation. TED offers a comprehensive dataset encompassing the technical characteristics, costs, and environmental implications of a diverse range of energy technologies, including established practices, cutting-edge advancements, and next-generation devices. Notably, TED incorporates quantitative data on technology characteristics and their environmental burdens, making it a valuable tool for environmental life cycle assessments within the electricity generation sector. Additionally, TED provides emission factors for a vast array of energy-consuming and producing technologies, enabling users to meticulously calculate the environmental loadings inherent within their modeled energy scenarios [94].

Table 24. Default GHG emission factors for stationary combustion [94]

Fuel Type/ GHG	Carbon Dioxide	Methane	Nitrous Oxide
	ton/ TJ	kg/ TJ	kg/ TJ
Hard Coal	92.64	1.0	1.5
Asphaltite	93.6	1.0	1.5
Lignite	99.11	1.0	1.5
Natural Gas	55.78	1.0	0.1
Oil	72.55	3.0	0.6
Solid Biomass	109.6 (Biogenic)	30.0	4.0
Gas Biomass (Biogas)	54.6 (Biogenic)	1.0	0.1

3.2.4.5. Cost Assessment of Electricity Generation

LEAP facilitates a comprehensive cost assessment of electricity generation by accounting for various cost components incurred by power plants. These cost categories encompass capital expenditures, fixed operation and maintenance (FOM) costs, variable operation and maintenance (VAROM) costs, and fuel costs. Capital costs represent the total investment required for construction and any other capitalized expenses associated with the power plant. Fixed O&M costs are independent of electricity production and are incurred regardless of the plant's operational state. Conversely, VAROM costs are directly proportional to the electricity generated and increase with each unit of electricity produced. Fuel costs represent the ongoing expense of acquiring the fuel source that powers the plant's electricity generation.

LEAP calculates the total cost of electricity generation by determining the net present value (NPV) of all system costs across the entire analysis period. This calculation is based on the methodology outlined in Equation [13].

$$TC = \sum_{t=1}^{Nt} \sum_{p} (Cc * Cap_t + FOM_t \cdot Ca_t + VAROM_t \cdot P_t + FC_t) * \frac{1}{(1+d)^t}$$

[13]

Where, TC is total cost, Nt is the total years from 2020 through to 2050, p is the process (technology), d is the discount rate, Cc is the initial capital cost, Cap_t is the capacity in year t, FOM_t is the fixed operation and maintenance costs in year t, $VAROM_t$ is the variable operation and maintenance costs in year t, P_t is the output power in year t, and FC_t is the fuel cost in year t, t is the time.

In this study, for the costs of the different technologies, cost data specific to the country context [95] was used in the calculations.

Table 25. Cost data for electricity generation [95]

Fuel Type	**Overnight capital cost**	**Fixed O&M cost**	**Variable O&M cost**	**Fuel Cost**
	US$/ kW	**US$/ kW**	**US$/ MWh**	**US$/ MWh**
Hard Coal	1100	35	3	29.2
Lignite	1200	40	4	30.3
Natural Gas	750	18	1	47.5
Hydro	1750	85	0.1	58.8
Wind	900	15	0.5	-
Geothermal	3750	40	10	-
Solar	650	15	0	-
Nuclear	7500	90	5	12.1
Oil	900	1160	2.66	-
Waste Heat Recovery	900	-	2.66	-
Biomass	2500	90	1	41.5

4. RESULTS AND DISCUSSION

The objective of this study is to estimate the prospective potential of the most utilized, sustainable and predictable biomass resources in Türkiye, which have been identified as a means of estimating the long-term bioelectricity production potential.

In order to determine these biomass potentials across diverse sectors and types, a range of statistical techniques and biomass-specific calculation instruments were utilized, as outlined in section 3.1. By evaluating the identified potentials for different amounts of bioenergy production under different biomass demand scenarios developed as outlined in this section, the bioenergy potential of Türkiye for electricity generation was calculated, as well as the contribution of this potential to Türkiye's long-term low-carbon electricity generation.

This chapter presents the results of biomass potential for each selected biomass resource and their bioenergy potentials over the projection period. The bioenergy potentials for solid/dry biomass resources, which include crop residues and firewood from roundwood, are expressed in petajoules. In the case of wet biomass, which encompasses animal manure, OFMSW, and sewage sludge, the potential for biogas production in cubic meters of methane is provided.

Subsequently, the LEAP modelling results are presented, which encompass the projection of key assumptions, the forecasting of electricity demand, and the projection of electricity supply for the four developed scenarios.

4.1. Biomass and Bioenergy Potential Forecasting Results

The biomass and bioenergy potential of selected biomass resources until 2050, as determined by the methodology outlined in Chapter 3, is presented below.

4.1.1. Crop Residues

This section explores the results of projected growth in crop production and the corresponding increase in crop residue production. It analyzes the potential for bioenergy production from various types of residues, highlighting their significance in future energy scenarios.

4.1.1.1. Forecasting result of crop production potentials

The study covers a comprehensive range of crops, including grains, oilseeds, tubers, fiber crops, nuts, and various fruits. According to the projection results, major grains like wheat and barley are expected to see steady growth, with maize showing a significant increase in production from 6,501.3 thousand tons in 2020 to 18,747.4 thousand tons by 2050. Among oilseeds, sunflower and soybean show notable increases, reflecting the growing demand for vegetable oils and protein. Cotton production is also projected to rise substantially. Table 26 outlines projected production potentials of selected crops and their associated residues from 2020 to 2050, along with the estimated energy potential of these residues (refer to Table A. 8 and Table A. 9 in Appendix 3 for annual production forecasts of crops).

4.1.1.2. Forecasting result of energy production potential by crop residue type by scenario

The energy potential of residues, such as straw, stover, husk, and pruning, generally correlates with the production volumes. Maize stover stands out with a significant energy potential increase from 126.3 PJ in 2020 to 364.2 PJ in 2050, highlighting its importance as a bioenergy source. Residues from fruit crops, particularly pruning from olive and grape cultivation, also contribute notably to the total energy potential. The total energy potential from all listed agricultural residues increases from 535.03 PJ in 2020 to 1140.20 PJ in 2050, reflecting a growing opportunity for bioenergy utilization (Table 26).

Different biomass energy utilization scenarios illustrate varying levels of bioenergy adoption. The LBDS projects up to 60% utilization by 2050, while the HBDS anticipates full (100%) utilization. These scenarios underscore the potential for significant increases in biomass energy contributions to the overall energy mix.

Table 26. Crop production forecast and energy production potentials of crop residues with utilization rates for each scenario until 2050

Crop Type	Residue Type	Parameter	2020	2025	2030	2035	2040	2045	2050
Wheat	Wheat	Production (thousand tons)	20,489.8	24,326.3	25,777.6	27,067.1	27,873.3	28,104.2	27,794.8
	Straw	Energy Potential (PJ)	49.4	58.7	62.2	65.3	67.2	67.8	67.0
Barley	Barley	Production (thousand tons)	8,300.4	8,232.9	8,640.1	8,957.6	9,523.9	10,463.5	11,746.2
	Straw	Energy Potential (PJ)	22.0	21.9	22.9	23.8	25.3	27.8	31.2
Oats	Oats	Production (thousand tons)	314.9	227.9	221.4	214.2	210.8	213.0	220.9
	Straw	Energy Potential (PJ)	0.9	0.6	0.6	0.6	0.6	0.6	0.6
Rye	Rye	Production (thousand tons)	295.4	358.5	376.6	392.1	404.8	415.0	422.6
	Straw	Energy Potential (PJ)	0.7	0.9	0.9	1.0	1.0	1.0	1.0
Maize	Maize	Production (thousand tons)	6,501.3	9,391.8	11,392.7	13,202.9	15,003.3	16,865.6	18,747.4
	Stover	Energy Potential (PJ)	126.3	182.4	221.3	256.5	291.4	327.6	364.2
	Cob		19.1	27.5	33.4	38.7	44.0	49.4	55.0
Rice	Rice	Production (thousand tons)	980.6	1,067.7	1,142.6	1,212.5	1,232.0	1,186.3	1,079.7
	Straw	Energy Potential (PJ)	13.3	14.4	15.4	16.4	16.7	16.0	14.6
	Husk		3.6	3.9	4.1	4.4	4.5	4.3	3.9
Sunflower	Sunflower	Production (thousand tons)	2,069.9	2,497.5	2,916.7	3,299.1	3,625.4	3,890.8	4,092.9
	Stalk	Energy Potential (PJ)	32.5	39.3	45.8	51.9	57.0	61.2	64.3
	Head		31.0	37.4	43.7	49.4	54.3	58.3	61.3

Crop Type	Residue Type	Parameter	2020	2025	2030	2035	2040	2045	2050
Soybean	Soybean	Production (thousand tons)	155.3	267.3	329.3	385.9	438.2	486.7	530.8
	Stalk	Energy Potential (PJ)	3.6	6.2	7.7	9.0	10.2	11.4	12.4
Dry bean	Dry bean	Production (thousand tons)	279.1	264.4	277.8	289.2	298.6	306.1	311.7
	Leaves	Energy Potential (PJ)	0.8	0.8	0.8	0.9	0.9	0.9	0.9
Chickpea	Chickpea	Production (thousand tons)	629.2	662.1	695.5	724.2	747.7	766.4	780.6
	Straw	Energy Potential (PJ)	1.9	2.0	2.1	2.2	2.3	2.3	2.4
Groundnut	Groundnut	Production (thousand tons)	215.8	232.4	279.0	321.2	362.0	402.9	442.8
	Straw	Energy Potential (PJ)	4.8	5.1	6.2	7.1	8.0	8.9	9.8
Sugar beet	Sugar beet	Production (thousand tons)	23,025.1	19,817.8	20,817.9	21,676.3	22,380.0	22,940.5	23,365.5
	Leaves	Energy Potential (PJ)	1.9	1.6	1.7	1.8	1.8	1.9	1.9
Cotton	Cotton	Production (thousand tons)	1,774.5	2,357.9	2,500.3	2,610.7	2,835.4	3,227.1	3,772.0
	Stalk	Energy Potential (PJ)	145.3	193.1	204.7	213.8	232.1	264.2	308.8
Hazelnut	Hazelnut	Production (thousand tons)	665.0	694.6	729.7	759.8	784.4	804.1	819.0
	Shell	Energy Potential (PJ)	1.1	1.2	1.2	1.3	1.3	1.4	1.4
	Pruning		20.3	21.2	22.2	23.1	23.9	24.5	24.9
Olives	Olives	Production (thousand tons)	1,316.6	1,975.7	2,242.0	2,461.2	2,866.8	3,541.8	4,461.0
	Pomace	Energy Potential (PJ)	8.8	13.2	14.9	16.4	19.1	23.6	29.7
	Pruning		8.7	13.1	14.9	16.3	19.0	23.5	29.6
Grapes	Grapes	Production (thousand tons)	4,208.9	4,714.8	4,952.7	5,156.9	5,324.3	5,457.7	5,558.8
	Pruning	Energy Potential (PJ)	14.0	15.7	16.5	17.2	17.7	18.2	18.5
Apples	Apples	Production (thousand tons)	4,300.5	3,542.6	3,648.9	3,754.0	3,747.2	3,597.6	3,319.2
	Pruning	Energy Potential (PJ)	7.0	5.8	5.9	6.1	6.1	5.8	5.4
Mandarin	Mandarin	Production (thousand tons)	1,585.6	1,872.4	2,303.3	2,689.3	3,117.3	3,619.3	4,181.3

Crop Type	**Residue Type**	**Parameter**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	Pruning	Energy Potential (PJ)	3.9	4.6	5.6	6.6	7.6	8.9	10.2
Orange	Orange	Production (thousand tons)	1,334.0	1,901.8	2,001.3	2,087.6	2,152.4	2,194.3	2,214.7
	Pruning	Energy Potential (PJ)	4.0	5.8	6.1	6.3	6.5	6.7	6.7
Lemon	Lemon	Production (thousand tons)	1,188.5	1,017.0	1,084.9	1,146.3	1,180.6	1,181.6	1,151.3
	Pruning	Energy Potential (PJ)	3.0	2.6	2.7	2.9	3.0	3.0	2.9
Peach	Peach	Production (thousand tons)	892.0	911.0	1,034.2	1,144.8	1,250.1	1,353.5	1,453.1
	Pruning	Energy Potential (PJ)	3.1	3.2	3.6	4.0	4.4	4.7	5.1
Apricot	Apricot	Production (thousand tons)	833.4	800.3	840.7	875.4	903.8	926.4	943.6
	Pruning	Energy Potential (PJ)	1.5	1.5	1.5	1.6	1.7	1.7	1.7
Cherry	Cherry	Production (thousand tons)	724.9	857.0	1,011.4	1,152.5	1,274.0	1,374.6	1,453.3
	Pruning	Energy Potential (PJ)	1.4	1.7	2.0	2.3	2.5	2.7	2.9
Pear	Pear	Production (thousand tons)	545.6	584.1	648.4	705.7	760.9	816.3	871.0
	Pruning	Energy Potential (PJ)	1.1	1.2	1.3	1.4	1.5	1.6	1.7
Total Energy Potential (PJ)			535.03	686.30	772.25	848.06	931.64	1029.84	1140.20
Biomass Energy Utilization by Scenario		LBDS	4%	7%	11%	17%	26%	39%	60%
		MBDS	4%	8%	12%	20%	31%	50%	80%
		HBDS	4%	8%	13%	22%	36%	60%	100%

Crop production forecasts predict significant increases for maize, sunflower, soybean, and cotton by 2050. The energy potential from these residues is also projected to rise substantially, with maize stover exhibiting the most significant growth. Fruit crop residues, particularly from olive and grape cultivation, offer additional potential. The total energy potential from agricultural residues could reach 1140.20 PJ by 2050. Different biomass utilization scenarios highlight the possibility of significantly increasing bioenergy's contribution to the overall energy mix. With full utilization (100% scenario), crop residues could provide a substantial renewable energy source for Türkiye in the future.

4.1.2. Firewood

Firewood, traditionally a major fuel source, represents a unique case in the field of biomass energy. This section examines the results of Türkiye's projected firewood production potential and its expected role in future energy scenarios.

4.1.2.1. Forecasting result of productive forest land area

To assess firewood production potential, this study first projected Türkiye's productive forest area by 2050 using the ARIMA method. In 2021, the productive forest area stood at 13.5 million hectares, with projections indicating an increase to 16.3 million hectares by 2050. Conversely, degraded forest area has exhibited a decline over the past two decades, decreasing from 9.6 million hectares in 2021 to 8.7 million hectares by 2050. Figure 25 illustrates the forecasted trends for both productive and degraded forest areas until the end of the projection period.

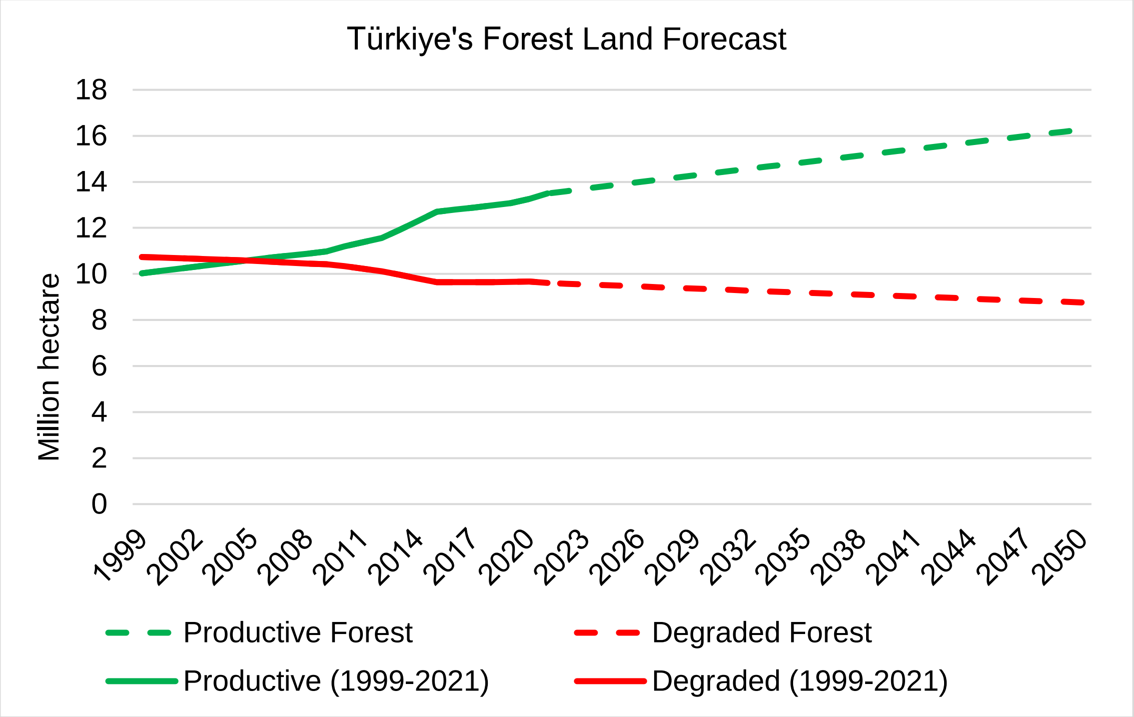


Figure 25. Türkiye’s forest land area forecast until 2050

4.1.2.2. Forecasting result of roundwood production potential by tree type

Regression analysis estimated Türkiye's total roundwood production to reach at 46 million m³ by 2050, with coniferous trees contributing a significant 77% share. Notably, industrial use dominates consumption at 86%, exceeding energy-related applications. Firewood consumption patterns have shifted over the past two decades, reflecting a decline in rural reliance. In 2021, coniferous firewood comprised only 10% of the total, while broad-leaved firewood accounted for 26%. This represents a substantial decrease from 2000 levels, where coniferous and broad-leaved firewood consumption stood at 27% and 74%, respectively. This trend coincides with Türkiye's industrial growth, which has driven up demand for roundwood resources.

To obtain a more robust estimate of firewood allocation within total production, a five-year rolling average approach was used in the analysis. This approach helps to mitigate fluctuations and provide a more reliable results. The analysis projected a potential production of 4.2 million m³ of coniferous firewood and 3.1 million m³ of broad-leaved firewood by 2050 (refer to Table A. 12 for firewood production potential forecast from roundwood by tree type). This downward trend suggests a gradual shift away from traditional firewood use in rural areas, likely due to factors such as urbanization, improved access to alternative energy sources, and government policies promoting sustainable forest management (Figure 27).

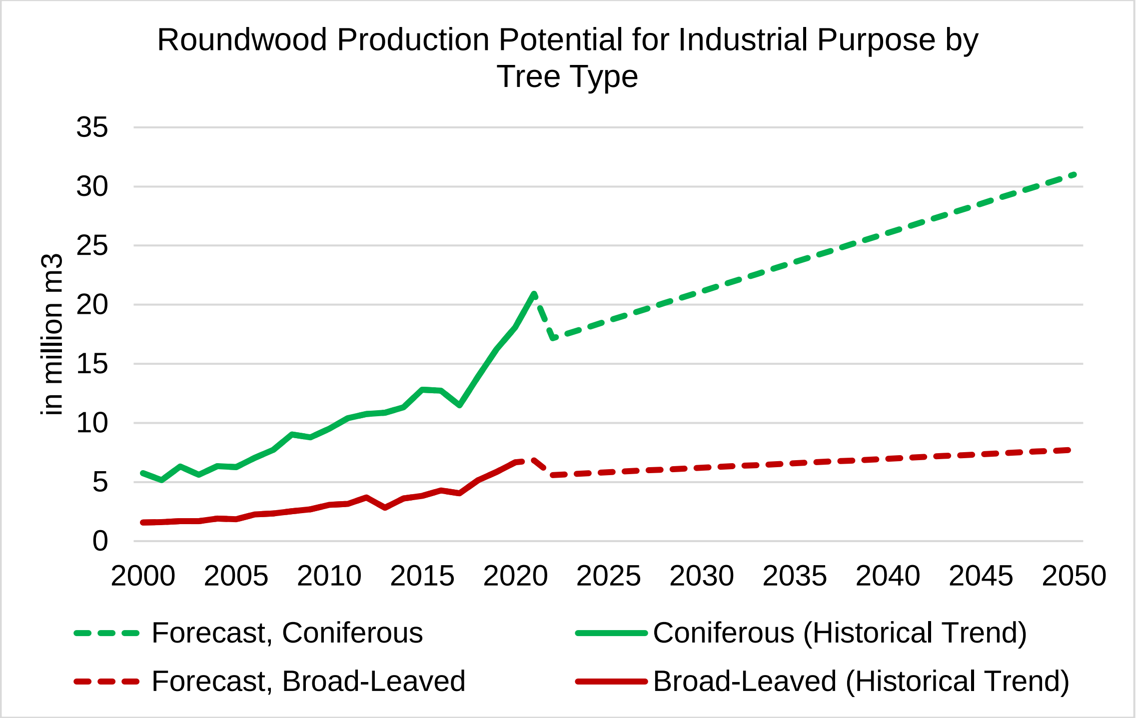


Figure 26. Forecasted industrial roundwood production by tree type

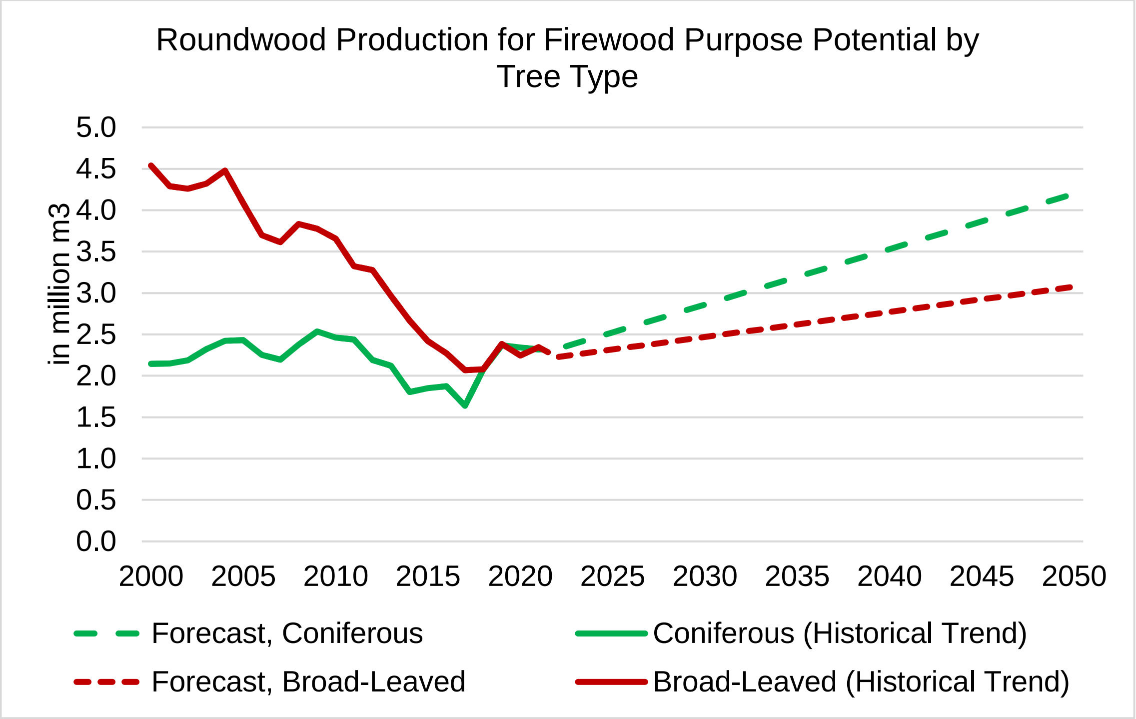


Figure 27. Forecasted roundwood production for firewood by tree type

4.1.2.3. Forecasting result of energy production potential from firewood by tree type by scenario

In 2020, Türkiye's total roundwood production converted into an energy potential of 36.5 PJ. Notably, broad-leaved wood contributed a higher proportion (57%) due to its superior energy content compared to coniferous wood. However, projections based on the shifting forest composition suggest a future with a more balanced energy contribution. By 2050, the energy potential from roundwood is expected to reach 56.6 PJ, with coniferous and broad-leaved sources each contributing roughly 50%. This trend reflects the projected increase in coniferous forest area, as highlighted in the previous section (Table 27).

The utilization rate of this potential is contingent on three distinct BDSs, each reflecting varying levels of ambition. The assumed utilization of wood for electricity generation in the reference year is set at 60% of the total energy potential. This percentage aligns with the base year installed capacity of the country's biomass power plants that use woody biomass as their feedstock. The utilization rates at the end of the year are established at 80% for the low scenario, 90% for the moderate scenario, and 100% for the high scenario, incorporating a growth trend analysis over the years. However, it is important to note that the 60% figure does not exclusively refer to firewood as the source of woody biomass. Other materials, such as wood pellets, chips, and waste from the paper industry, contribute to the overall capacity. To ensure accurate results, it is assumed that 60% of this potential is utilized for bioenergy production, as predicting the long-term potentials of other resources is not possible.

Table 27. Energy production potential of firewood by tree type with utilization rates for each scenario until 2050 (in petajoule)

Energy potential by tree type	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coniferous tree (PJ)	15.7	16.9	19.2	21.4	23.7	25.9	28.1
Broad-Leaved tree (PJ)	20.8	21.5	22.9	24.3	25.7	27.1	28.5
Total Energy Potential (PJ)	36.5	38.4	42.1	45.7	49.4	53.0	56.6
LBDS	60%	63%	66%	69%	73%	76%	80%
MBDS	60%	64%	69%	73%	79%	84%	90%
HBDS	60%	65%	71%	77%	84%	92%	100%

The analysis projects a decrease in overall firewood use due to urbanization, alternative energy sources, and sustainable forest management policies. However, total roundwood production is expected to reach 46 million m³ by 2050, with coniferous trees making up the majority. This shift in forest composition will also influence the energy potential from roundwood, with coniferous and broad-leaved sources each contributing roughly 50% by 2050. The utilization rate of this potential for bioenergy production depends on various scenarios, with the high scenario estimating 100% utilization by 2050. While firewood is not the sole source of woody biomass, this study suggests that Türkiye's forests have the potential to contribute significantly to the country's future energy needs.

4.1.3. Animal Manure

Animal manure represents a significant potential source of renewable energy in the form of biogas. This section examines the results of Türkiye's projected animal population growth and the corresponding increase in manure production suitable for biogas production.

4.1.3.1. Forecasting result of the cattle population

This study forecasts cattle population growth of Türkiye driven by rising per capita milk demand. Dairy cow population is projected to exhibit a significant increase, reaching 11.74 million head by 2050 compared to 6.88 million head in 2020 (Figure 28). This trend indicates growth in both culture and crossbred dairy cow population, while domestic cow numbers are expected to experience a slight decrease over the projection period. By 2050, culture breeds are anticipated to constitute the dominant share of the dairy cattle population at 55%, followed by crossbreeds at 40% and domestic breeds at 5%.

The population of other cattle (non-dairy cattle), excluding those raised for dairy production, was estimated based on the assumption that dairy cows comprise 40% of the total cattle population (as an average share between the two over the last two decades.). The remaining 60% of the total population was attributed to other cattle population in a year excluding buffalo.

Following this approach and projections, the other cattle population is expected to reach 17.23 million head by 2050, a substantial increase from 11.09 million head in 2020. The distribution of other cattle by breed reflects same with that of dairy cattle, with culture breed accounting for 55%, crossbred for 40%, and domestic breed for 5% of the total number of other cattle (Figure 29).

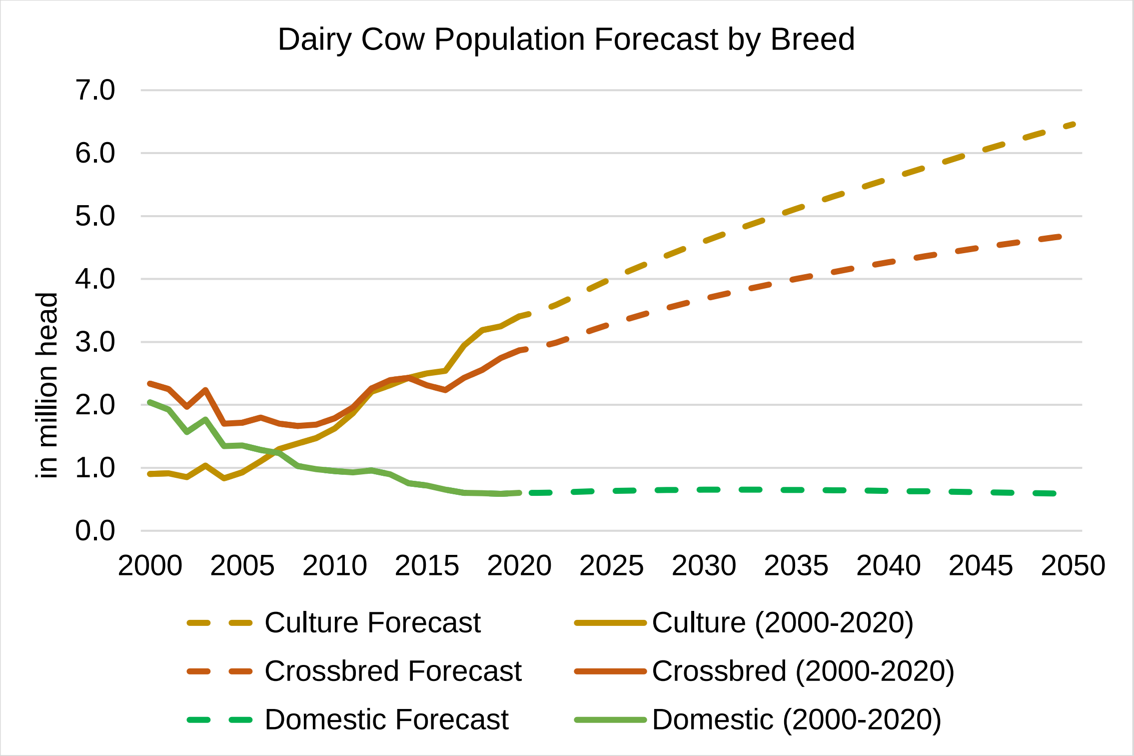


Figure 28. Dairy cow population forecast until 2050

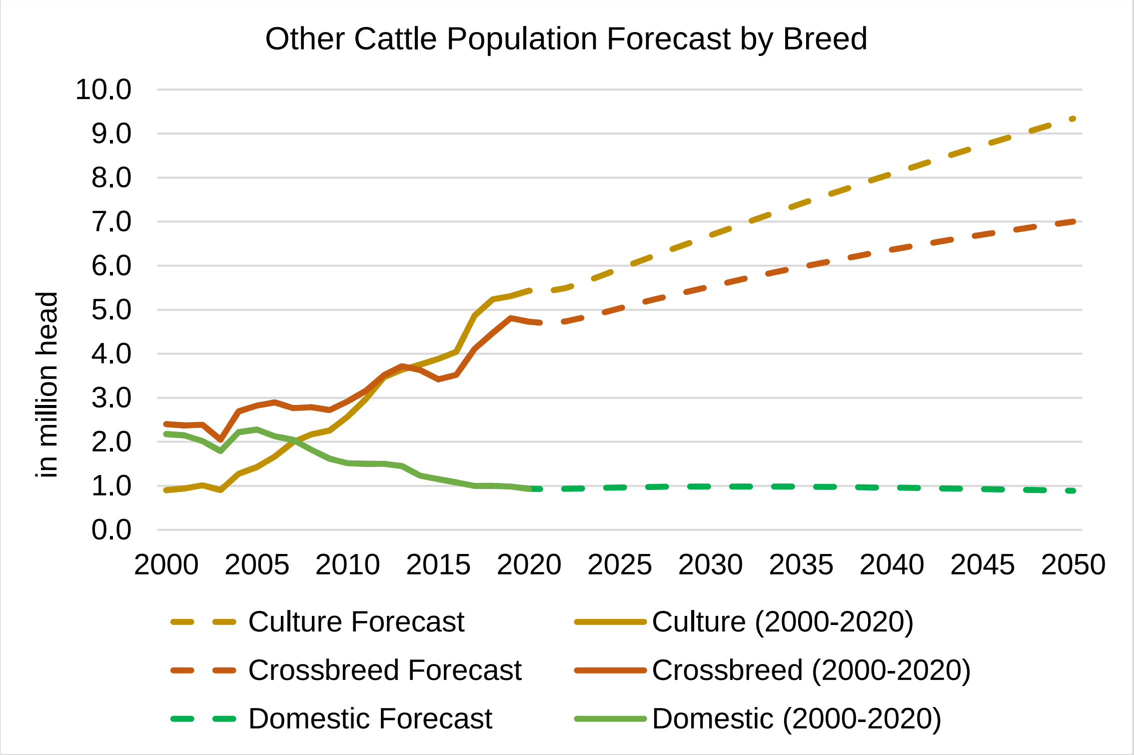


Figure 29. Other cattle population forecast until 2050

4.1.3.2. Forecasting result of sheep and goat populations

This study examines future trends in Türkiye's sheep and goat population, considering the projected rise in per capita demand for meat and milk. The analysis utilized data from the base year to establish a baseline.

The sheep population stood at 42.1 million head in this period, and forecasts suggest a significant increase to 71.4 million head by 2050. Similarly, goat population is anticipated to experience substantial growth, rising from 12.0 million head to 27.9 million head by 2050 (Figure 30). This projected expansion highlights the growing importance of sheep and goat production in meeting Türkiye's future demands for meat and milk products.

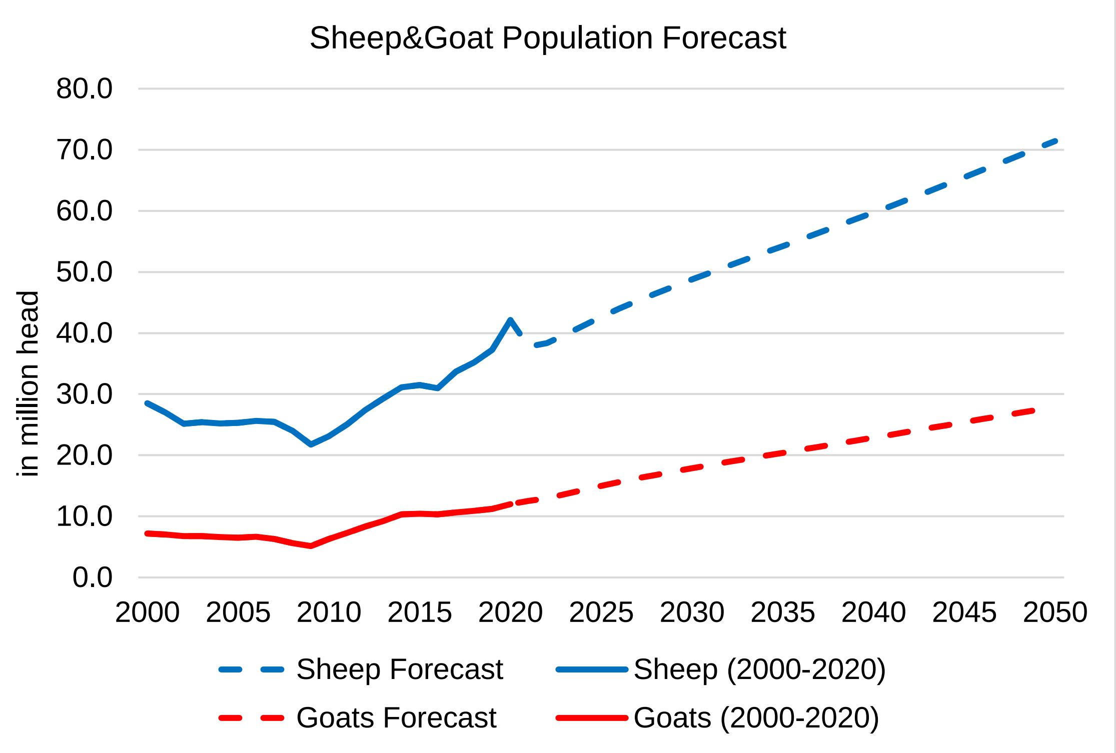


Figure 30. Sheep and Goat population forecast until 2050

4.1.3.3. Forecasting result of the chicken population

Chicken population was estimated, considering projected increases in per capita egg and meat consumption The analysis utilized baseline data to estimate the annual stock of layer and broiler chickens over the projection period.

In 2020, the population of chicken layers stood at 121.30 million head. Forecasts suggested a significant increase to 173.69 million head by 2050. Similarly, the broiler chicken population, initially at 258.07 million head, was projected to experience substantial growth, reaching an estimated 666.81 million head by 2050. This anticipated expansion reflects the growing demand for chicken meat and eggs in Türkiye, highlighting the sector's importance in meeting future chicken egg and meat consumption needs.

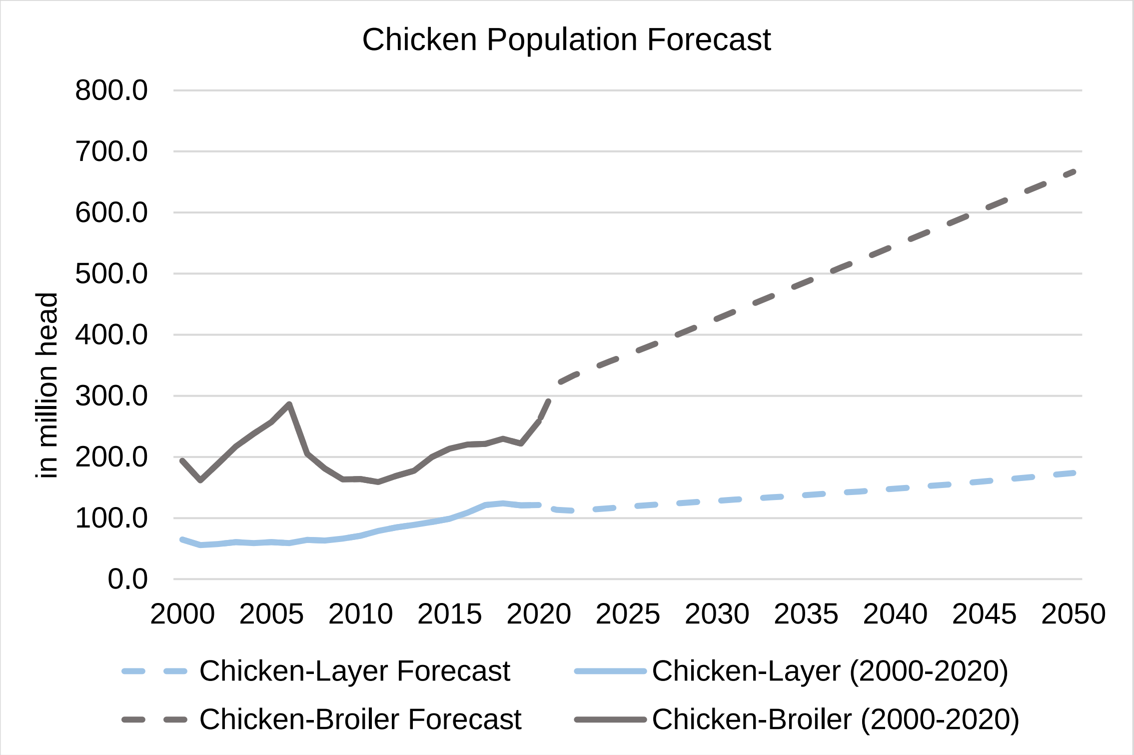


Figure 31. Chicken population forecast until 2050

4.1.3.4. Forecasting result of manure and biogas production potential from animal manure by animal type by scenario

The quantity of manure produced by each animal was calculated based on the animal's daily production parameters and the collectibility rate. The estimated quantity of manure produced by cattle by 2050 is approximately 179 Mt, with a collectibility rate of 65%. Additionally, sheep and goat are expected to produce 11.3 Mt of manure, with a collectibility rate of 13%. Meanwhile, it is projected that chickens will produce 54.8 Mt of manure in 2050, with a high collectibility rate of 99% (Table 28).

The projections presented in Table 29 illustrate the theoretical biogas production potential from animal manure, categorized by animal species, with utilization rates of this potential by three BDSs, until the year 2050. The total biogas production (as biomethane) from all animal species is projected to increase steadily, reaching 7.25 billion m^3 CH_4 by the end of 2050 (Figure 32). Cattle (dairy cows and other cattle), which contribute significantly to biogas production, are expected to demonstrate a gradual increase over the projection period, with total biogas production reaching 4.85 billion m^3 CH_4 by 2050.

The utilization rate of this potential depends on three different BDSs, each representing a different level of ambition. The assumed use of biogas production for electricity generation in the base year was determined on the basis of animal contributions to production as a result of internet search. The total contribution percentage is equal to the installed capacity of the country's biomass power plants using animal manure as feedstock in the base year. Cattle and chicken manure had the highest potential for use, while sheep and goat contributed minimally to biogas production in Türkiye. Consequently, the end-year rates were adjusted accordingly (Table 29).

Table 28. Forecasted animal population and manure for biogas production

Animal Species	Parameter	2020	2025	2030	2035	2040	2045	2050
Dairy Cow - Culture	Population (million head)	3.41	4.01	4.60	5.11	5.59	6.04	6.46
	Available Manure for biogas production (Mt)	36.15	42.50	48.79	54.26	59.28	64.06	68.52
Dairy Cow - Crossbred	Population (million head)	2.86	3.29	3.68	4.00	4.27	4.50	4.70
	Available Manure for biogas production (Mt)	22.78	26.14	29.30	31.80	33.92	35.78	37.35
Dairy Cow - Domestic	Population (million head)	0.60	0.63	0.65	0.65	0.63	0.61	0.59
	Available Manure for biogas production (Mt)	3.19	3.35	3.45	3.43	3.36	3.25	3.11
Other Cattle - Culture	Population (million head)	5.43	5.93	6.69	7.41	8.08	8.73	9.34
	Available Manure for biogas production (Mt)	25.02	27.33	30.81	34.12	37.24	40.23	43.03
Other Cattle - Crossbred	Population (million head)	4.73	5.03	5.53	5.97	6.36	6.71	7.00
	Available Manure for biogas production (Mt)	16.60	17.67	19.41	20.96	22.33	23.54	24.58
Other Cattle - Domestic	Population (million head)	0.93	0.96	0.99	0.98	0.96	0.93	0.89
	Available Manure for biogas production (Mt)	2.24	2.32	2.37	2.35	2.30	2.23	2.13
Sheep	Population (million head)	42.13	42.64	48.78	54.25	59.72	65.49	71.43
	Available Manure for biogas production (Mt)	4.80	4.86	5.55	6.18	6.80	7.46	8.13
Goat	Population (million head)	11.99	15.00	17.86	20.40	22.89	25.41	27.91
	Available Manure for biogas production (Mt)	1.36	1.70	2.02	2.31	2.59	2.88	3.16
Chicken - Layer	Population (million head)	121.30	118.63	128.25	137.49	147.94	160.14	173.69
	Available Manure for biogas production (Mt)	5.70	5.57	6.02	6.46	6.95	7.52	8.16
Chicken - Broiler	Population (million head)	258.05	367.66	426.48	486.39	546.16	606.14	666.81
	Available Manure for biogas production (Mt)	17.72	25.24	29.28	33.39	37.50	41.62	45.78

Table 29. Biogas production potential from animal manure with utilization rates for each sceanrio structure by animal type until 2050 (in billion m^3 CH$_4$)

Animal Species	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Cattle, total	2.92	3.25	3.64	3.99	4.30	4.59	4.85
LBDS	12%	16%	23%	31%	43%	58%	80%
MBDS	12%	17%	23%	33%	46%	64%	90%
HBDS	12%	17%	24%	35%	49%	70%	100%
Sheep and Goat, total	0.21	0.22	0.25	0.28	0.31	0.35	0.38
LBDS	1%	2%	4%	8%	15%	30%	60%
MBDS	1%	2%	4%	8%	17%	34%	70%
HBDS	1%	2%	4%	9%	19%	39%	80%
Chicken, total	0.88	1.16	1.33	1.50	1.67	1.85	2.03
LBDS	10%	14%	20%	28%	40%	57%	80%
MBDS	10%	14%	21%	30%	43%	62%	90%
HBDS	10%	15%	22%	32%	46%	68%	100%
Total	4.00	4.63	5.22	5.77	6.28	6.78	7.25

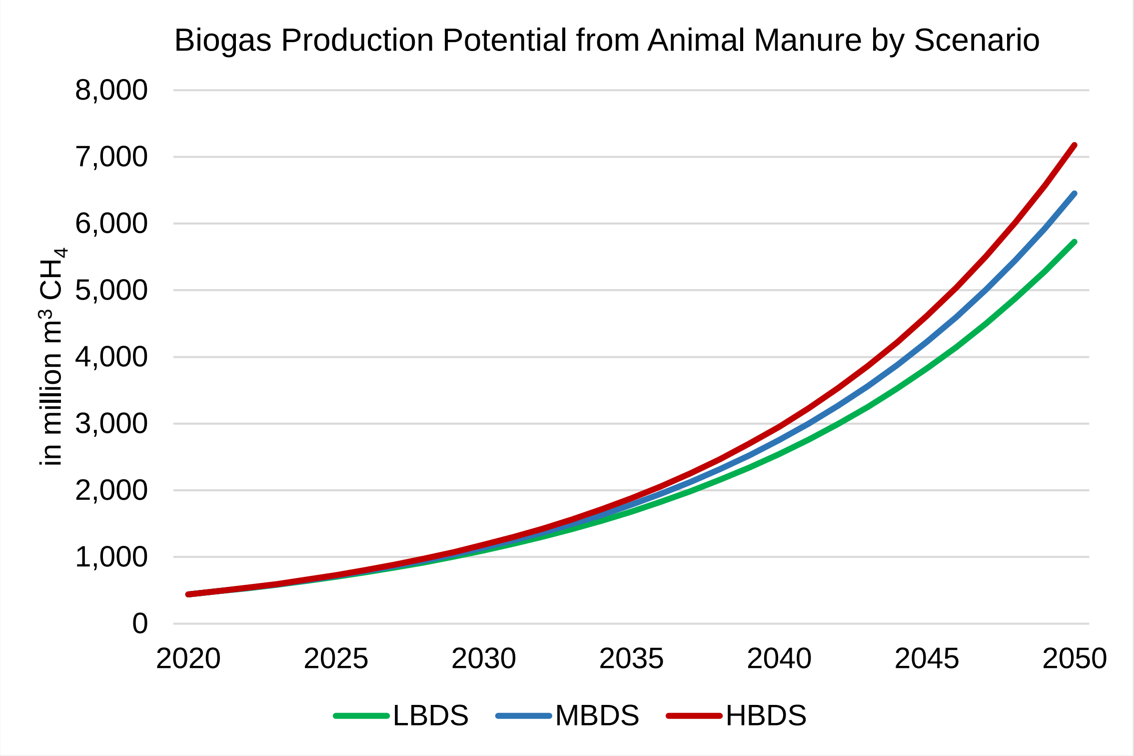


Figure 32. Biogas Production Potential from Animal Manure by Scenario

The projections show that the cattle population is expected to reach 29 million head by 2050, with dairy breeds experiencing the largest increase. Sheep and goat populations are also expected to grow significantly, reaching 71.4 million head and 27.9 million head, respectively, by 2050. This expansion in livestock production provides an opportunity to increase manure collection and biogas production. The study estimates that the total biogas production potential from animal manure could reach 7.25 billion m³ CH_4 by 2050, with cattle manure being the largest contributor. Further research is recommended to explore strategies for improving manure management and biogas utilization to achieve sustainable development in Türkiye's livestock sector.

4.1.4. Municipal Solid Waste

The amount of MSW generated in Türkiye was projected to increase from 34.7 Mt in 2020 to 43.8 Mt in 2050, based on the regression analysis results. This implies a 26% increase in the MSW generation over the next three decades, which poses a challenge for the waste management system and the environment.

The waste collection rate, which is the percentage of MSW that is collected and treated by the waste management system, was expected to improve from 93% in 2020 to 100% by 2036, according to the projection results. This means that all the MSW generated in Türkiye will be collected and treated by 2036, which is a significant achievement for the waste management system and the public health. The scenario structure was set so that LFG production directly from sanitary landfill areas, which is a less desirable process for generating biogas, will be more prominent in the LBDS compared to biogas-AD production from OFMSW. Specifically, by 2050, at most 30% of the collected waste will be allocated for LFG production, 69% will be directed to AD plants, and 1% will be sent to composting plants following mechanical separation treatment.

Biogas production from the AD system is more encouraged in the MBDS and HBDS, where 84% and 94% of all collected waste is directed to biogas production through AD plants by 2050, respectively. The MBDS and HBDS assume different levels of energy demand, which affect the economic feasibility and attractiveness of biogas production from MSW (Table 30).

Table 30. Distribution of collected MSW for biogas production by scenario

Parameter		2020	2025	2030	2035	2040	2045	2050
MSW, generated, Mt		34.75	35.93	37.66	39.09	40.58	42.27	43.97
MSW, collected, % of generated		93%	95%	97%	99.7%	100%	100%	100%
LBDS	MSW to LFG	69.4%	59.6%	51.9%	45.3%	39.5%	34.4%	30%
	OFMSW sent to AD plants	13.2%	25.64%	36.03%	45.45%	54.01%	61.83%	69.00%
	Others	17.2%	14.76%	12.07%	9.25%	6.49%	3.77%	1.00%
MBDS	MSW to LFG	69.4%	53.1%	41.2%	32.0%	24.9%	19.3%	15%
	OFMSW sent to AD plants	13.2%	33.51%	49.50%	62.85%	74.14%	79.69%	84.00%
	Others	17.2%	13.39%	9.30%	5.15%	0.96%	1.01%	1.00%
HBDS	MSW to LFG	69.4%	44.2%	28.6%	18.5%	12.0%	7.7%	5%
	OFMSW sent to AD plants	13.2%	43.77%	64.90%	80.52%	87.05%	91.27%	94.00%
	Others	17.2%	12.03%	6.50%	0.98%	0.95%	1.03%	1.00%

4.1.4.1. Forecasting result of LFG production potential from MSW by scenario

The potential for methane production in landfills equipped with LFG production systems was assessed using the LandGEM tool. Projections indicate that by 2050, the LFG production potential is expected to reach 1.43 billion m³ of CH_4 in the LBDS, 1.03 billion m³ of CH_4 in the MBDS, and 674.9 million m³ of CH_4 in the HBDS, assuming a 50% methane content in LFG (Figure 33).

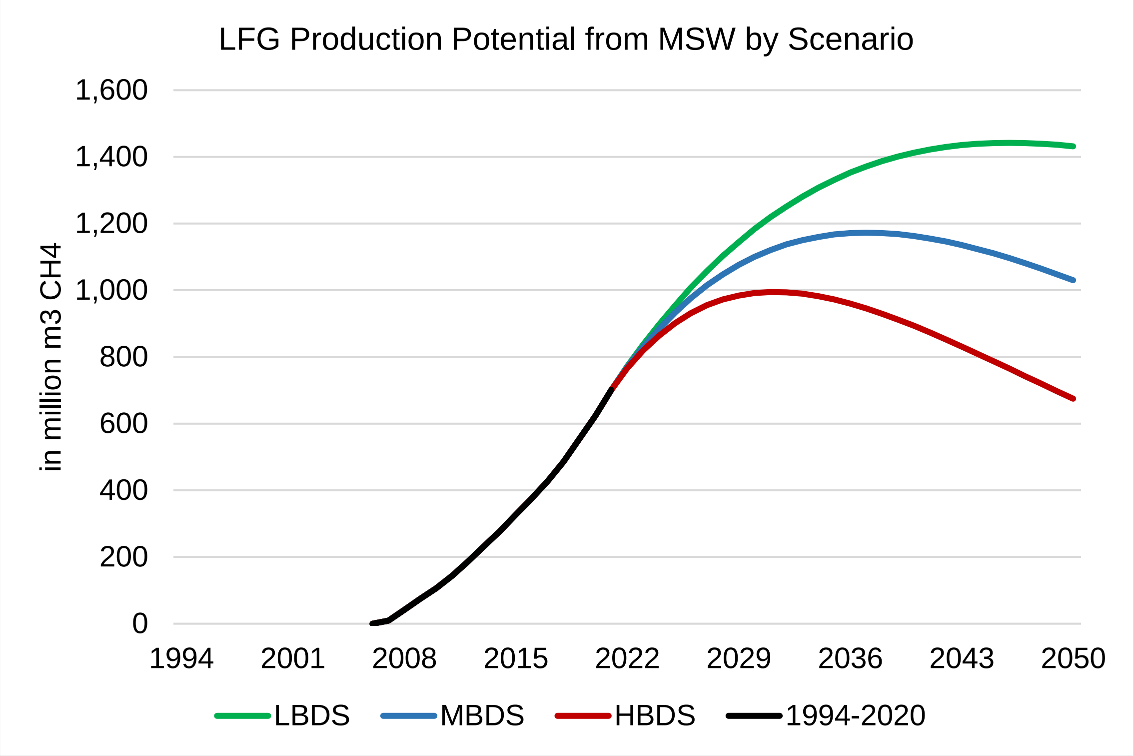


Figure 33. LFG Production Potential from MSW by Scenario

4.1.4.2. Forecasting result of biogas production potential from OFMSW by scenario

The biogas production potential resulting from the collection of MSW, which is then directly sent to AD plants following the separation of its biodegradable component through MBT units, was estimated for three different BDSs. By 2050, the LBDS is expected to produce 2.32 billion m³ of CH_4, the MBDS is projected to produce 2.82 billion m³ of CH_4, and the HBDS is expected to produce 3.16 billion m³ of CH_4 (Figure 34).

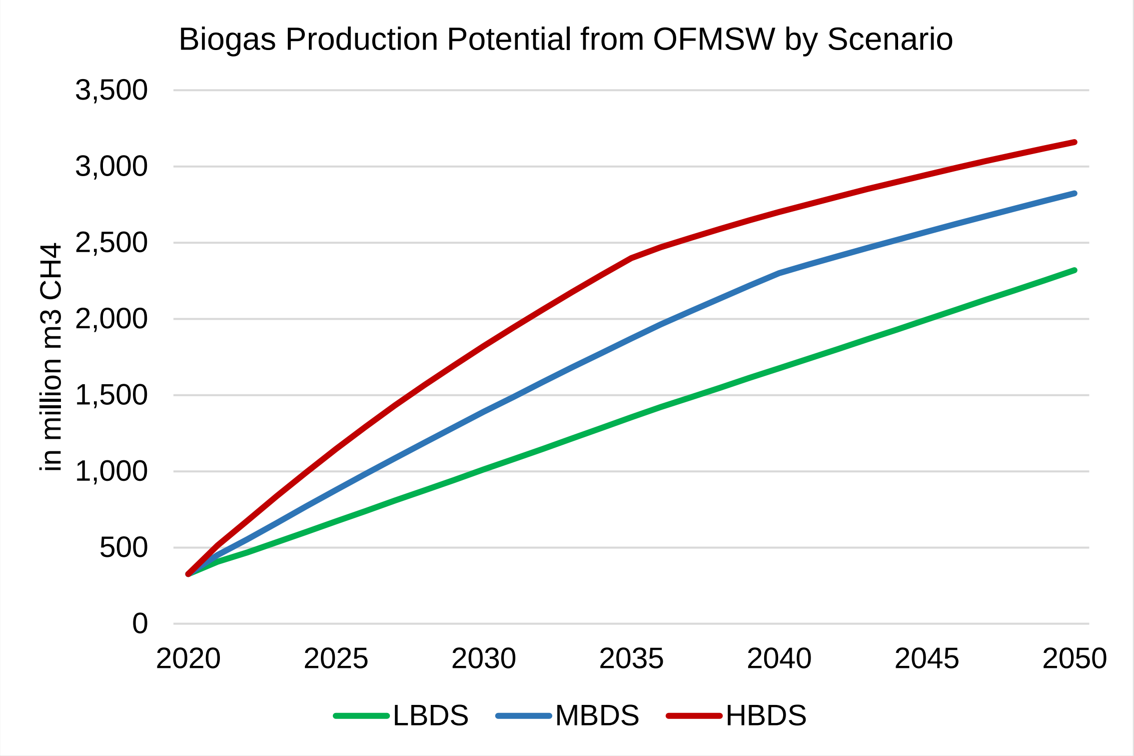


Figure 34. Biogas production potential from MSW by scenario

The analysis revealed a significant increase in MSW generation by 2050, highlighting the need for improved waste management practices. While all scenarios project a rise in waste collection rates, the distribution of collected waste for bioenergy production varied. The LBDS prioritizes LFG production, while the MBDS and HBDS increasingly favor biogas generation through AD plants. This shift towards AD demonstrates a preference for a more sustainable biogas production method. AD offers several advantages over LFG production. Biogas from AD plants captures methane emissions that would otherwise escape from landfills, mitigating their contribution to climate change. Furthermore, AD generates a usable biofertilizer as a byproduct, promoting resource recovery and reducing reliance on chemical fertilizers. The efficiency of AD in converting waste to biogas is also superior to LFG production, maximizing the potential for renewable energy generation. These environmental and economic benefits make the HBDS scenario, with its emphasis on AD technology, the most favorable option for sustainable MSW management in Türkiye. By applying AD, Türkiye can transform waste into a valuable resource, promoting environmental responsibility and energy security.

4.1.5. Municipal Wastewater Treatment Sludge

Another potential biomass resource is sewage sludge, an end-process product of WWTPs. This section examines the potential for the production of sludge from the biological treatment of municipal waste for the purpose of biogas production.

4.1.5.1. Forecasting result of biologically treated wastewater amount potential

In order to estimate the potential for sludge and biogas production in the BioWATT tool, it is first necessary to estimate the amount of biologically treated wastewater over the projection period. The initial step is to estimate the municipal population rate.

According to the TURKSTAT data [89], the percentage of people living in municipalities in Türkiye increased from 76% in 1994 to 94% in 2020, and via growth trend anaylsis this share is projected to reach 97% by 2050, which corresponds to 101.6 million people (Figure 35).

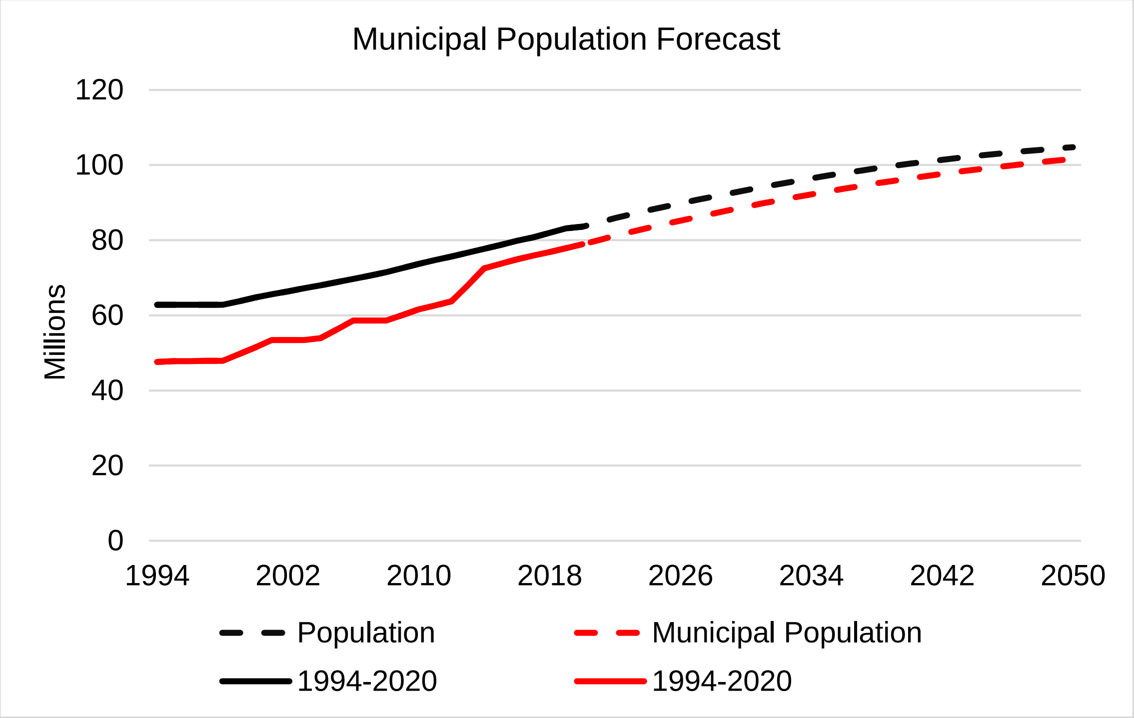


Figure 35. Municipal population forecast by 2050

The second step is estimating the percentage of population in municipalities that have access to sewerage system and wastewater treatment plant (WWTP). This percentage rose from 12.7% in 1994 to 77.6% in 2020, and is estimated to reach 94% in 2050 (Figure 36).

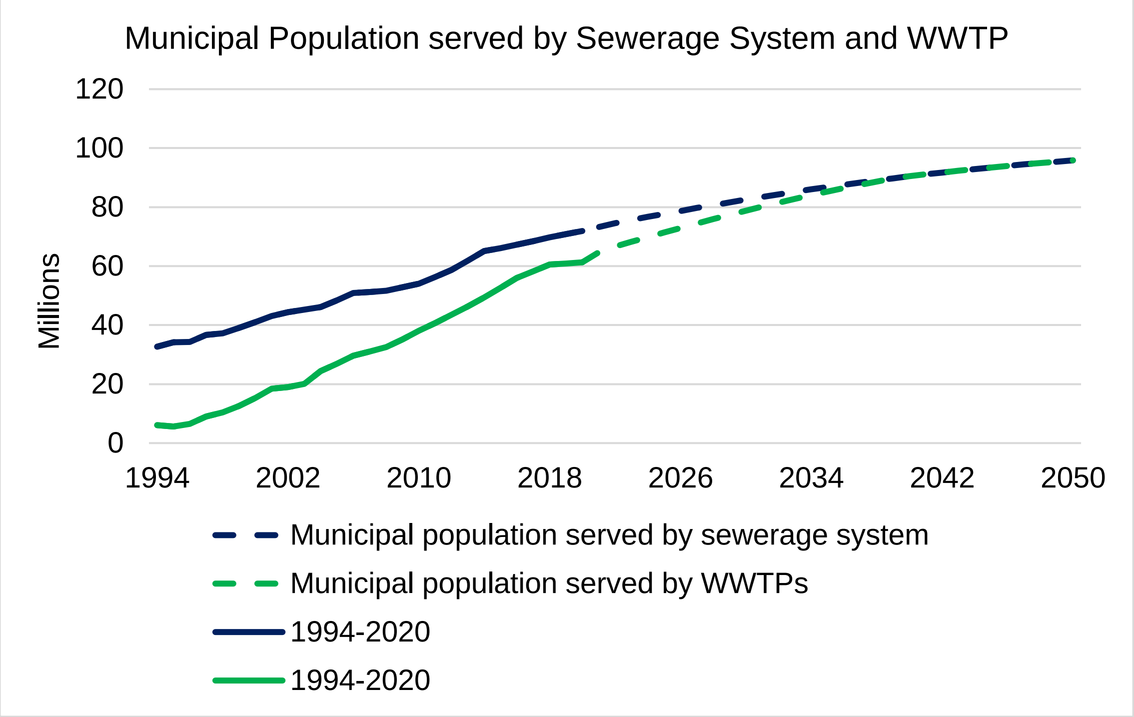


Figure 36. Municipal population served by sewerage and WWTP by 2050

This study employed per capita wastewater production rates to estimate future wastewater generation in Türkiye. The analysis began by establishing a historical trend. Daily per capita wastewater production rose from 126.5 liters in 1994 to 189 liters in 2020. This trend was then projected forward using a simple regression analysis, with municipal population serving as the independent variable and per capita wastewater rate as the dependent variable. This projection suggests a further increase to 212 liters per capita daily by 2050.

By multiplying the projected per capita production rate with the anticipated municipal population, annual wastewater generation was calculated. This revealed a significant rise, with annual municipal wastewater production growing from 1.5 billion m^3 in 1994 to 4.9 billion m^3 in 2020. Following the established trend, projections indicate that annual wastewater production will reach 7.4 billion m^3 by 2050 (Figure 37).

The analysis also examined wastewater treatment capacity. In 1994, only 10% of the total wastewater generated (150,000 m^3) received treatment. This figure rose dramatically to 4.4 billion m^3 in 2020, representing a treated volume of 88% of the total wastewater produced. The projection results show that treated wastewater will reach 7 billion m^3 by 2050 (Figure 37), showing a significant improvement with a treatment rate of 90% of the total wastewater generated.

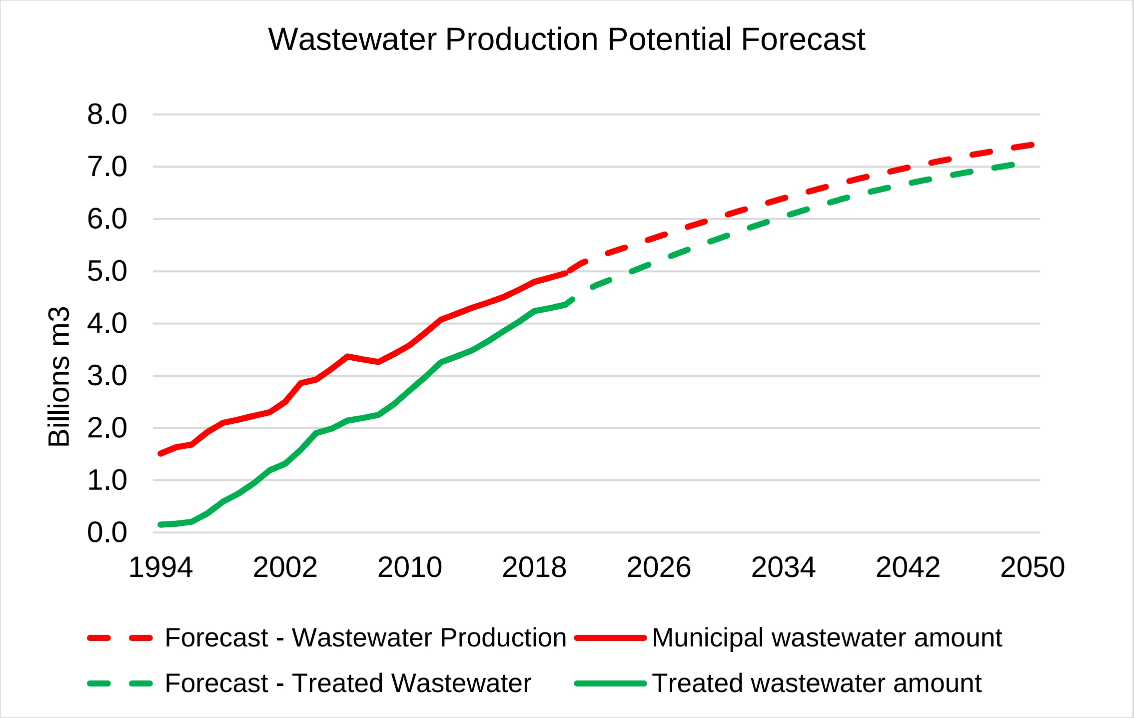


Figure 37. Municipal wastewater production forecast by 2050

An examination of wastewater treatment methods in Türkiye reveals a growing emphasis on biological processes. In 1994, biological treatment methods only accounted for approximately 48% of all treatment methods employed. This share, however, exhibited a significant increase by 2020, reaching 78% of all treatment methods utilized. Conversely, the use of non-biological methods has seen a corresponding decline.

This trend towards biological treatment is projected to continue. Based on an analysis of historical data, the forecasting result shows that by the mid-2040s, biological and advanced treatment methods will dominate the wastewater treatment landscape in Türkiye. This dominance is expected to be complete, with these combined methods accounting for 100% of all wastewater treatment approaches. As a result, the volume of treated wastewater is projected to increase to 7 billion m^3 by 2050, as shown in Figure 38.

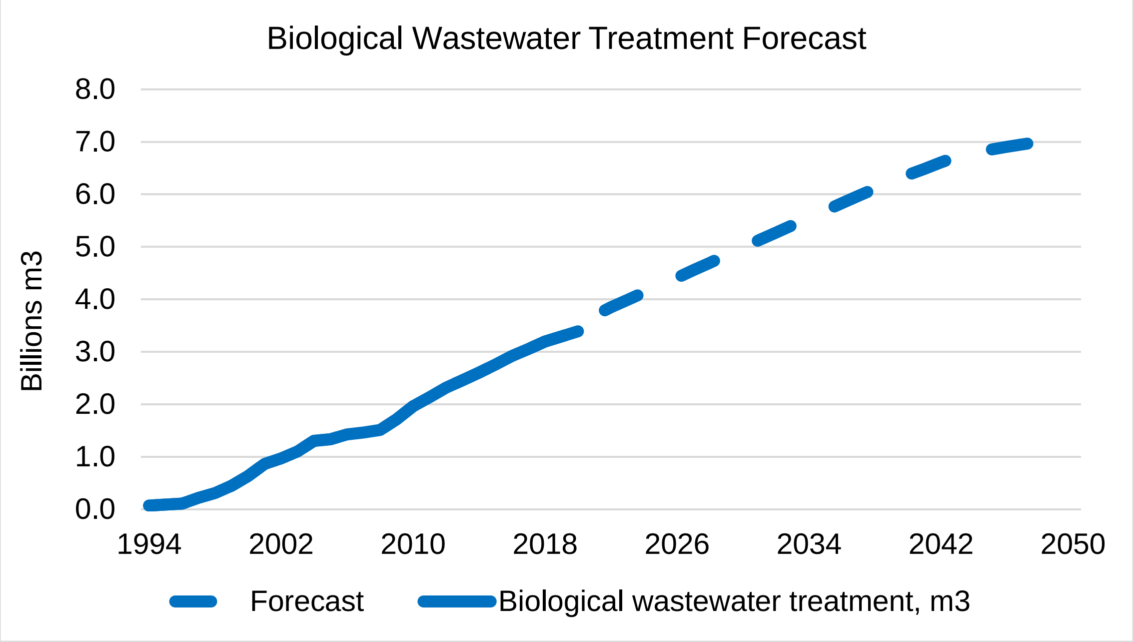


Figure 38. The forecast of biological treated wastewater amount by 2050

4.1.5.2. Forecasting result of sludge production and biogas production potentials

In order to estimate the potential for sludge production and biogas production over the projection period, the forecasted amount of biologically treated wastewater was entered into the BioWATT tool.

The BioWATT model utilized default parameters sourced from various references (see Table 19), including average BOD concentration in influent wastewater, VSS/TSS concentration, BOD$_5$, and TSS removal efficiency of primary settling tank and waste activated sludge, to estimate the potential production of sludge. According to this study findings, the total estimated sludge production potential is projected to increase from 1.14 billion tons in DS to 2.39 billion tons in DS by the year 2050 (Figure 39).

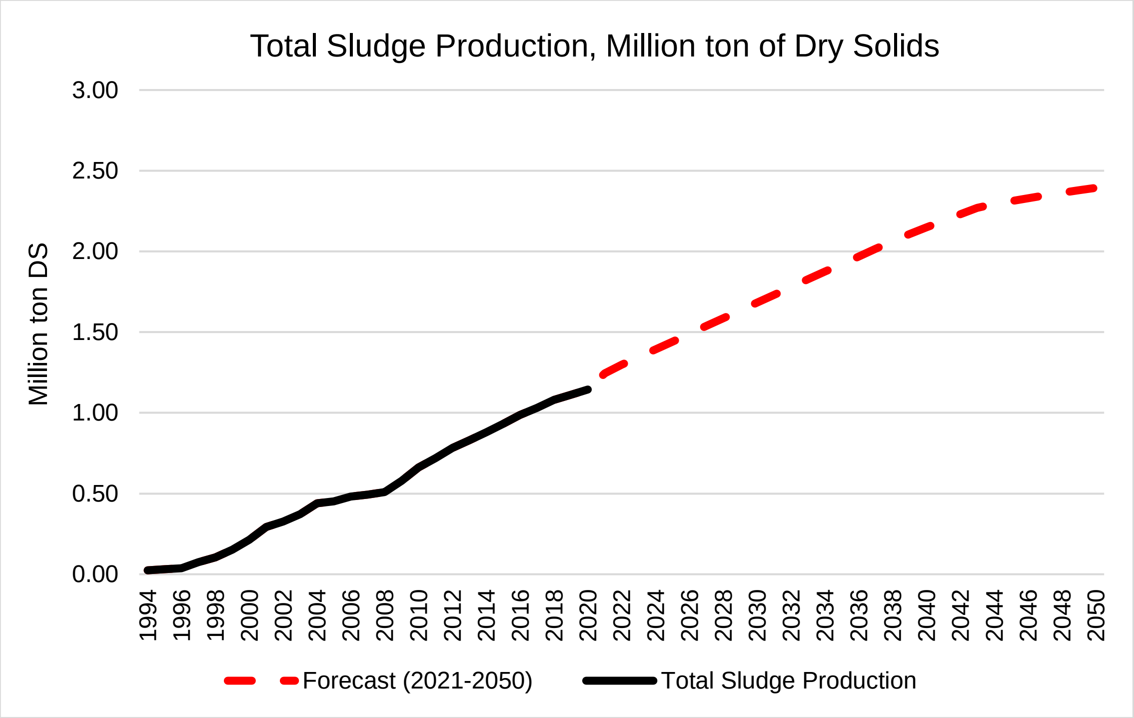


Figure 39. The forecast of sludge production potential by 2050

Based on available data from 2020, it is estimated that existing municipal WWTP biogas production capacity utilizes approximately 30% of the total theoretical potential for sludge-based biogas production in Türkiye. This figure serves as the baseline for projections of future biogas production from sewage sludge.

To assess the potential future utilization of sludge for biogas production, three scenarios were developed. These scenarios mirror those used for other biomass resources in the study. In the LBDS, a conservative approach was taken, with a lower allocation of sludge for biogas production throughout the projection period. Conversely, the HBDS assumed a more optimistic outlook, with a projected 100% utilization rate for sludge in biogas production by 2050.

Table 31 depicts the allocation of sludge for biogas production under each scenario. The table also presents the theoretical potential for biogas production, expressed as destructible volatile solids (VS) in dry solids (DS). The sludge potential as destructible VS could reach 897 Mt of $VS_{destroyed}$ by 2050. This potential was found 429 Mt $VS_{destroyed}$ in 2020. According to the sludge utilization scenarios, under LBDS the utilization rate of the total potential is assumed to reach 70%, under MBDS scenario this potential is assumed to reach 85% and under HBDS the entire potential is assumed to be used for biogas production by 2050.

Table 31. Sludge and biogas production and utilization by scenario

Parameter	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Sludge production potential (PS+WAS), Mt of DS	1144.4	1441.2	1682.7	1921.8	2148.5	2311.8	2394.0
Destroyed sludge potential in digesters, Mt of $VS_{destroyed}$	429.2	540.5	631.0	720.7	805.7	866.9	897.7
Biogas Production Potential, million m^3 of CH_4	251.1	316.2	369.1	421.6	471.3	507.1	525.2
LBDS	30%	35%	40%	46%	53%	61%	70%
MBDS	30%	36%	43%	51%	60%	72%	85%
HBDS	30%	37%	45%	55%	67%	82%	100%

Consequently, the theoretical biogas potential from treatment sludge was estimated to reach 525.2 million m³ CH_4 by the year 2050. Figure 40 illustrates the forecasted utilization of biogas under different scenarios throughout the projection period. In the reference year (2020), the overall biogas production amounted to 75.7 million m³ CH_4, representing approximately 30% of Türkiye's theoretical potential from municipal wastewater treatment sludge in 2020. Considering the assumed utilization rates for this potential across the projection period under different scenarios, it is estimated that biogas production from sludge could reach 367.6 million m³ CH_4 for the LBDS, 446.4 million m³ CH_4 for MBDS, and 525.2 million m³ CH_4 for the HBDS by the year 2050.

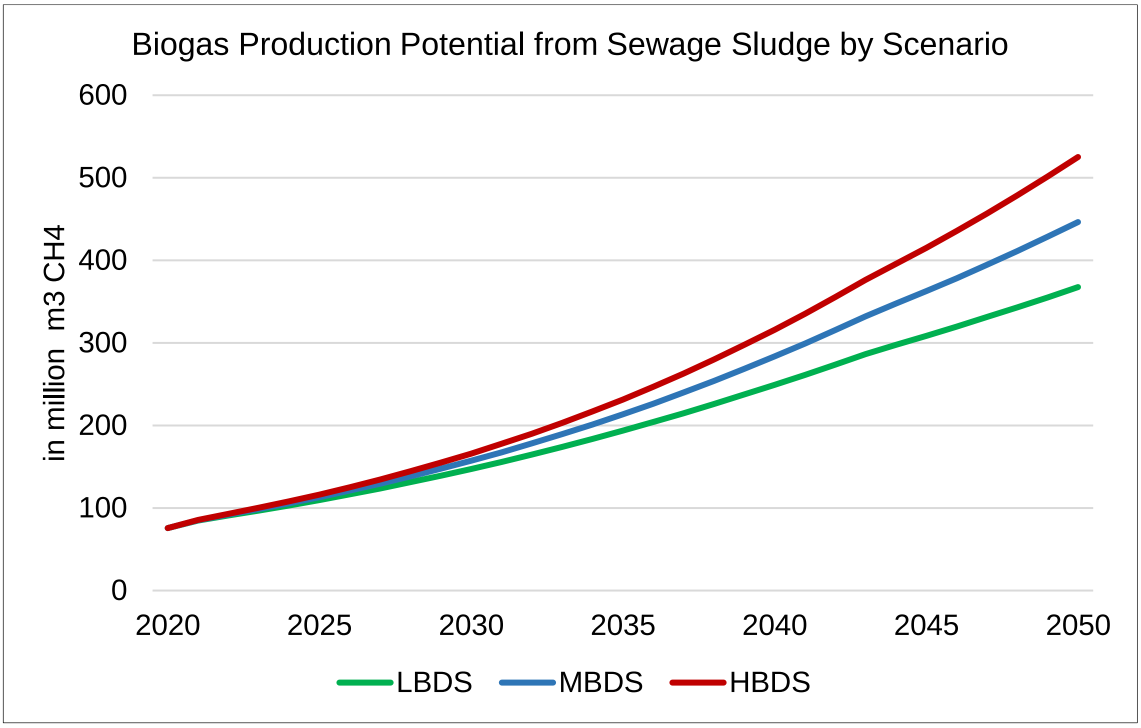


Figure 40. Biogas production potential from sewage sludge by scenario

Sewage sludge generated from municipal WWTPs presents a promising potential for biogas production in Türkiye. This study projects a significant increase in wastewater generation and treatment capacity by 2050, with biological treatment methods becoming dominant. This trend aligns with the projected growth of sludge production potential, reaching 2.39 billion tons in dry solids by 2050. Three scenarios were developed to assess the potential future utilization of sludge for biogas production. The most optimistic scenario (HBDS) estimates 100% utilization by 2050, which could translate to a theoretical biogas potential of 525.2 million m³ CH_4. While current utilization sits around 30% of the potential, this study highlights the significant opportunity for Türkiye to increase biogas production from sewage sludge in the future.

Assessment of future bioenergy potential reveals significant contributions from both solid and wet biomass sources. Solid biomass resources, particularly residues from maize and cotton cultivation (maize stover and cotton stalk, respectively), are projected to contribute a substantial 673 PJ of energy by 2050. This represents approximately 56% of the total estimated solid biomass energy potential of 1197 PJ. Firewood remains a relevant contributor at 56.6 PJ, while other noteworthy sources include wheat straw (67 PJ), sunflower stalk (64.3 PJ), and sunflower head (61.3 PJ).

Wet biomass resources also exhibit considerable potential for biogas production. The analysis indicates a total potential of 11.61 billion m^3 CH_4 by the year 2050. The analysis reveals that animal manure represents the most significant contributor, with an estimated potential of 7.25 billion m^3 CH_4, accounting for approximately 62.4% of the total anticipated biogas production from wet biomass. MSW contributes 33% to the biogas potential, whereas the sludge-based potential accounts for only 4.6% of the total. These findings illustrate the multifaceted contributions of diverse biomass resources to the broader bioenergy landscape.

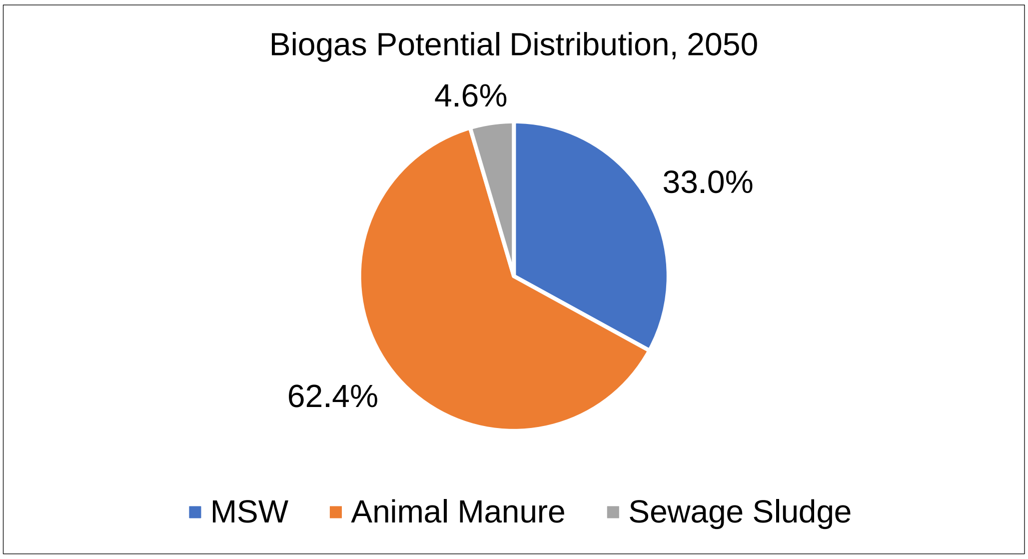


Figure 41. Biogas (biomethane) Potential by biomass resource (2050)

4.2. LEAP Modelling Results

This section analyzes Türkiye's projected electricity demand by sector until 2050. It presents the results for four distinct scenarios: the Reference Scenario (RS), Low Bioenergy Demand Scenario (LBDS), Moderate Bioenergy Demand Scenario (MBDS), and High Bioenergy Demand Scenario (HBDS). The analysis goes beyond just demand, exploring the electricity supply mix under each scenario. Furthermore, it examines the environmental and cost implications of these scenarios, offering a comprehensive evaluation of their potential impact on Türkiye's energy future by 2050.

4.2.1. Key Assumptions

In long-term scenarios, key assumptions are crucial for determining projections. These assumptions shape future developments. This study examines the potential of various energy sources to contribute to Türkiye's projected electricity mix in different scenarios by 2050. In the LEAP modelling tool, the country's sectoral-based electricity demand was estimated using a set of key assumptions, including population growth, GDP, sectoral contribution to GDP, household size, and number of households.

4.2.1.1. Population Projection

This study utilizes population projections from TURKSTAT [96]. The findings indicate that population growth will continue during the projection period, albeit at a declining rate. The expected growth rates are 1.2% from 2020 to 2030, 0.8% from 2030 to 2040, and 0.4% from 2040 to 2050. The population of Türkiye was approximately 83.6 million in 2020, and it is projected to reach 104.7 million by 2050 (Figure 42).

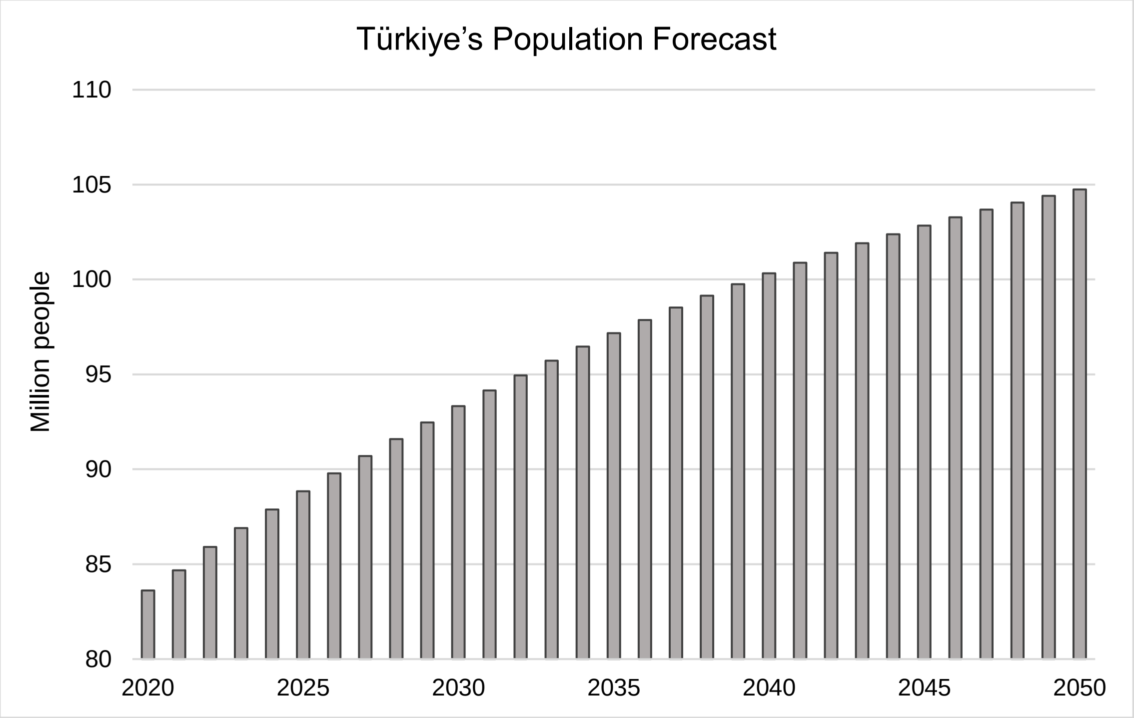


Figure 42. Türkiye’s population forecast until 2050 [96]

4.2.1.2. Gross Domestic Product Projection

In 2020, according to the World Bank, Türkiye's GDP was 720.3 billion US$ (current prices), and when adjusted for inflation to 2015 constant prices, it stood at 1015.7 billion US$ [97]. The OECD provides long-term forecasts for Türkiye's real GDP [98]. Their projection for Türkiye spans from 2020 to 2060, measured in constant 2010 billion US$. Using the same growth rate, the real GDP growth is estimated until 2050, expressed in constant 2015 US$. According to these forecasts, between 2020 and 2030, Türkiye's economy is expected to expand at an average annual rate of 6.2%. However, it is anticipated to decelerate in the subsequent years due to demographic stabilization and reduced investment rates. On average for the period from 2020 to 2050, the projected annual growth rate is 5.4% (Figure 43).

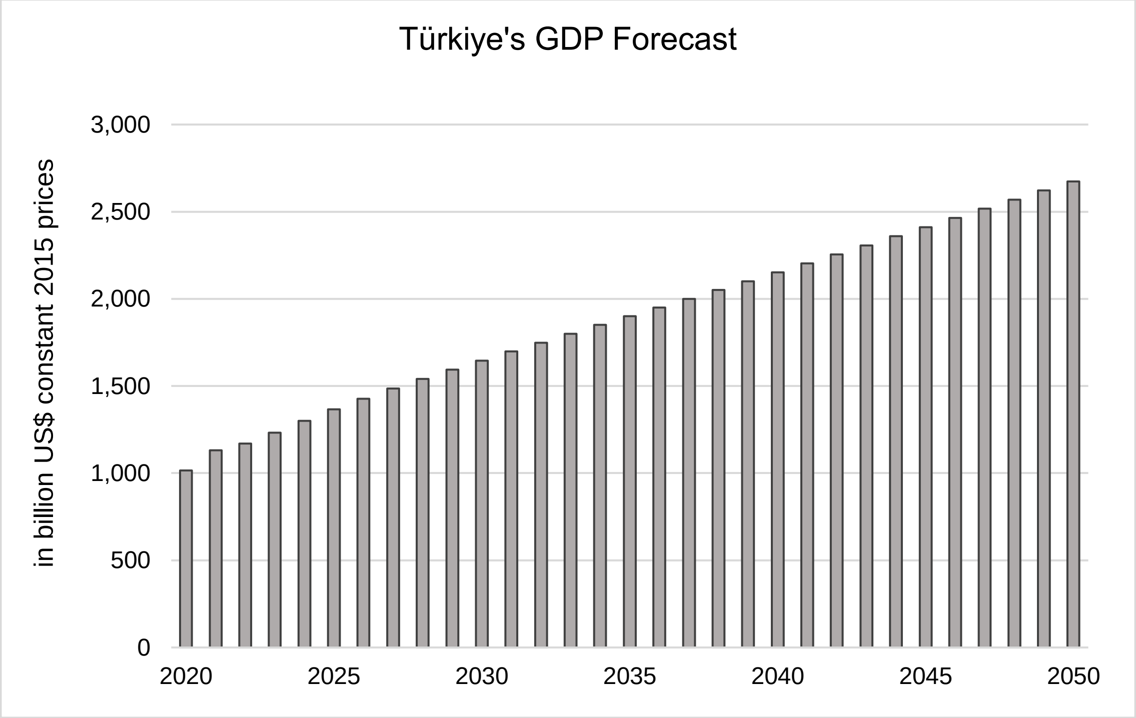


Figure 43. Türkiye’s GDP forecast until 2050 [97]**,** [98]

4.2.1.3. Sectoral gross value added to GDP

From 2000 to 2022, there were significant shifts in the composition of Türkiye's GDP, with notable changes occurring across various sectors. The agriculture sector experienced a gradual decline, dropping from 10% in 2000 to a stable 6% by 2022. In contrast, the industry sector, including construction, maintained a consistent 25-29% until 2019, rising to 32% in 2022 due to infrastructure projects. The manufacturing sector experienced a decline from 19% in 2000 to 15% in 2009, subsequently exhibiting a stabilization at 18-19% until 2019. From 2020 to 2022, there was an increase to 22%. The services sector has consistently constituted the dominant component of GDP, with a starting value of 53% in 2000, a peak of 57% in 2009, and a subsequent range of 51% to 56% from 2010 to 2022.

To calculate the electricity intensity of sectors, values were adjusted using a scaling factor (0.96 in 2020), resulting in the following sectoral contributions: The gross value added for each sector to GDP was calculated by multiplying the GDP by the scaling factor. This yields the following contributions: agriculture (6.37%), services (52.39%), and industry (encompassing construction and manufacturing)

(41.24%). These projections maintain the assumption of constant sectoral shares from 2020. The resulting forecasts are presented in Figure 44.

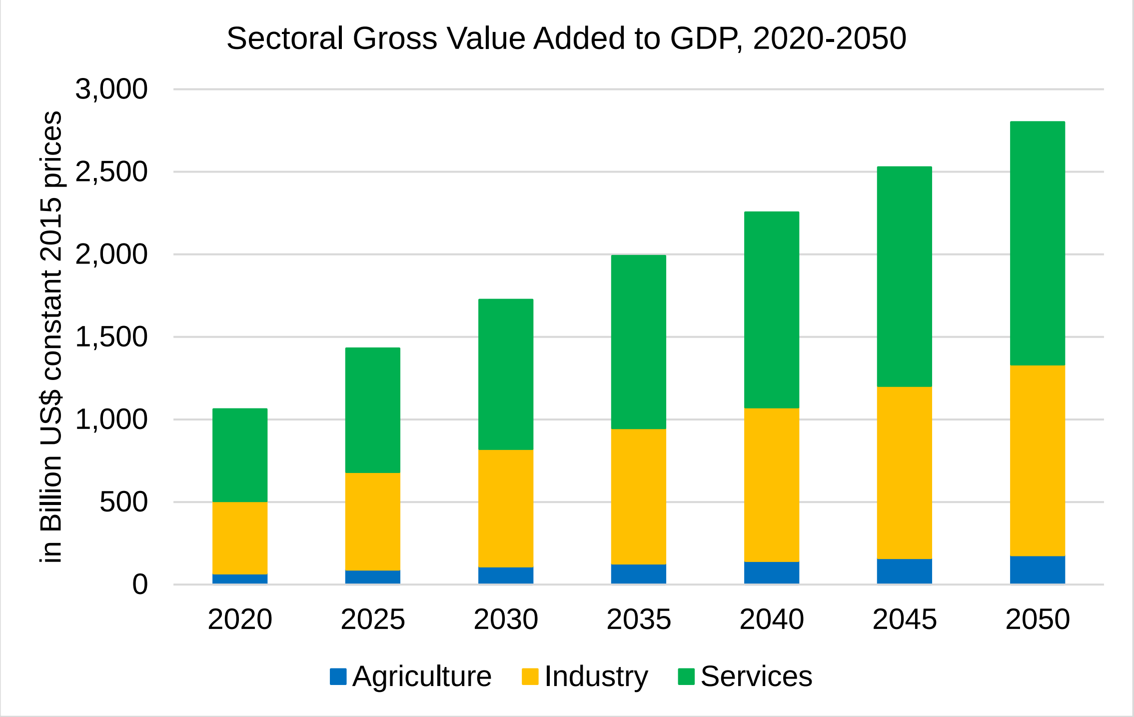


Figure 44. Forecasting Türkiye's sectoral GVA to GDP

4.2.1.4. Household and Household Size

The forecasting of future household numbers is a crucial aspect of estimating the residential sector’s electricity demand over a projection period. This is dependent on the analysis of two key data sets: the number of households and the size of these households. As indicated by data from TURKSTAT [99] , the demographic profile of the population in Türkiye is undergoing a significant transformation.

Over the past decade, there has been a notable decline in the average number of individuals per household. In 2010, the mean household size was 4.17, while by 2020, it had decreased to 3.38. It is important to note that despite the reduction in the average household size, the total number of households has increased. In 2010, there were 17.7 million households in Türkiye. By 2020, this number had risen to 24.7 million. This indicates that more houses and apartments are being constructed, despite the fact that the average number of people per household has decreased (Table 32).

Table 32. Türkiye's household number and household size [99]

Year	**Number of households**	**Population**	**Average Household Size**
2010	17,688,527	73,722,988	4.17
2011	18,338,833	74,724,269	4.07
2012	19,013,020	75,627,384	3.98
2013	19,807,245	76,667,864	3.87
2014	20,585,865	77,695,904	3.77
2015	21,351,094	78,741,053	3.69
2016	22,033,680	79,814,871	3.62
2017	22,714,025	80,810,525	3.56
2018	23,268,973	82,003,882	3.52
2019	24,130,958	83,154,997	3.45
2020	24,737,413	83,614,362	3.38

A 10-year trend analysis was conducted to determine the most appropriate method for projecting household size and number for the next 30 years. The ARIMA method was selected for this purpose, as it is a well-established technique for forecasting time series data. The resulting projections were then used to estimate sector electricity demand. The forecast indicates that the average number of persons per household is anticipated to decrease from 3.4 in 2020 to 2.9 in 2050 (Figure 45). Consequently, the total number of households is projected to increase from 24.8 million in 2020 to 35.8 million in 2050 (Figure 46).

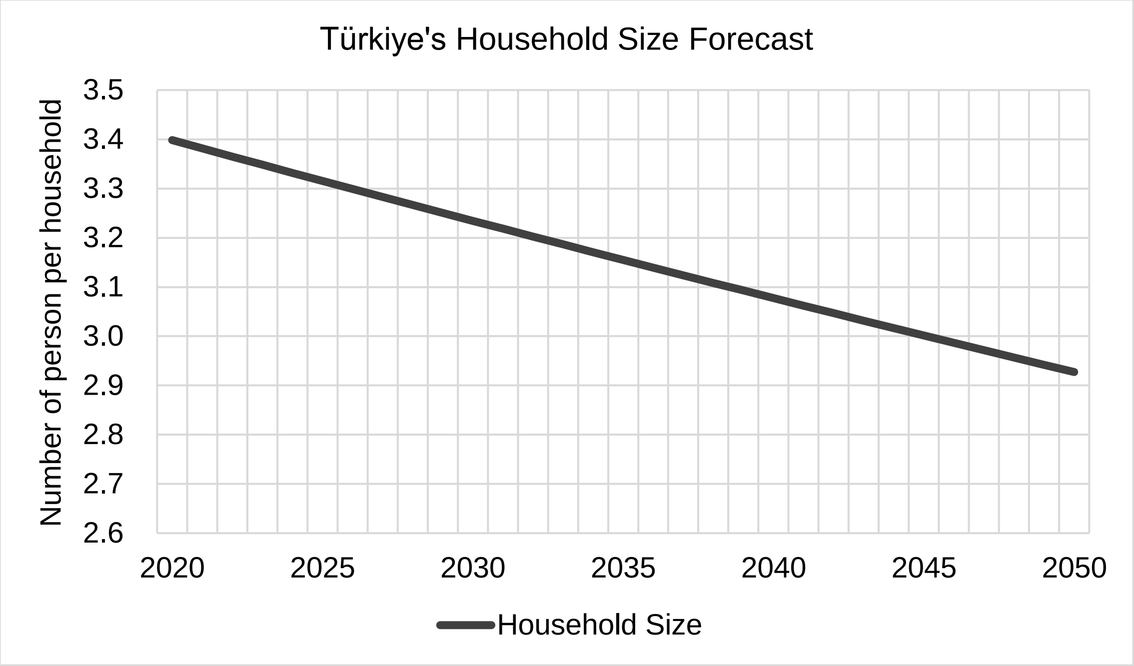


Figure 45. The forecast of household size until 2050

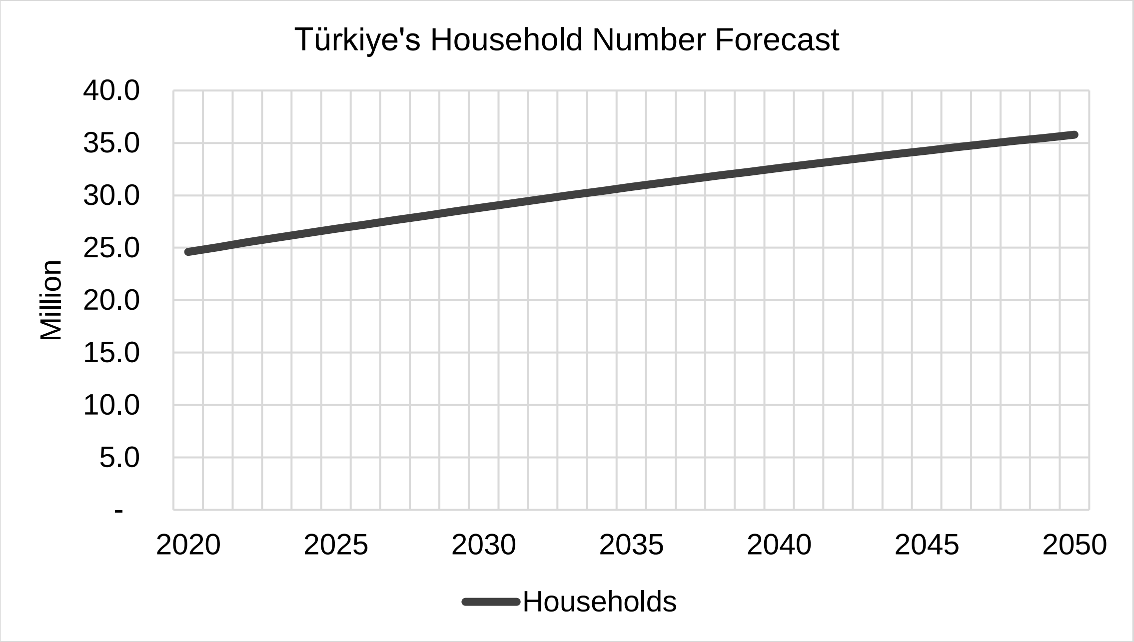


Figure 46. The forecast of household number until 2050

4.2.2. Electricity Demand

According to the LEAP modelling result, the total electricity demand was projected to reach approximately 642.5 TWh by 2050, a substantial increase from the 259.8 TWh recorded in 2020, representing a remarkable 147% surge from the base year (Figure 47).

In the residential sector, the electricity demand of 60.4 TWh in 2020 is expected to increase to 84.1 TWh by 2050, indicating a significant 39% rise. The services sector, which consumed 69.0 TWh in 2020, is forecasted to play a substantial role in the economy, reaching 193.8 TWh by 2050, marking a noteworthy 180% increase.

The agriculture and industry sectors demonstrate impressive growth, with electricity demand expected to reach 35.3 TWh (a 208% increase) and 325.6 TWh (a 177% increase) by 2050, respectively. In the transport sector, the minimal 1.44 TWh demand in 2020 is projected to rise to 3.72 TWh by 2050, reflecting a substantial 158.3% increase associated with economic growth (Figure 47).

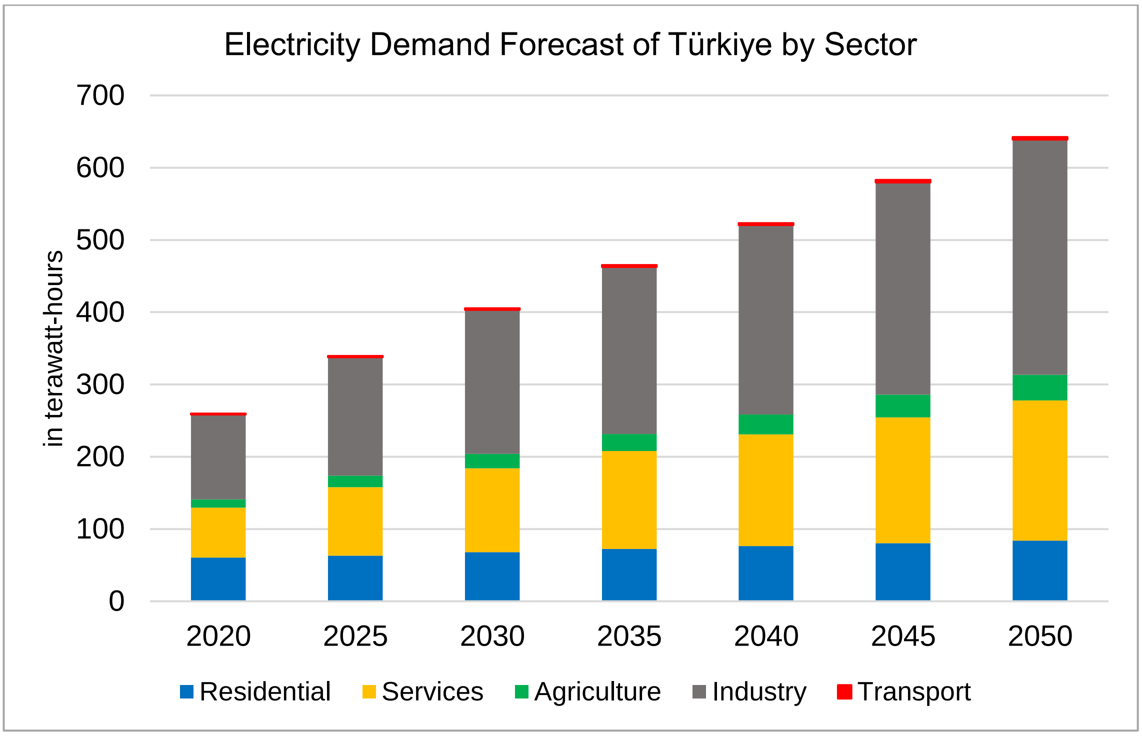


Figure 47. Electricity demand forecast of Türkiye, 2020-2050

4.2.3. Electricity Supply

The RS for energy supply is designed based primarily on the Plan [18]. This Plan is projected the total installed capacity by energy source until 2035. The 15 years extension was applied until 2050 by using same fuel-specific growth rates and also using other official targets for specific fuels. The Plan aims to increase the share of renewables in the electricity mix to 65% by 2035, focusing primarily on solar and wind power expansion. Targets include a rise in solar power capacity from 6.7 GW in 2020 to 52.9 GW in 2035, wind power from 8.8 GW to 29.6 GW, and nuclear capacity of 7.2 GW. Hydropower capacity will slightly increase, while biomass and geothermal power capacity are estimated to reach 5.1 GW in 2035. Fossil fuel capacity, including coal and natural gas, is projected to increase, and total electricity consumption is forecasted to reach 510.5 TWh by 2035.

The LEAP modelling results demonstrate Türkiye's dedication to cleaner energy, highlighting significant advances in renewable sources such as wind, solar, geothermal, and hydro. By 2050, wind and solar capacities are projected to reach 48.00 GW and 82.13 GW, respectively. However, biomass has not reached its full capacity while traditional fossil fuels like hard coal and lignite have shown minimal progress. The total installed capacity is projected to reach 264.9 GW in 2050, up from 95.8 GW in 2020 (Figure 48).

Under the RS, The total electricity generation is expected to increase significantly, from 307 TWh in 2020 to 756 TWh in 2050. There is also an anticipated increase in the use of solar power, from 11.0 TWh in 2020 to 187.6 TWh in 2050, accompanied by an escalation in the rate of use from 3.6% in 2020 to 25% in 2050. Wind power is also expected to grow significantly, from 24.8 TWh in 2020 to 145.3 TWh in 2050, with an increase in the utilization rate from 8.1% in 2020 to 19% in 2050 (Figure 49).

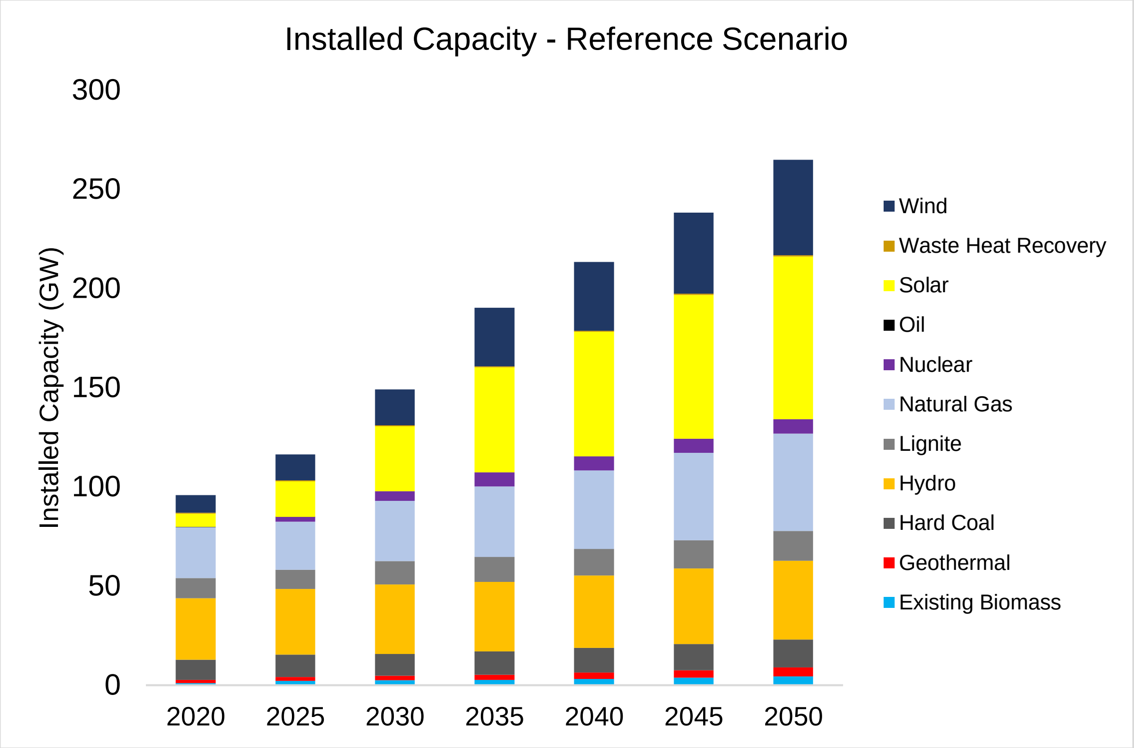


Figure 48. Projected installed capacity by fuel type under the RS

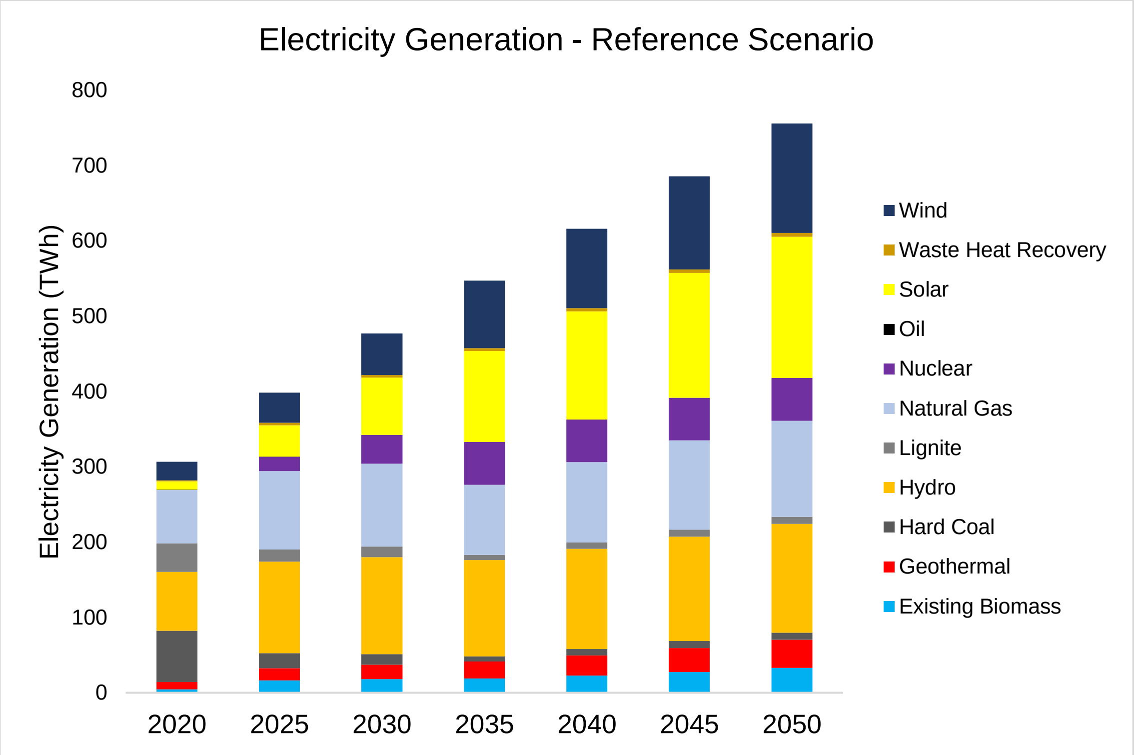


Figure 49. Projected electricity generation by fuel type under the RS

In 2020, biomass energy constituted 1.5% of the total electricity generation and is expected to expand its share to about 4.3% by 2050, resulting in an increase from 4.5 to 33 TWh. The overall share of renewables is projected to reach 73% by 2050 (Figure 49).

Figure 50 illustrates the LBDS results, depicting a lower utilization of biomass for installed electricity capacity and generation throughout the projection period. According to the findings, the projected capacity for new biomass, including biogas CHP and direct combustion CHP, is 11.2 GW, contributing 81.2 TWh to electricity supply in 2050 (Figure 51). The share in generation is expected to increase to 11% by 2050, and the total renewable energy share in overall electricity generation is projected to reach 78% under this scenario.

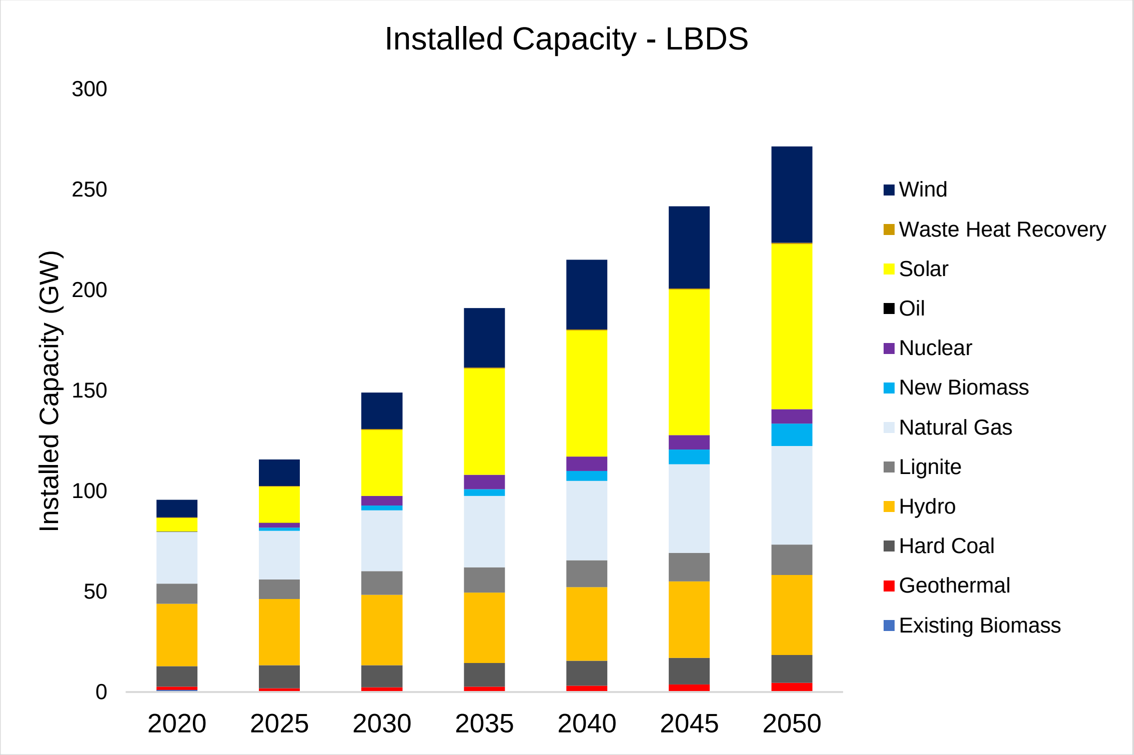


Figure 50. Projected installed capacity by fuel type under the LBDS

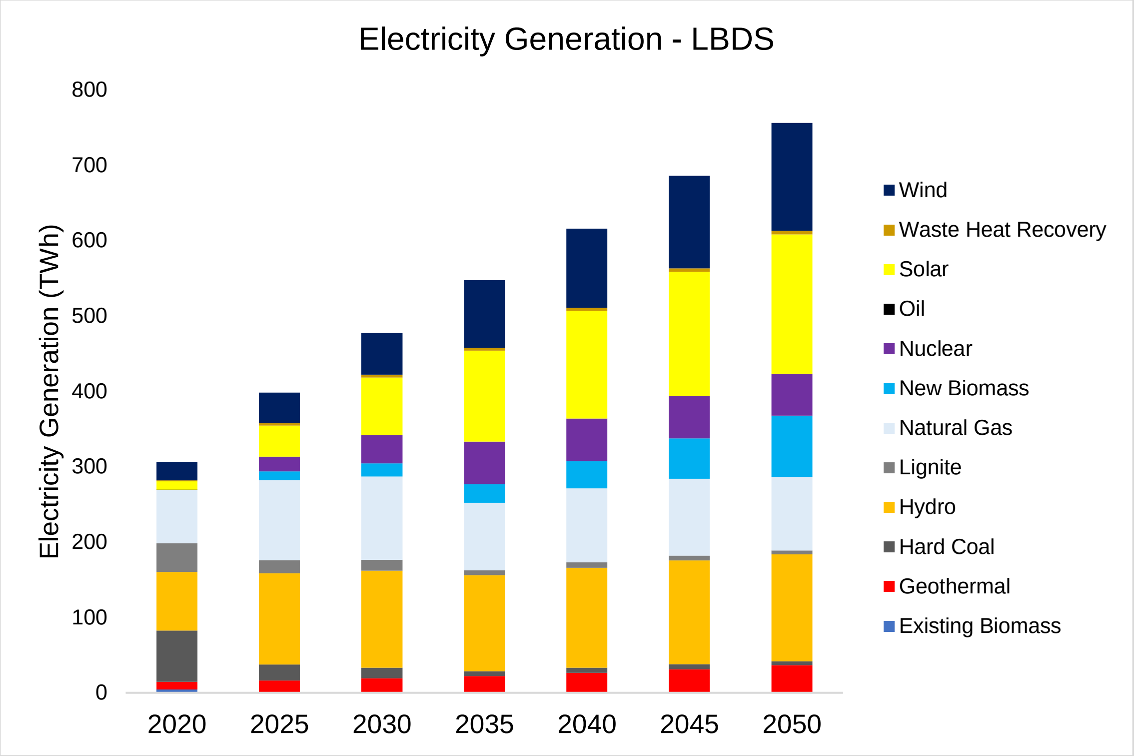


Figure 51. Projected electricity generation by fuel type under the LBDS

In Figure 52, the MBDS results are presented, depicting a more substantial integration of biomass for electricity installed capacity and generation throughout the projection period. According to the results, the capacity for new biomass, including biogas CHP and direct combustion CHP, is projected to reach 14.13 GW, contributing significantly with 101.2 TWh to electricity supply by the year 2050 (Figure 53). The bioenergy share in generation is anticipated to increase to 13% by 2050, while the total renewable energy share in overall electricity generation is projected to achieve 80% under the MBDS.

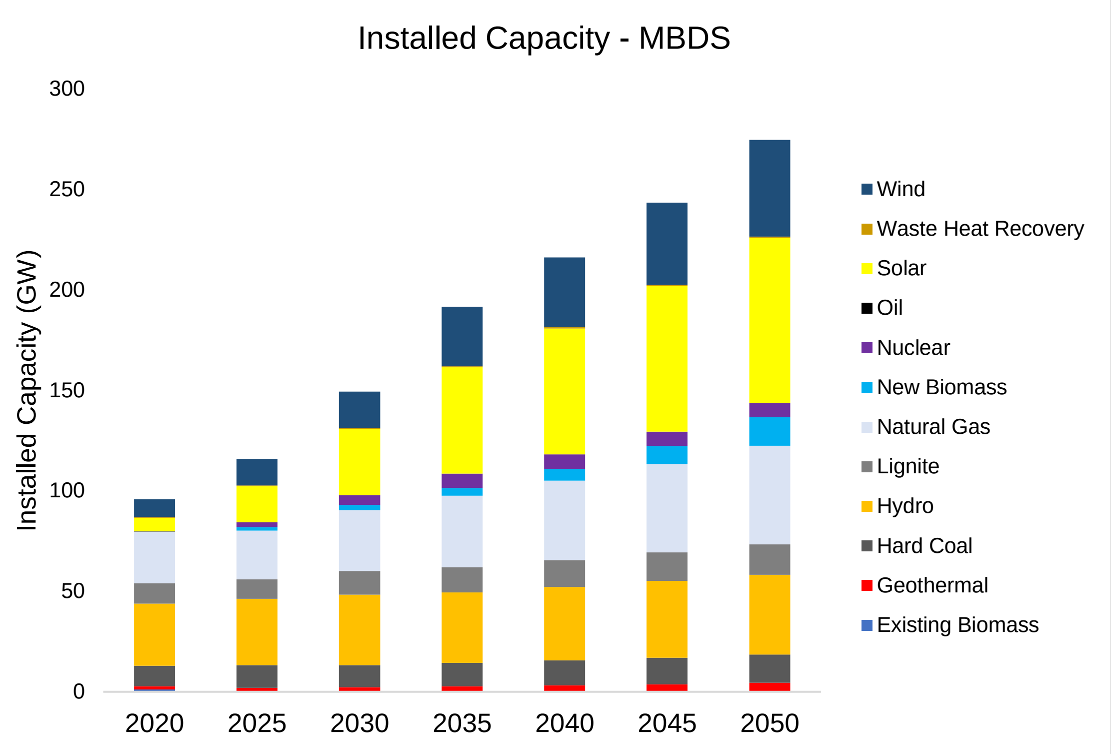


Figure 52. Projected installed capacity by fuel type under the MBDS

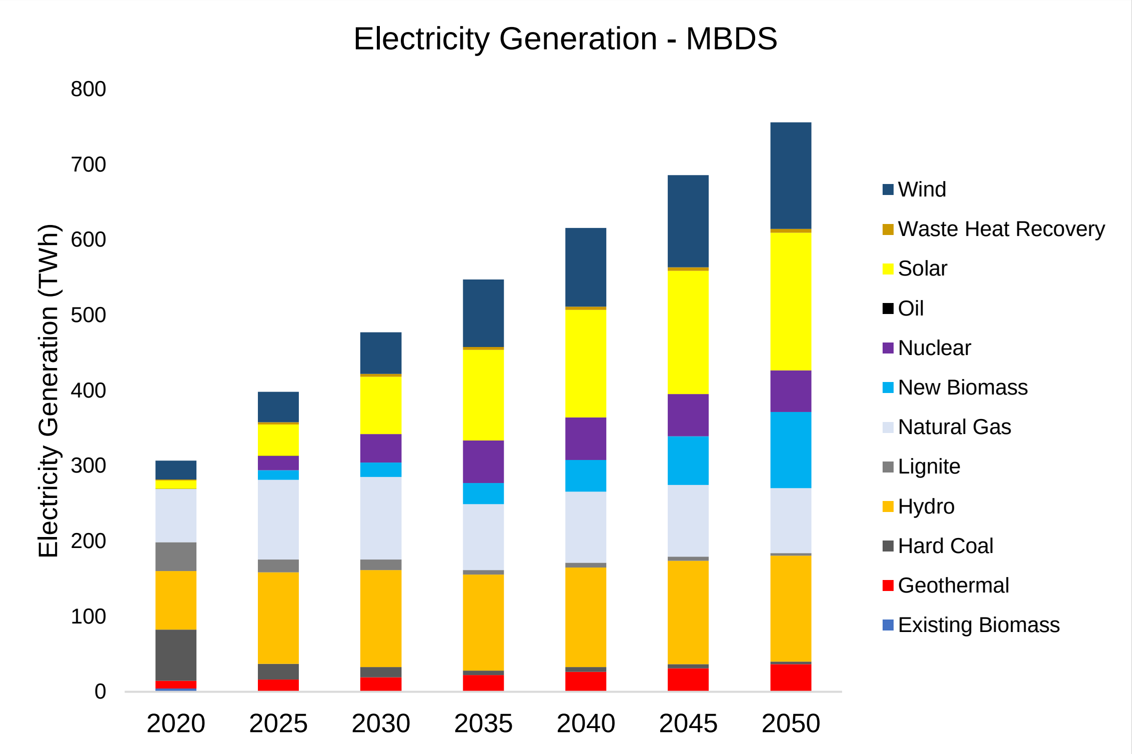


Figure 53. Projected electricity generation by fuel type under the MBDS

In Figure 54, the HBDS results showcase a heightened emphasis on biomass utilization for electricity installed capacity and generation over the projection period. The projected capacity for new biomass, encompassing biogas CHP and direct combustion CHP, is estimated at 17 GW, making a substantial contribution of 120.3 TWh to electricity supply by 2050 (Figure 55). The bioenergy share in generation is expected to see a significant increase, reaching 16% by 2050, while the total renewable energy share in overall electricity generation is projected to reach 82% under the HBDS.

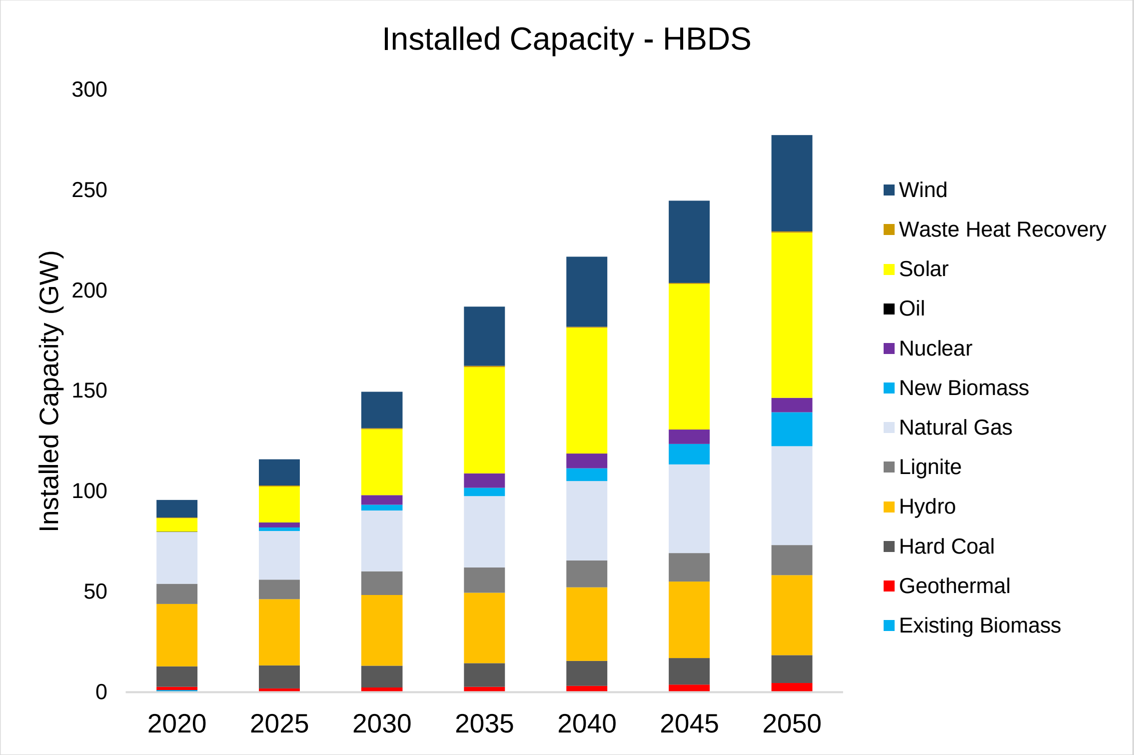


Figure 54. Projected installed capacity by fuel type under the HBDS

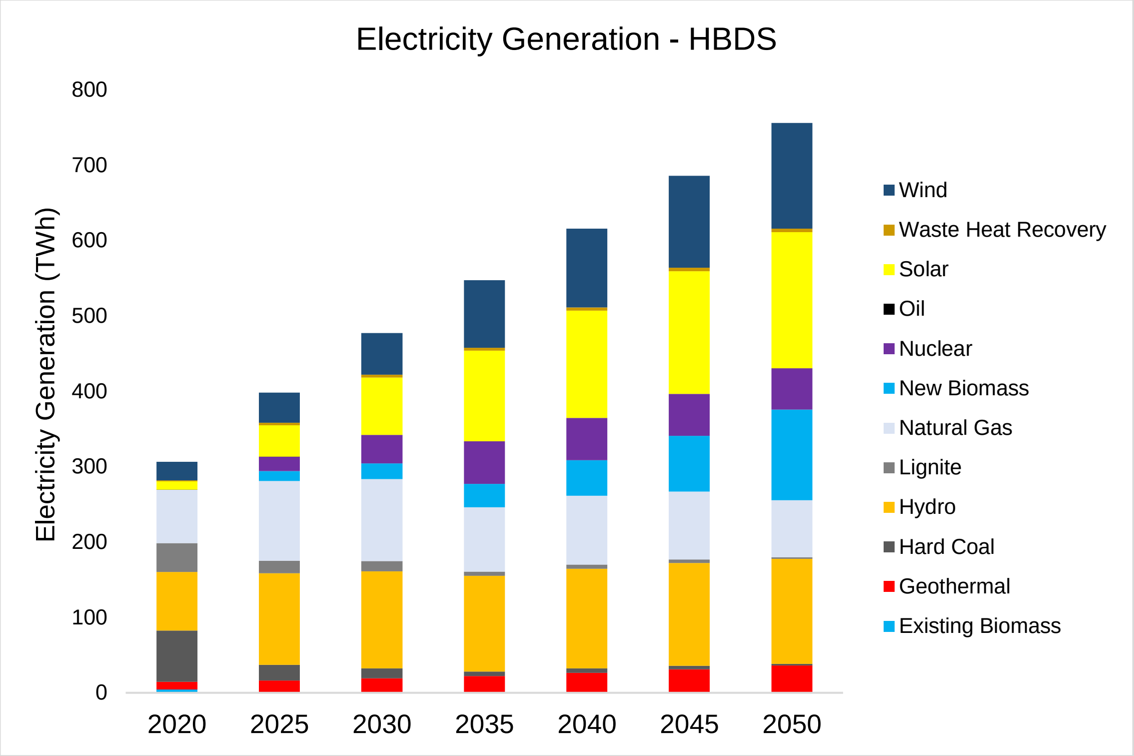


Figure 55. Projected electricity generation by fuel type under the HBDS

4.2.4. Environmental and Cost Assessment of Electricity Generation

GHG emissions from electricity generation exhibit a significant decline across all scenarios throughout the projection period, indicating a notable shift from traditional fossil fuels to cleaner, sustainable energy sources. In the RS scenario, primarily incorporating solar, wind, and nuclear power plants contributes to a reduction in GHG emissions of approximately 48% by the year 2050, reduction from 132 Mt to 68 Mt CO_2eq.

Bioenergy plays a crucial role in significantly reducing GHG emissions during electricity generation, consistently resulting in much lower levels by 2050 compared to the RS. For example, the LBDS leads to a reduction in emissions to 48 Mt CO_2eq, corresponding to a 64% reduction relative to the base year value. In the MBDS, emissions decrease to 41 Mt CO_2eq, with a reduction rate of 69%. The HBDS forecasts emissions of 35.2 Mt CO_2eq in 2050, contributing to a substantial 73% reduction relative to base year emissions. These figures highlight the effectiveness of increased bioenergy utilization in achieving significant reductions in GHG emissions (Figure 56).

After 2035, emissions show a marginal increase in the different scenarios, mainly due to a slowdown in the expansion of renewable energy capacity, especially solar and wind, in contrast to the significant growth observed between 2020 and 2035. A realistic perspective is to expect a more gradual expansion in the deployment of these sources, recognizing their potential to meet almost all of the country's electricity needs over the next fifteen years. In addition, the Plan assumes the continued operation of two planned nuclear power plants in Türkiye until 2035, with no subsequent capacity expansion, thereby contributing to the increase in emissions from 2035 onward.

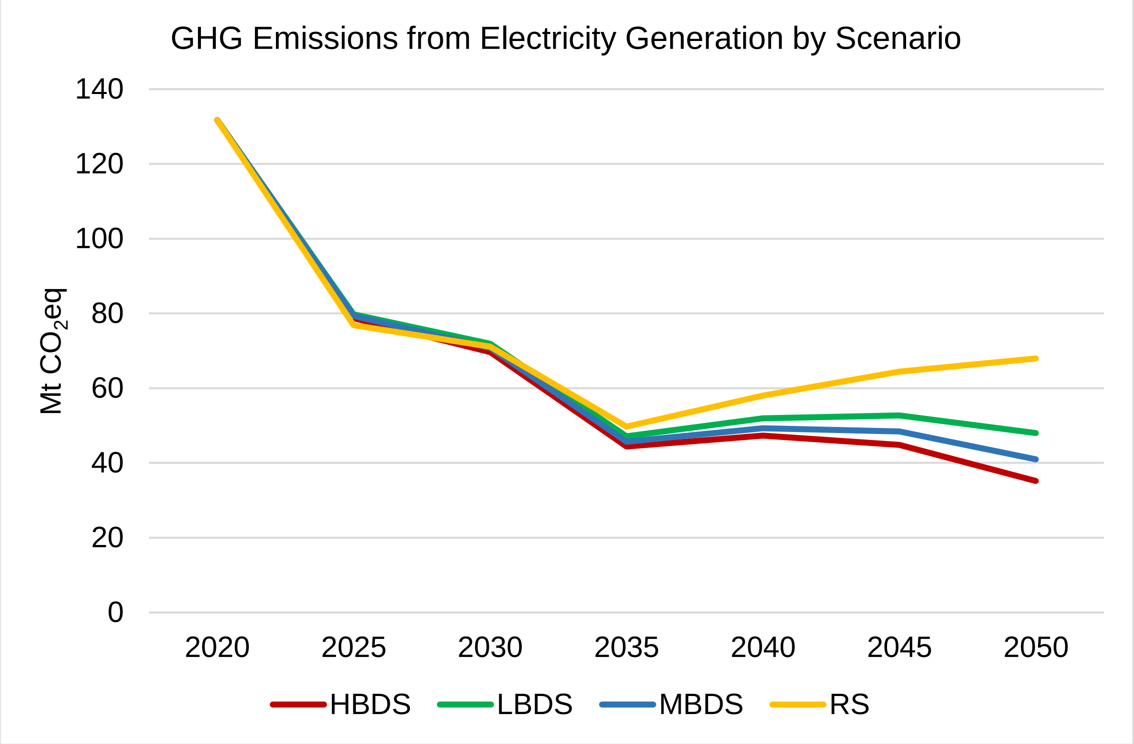


Figure 56. GHG emissions from electricity generation by scenario

The substitution of bioenergy with coal (lignite and hard coal) led to further reductions in emissions across all BDSs. To illustrate, in 2050, the total emissions from coal-to-electricity in the RS reached 20.12 Mt CO_2eq. This figure decreased to 10.37 Mt CO_2eq for LBDS, 7.34 Mt CO_2eq for MBDS, and 5.06 Mt CO_2eq for HBDS. In the RS, bioenergy contributes 280 thousand tons of CO_2eq in 2050. In the BD scenarios, the corresponding figures are 1.17 Mt CO_2eq for LBDS, 1.52 for MBDS, and 1.98 for HBDS in 2050 (Figure 57).

The generation of electricity from bioenergy sources has been identified as a significant contributor to CH_4 and N_2O emissions. In 2050, under the RS, bioenergy is estimated to contribute 130 thousand tons of CH_4, which corresponds to 80% of all CH_4 emissions for that same year. An increase in the proportion of bioenergy results in an elevated level of methane emissions. Consequently, under the HBDS, the CH_4 emissions from bioenergy could reach a maximum of 909 thousand tons, representing 98% of the total CH_4 emissions for the same year (Figure 58).

Figure 59 depicts the distribution of N_2O emissions during electricity generation across all scenarios. In 2050, under the RS, bioenergy contributes 151 thousand tons of N2O, which corresponds to 59% of all N_2O emissions for that year. An increase in the proportion of bioenergy results in an elevated level of N_2O emissions. Consequently, the N_2O emissions from bioenergy under the HBDS could reach 1.07 Mt, representing 97% of the total N_2O emissions for that year.

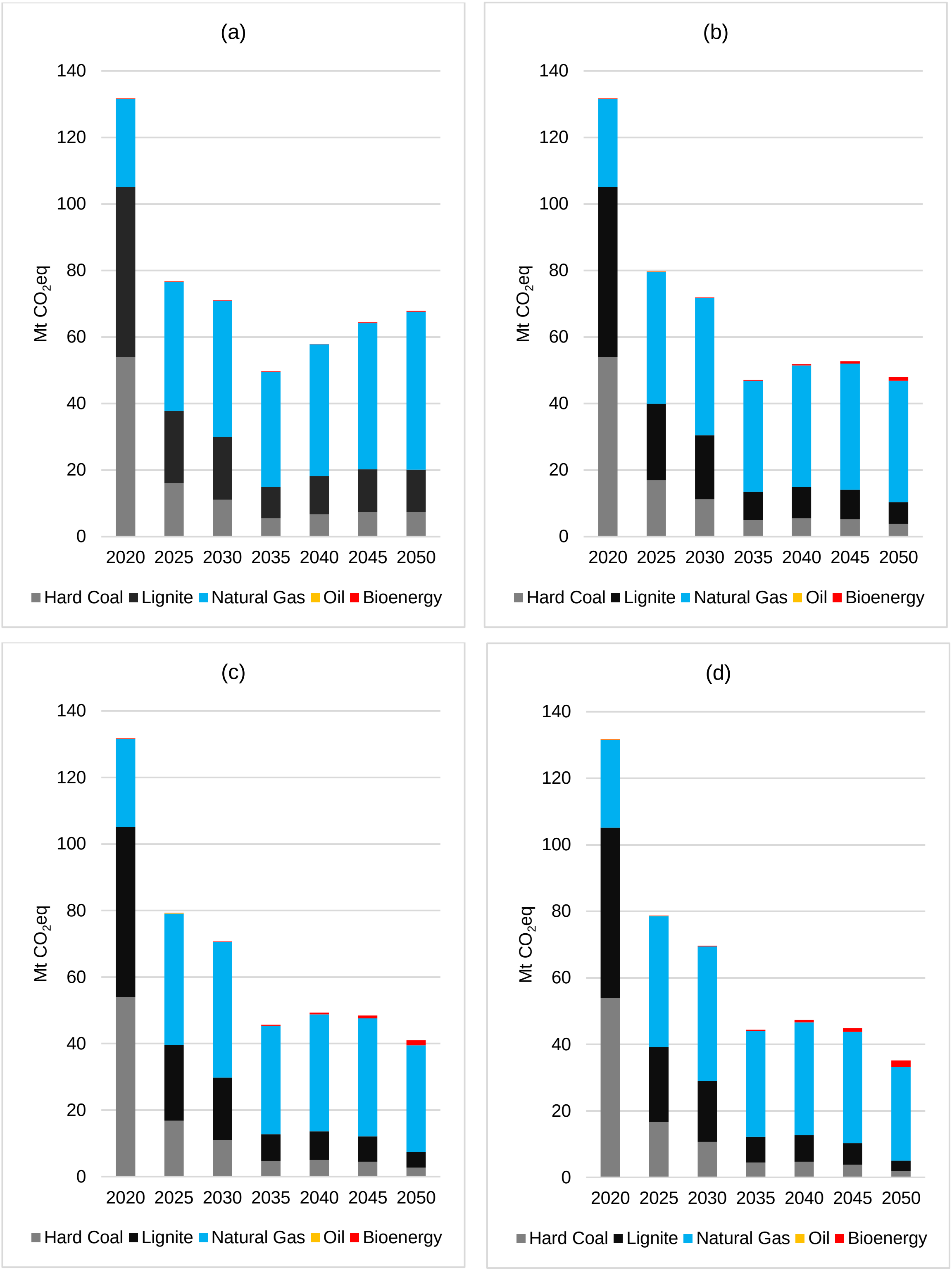


Figure 57. GHG emissions (CO$_2$eq) during electricity generation by fuel type (a) RS, (b) LBDS, (c) MBDS, (d) HBDS

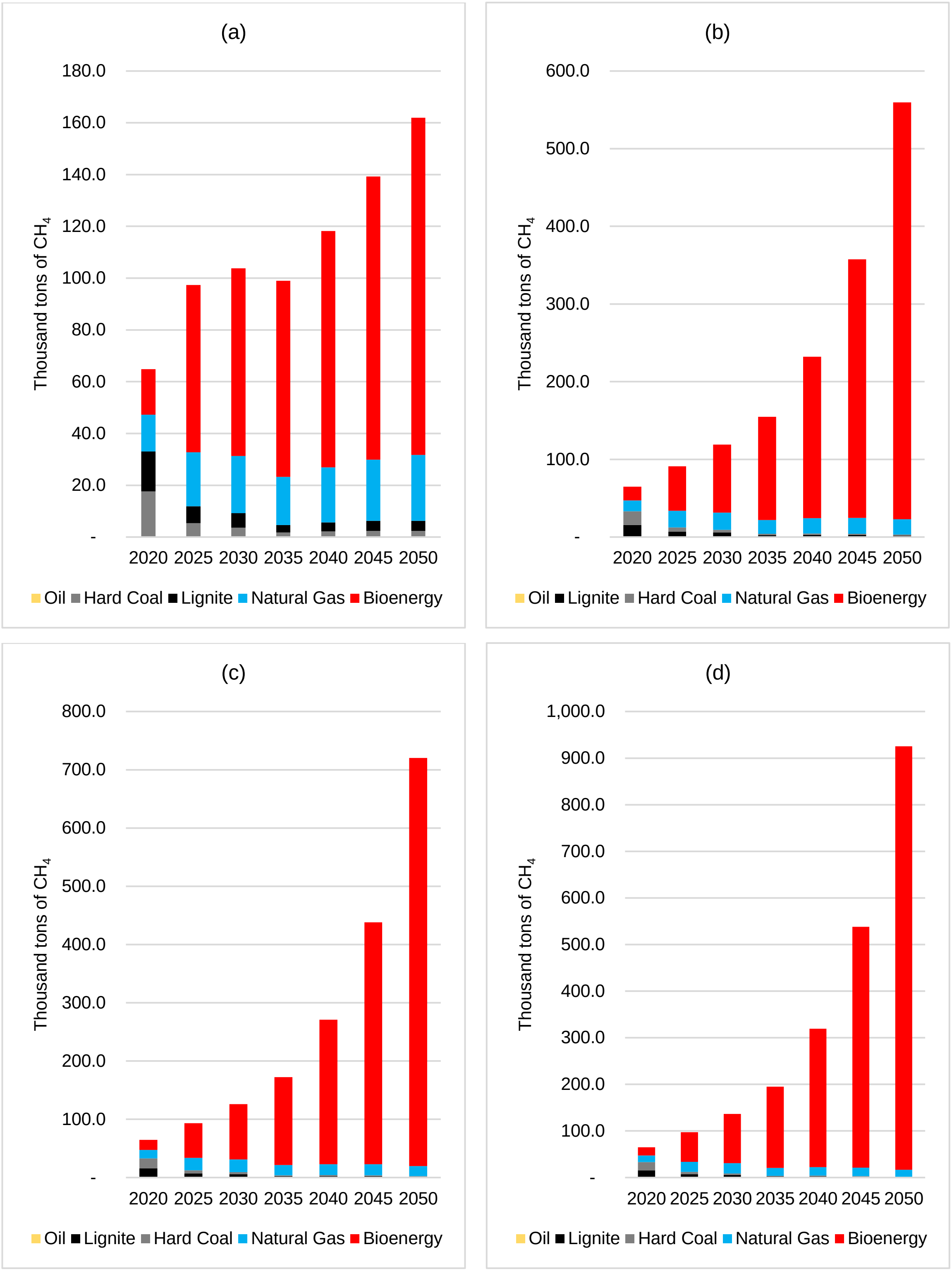


Figure 58. CH_4 emissions during electricity generation by fuel type (a) RS, (b) LBDS, (c) MBDS, (d) HBDS

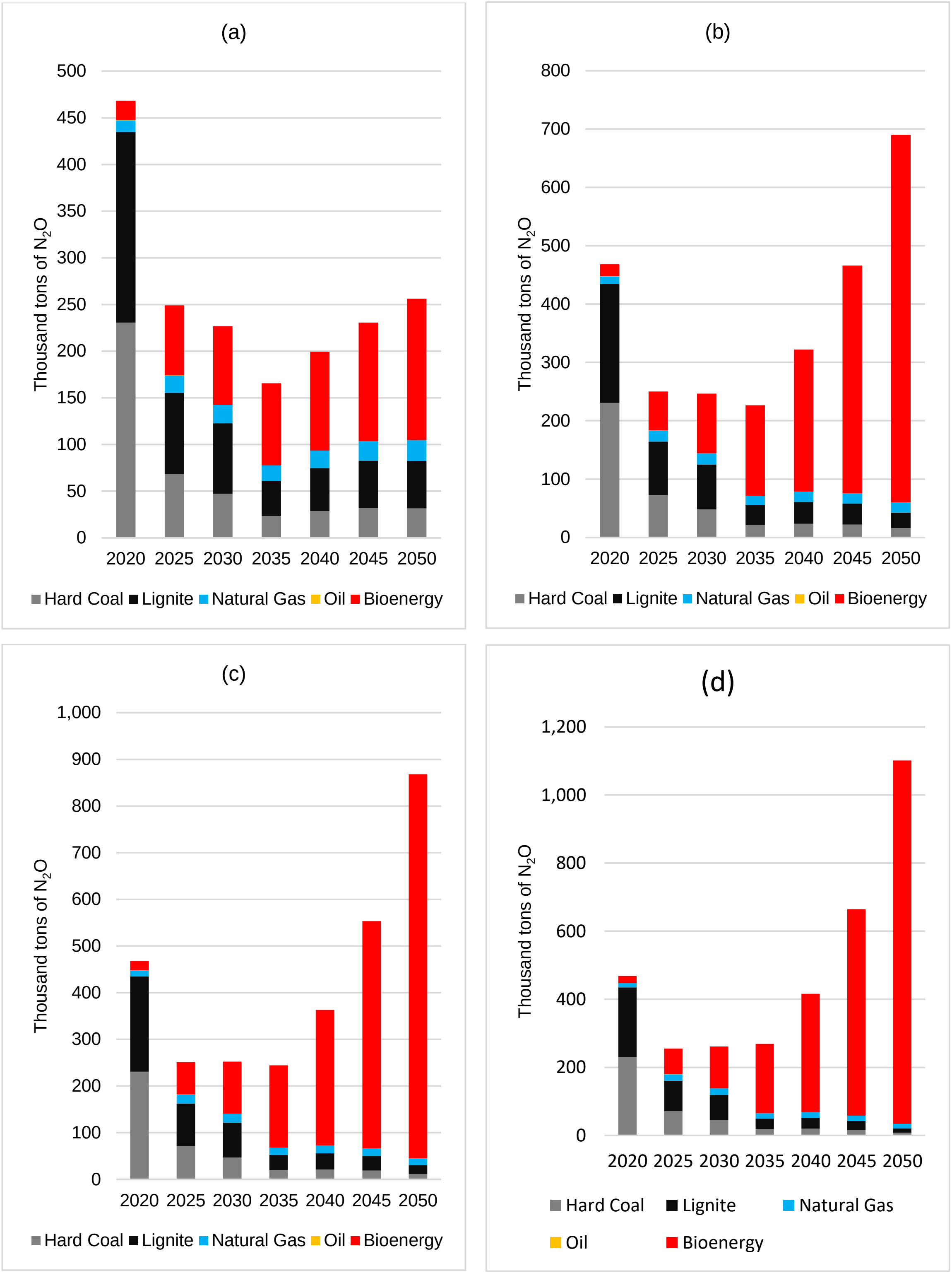


Figure 59. N_2O emissions during electricity generation by fuel type (a) RS, (b) LBDS, (c) MBDS, (d) HBDS

While BDSs achieve greater GHG reductions, they come at a slightly higher cost compared to the RS. Bioenergy's capital costs are higher than traditional fossil fuels, leading to slightly higher total cumulative costs across all BDSs (ranging from 37,455 to 37,830 million 2020 US$) compared to the RS (37,047 million 2020 US$). The additional cost burden relative to the RS is marginal, ranging from 408 to 783 million 2020 US$ (Table 33). The benefit of bioenergy lies in its substantial GHG savings. Compared to the RS, BDSs achieve significant additional reductions: 36.6 Mt CO_2eq for LBDS, 53.7 Mt CO_2eq for MBDS, and 67.9 Mt CO_2eq for HBDS (Table 33). Importantly, the cost per ton of avoided GHG emissions remains consistent across all bioenergy scenarios, ranging from 11.1 to 11.5 US$/ton. This indicates that the additional cost of bioenergy is largely offset by the avoided GHG emissions it generates.

Table 33. Cumulative costs of electricity generation by scenario

Indicator	RS	LBDS	MBDS	HBDS
Total Cumulative Costs (Million 2020 US$)	37,047	37,455	37,650	37,830
Net Present Value (Electricity Generation) (Million 2020 US$)	-	407.8	603.2	782.8
GHG Savings (Mt CO_2eq)	-	36.6	53.7	67.9
Cost of Avoided GHGs (US$/Ton)	-	11.1	11.2	11.5

The findings demonstrate a significant decline in GHG emissions across all scenarios by 2050, with the most reduction occurring in bioenergy scenarios (LBDS, MBDS, HBDS). These scenarios achieved emission reductions of 64%, 69%, and 73% respectively, compared to the base year, highlighting the effectiveness of bioenergy in achieving this goal. While bioenergy use leads to slightly higher costs than the reference scenario that relies on solar, wind, and nuclear power, the additional cost is minimal when compared to the substantial GHG savings achieved. Bioenergy's contribution to GHG emissions comes mainly from N_2O emissions, and these emissions increase with a larger role for bioenergy in the electricity mix. The study suggests that despite this, the cost per ton of avoided GHG emissions remains consistent across bioenergy scenarios, indicating that the economic benefits outweigh the additional cost.

Bioenergy production integrated into existing power infrastructure can offer significant cost advantages compared to building dedicated bioenergy plants. Co-firing biomass with coal in thermal power plants is a very attractive approach to reduce costs. This allows bioenergy to use existing power plant infrastructure, minimizing capital costs. Similarly, upgrading biogas to biomethane and injecting it into the natural gas grid allows bioenergy to use the existing natural gas infrastructure, again avoiding the high capital costs of dedicated bioenergy plants. This integration with the natural gas system is considered a key factor in reducing the cost of bioenergy.

4.3. Discussion

In this section, the scope of the study is assessed by evaluating selected biomass types for their long-term energy potential. Other biomass resources that are unsuitable for long-term electricity production potential estimations are also discussed. The results of this study, particularly the electricity generation potential from biomass, are compared with findings from similar studies worldwide and Türkiye, and the differences are analyzed. For comparison purposes, the highest potential values from this study, which are commonly referenced in the literature, are used.

The methodology and key assumptions used in the study are also covered in this section. Challenges and limitations in bioenergy production are addressed, and future opportunities in this field are explored. Through these discussions, a comprehensive understanding of the potential and feasibility of bioenergy production from various biomass resources is provided, highlighting both the constraints and the prospects for future development.

4.3.1. The scope of this study in long-term bioenergy potential

This study assesses the long-term potential of predictable and sustainable biomass resources for electricity generation, considering a range of bioenergy demand scenarios. The selected biomass types for this study are crop residues, firewood, animal manure, the organic fraction of municipal solid waste, and municipal wasterwater treatment sludge. To generate electricity from these resources, two distinct technologies were employed:

- Direct combustion for solid biomass (crop residues and firewood) and,
- biogas and LFG production for wet biomass (animal manure, organic municipal waste, and sewage sludge).

It is important to note that the objective of this study was not to estimate the theoretical biomass potential of Türkiye. A number of resources were excluded from the calculations, and the following reasons explain why some of the biomass were excluded:

- Crops and their residues with low energy potentials,
- Crop residues with low availability for energy production,
- Crops with weak correlation with key variables in regression analysis for long-term potential estimations,
- Animal manure from less commonly farmed animals ,
- Animal species whose manure is not suitable for biogas production,
- Animal species with weak correlation with key variables in regression analysis,
- Non-organic municipal waste sent to incineration as Refuse Derived Fuel (RDF)

Moreover, this study also excluded various other available biomass resources in Türkiye, such as wastes from different sectors, other woody biomass and energy crops (Table 34). The utilization of additional biomass will make a more substantial contribution to bioenergy capacity and further contribute to the reduction of GHG emissions from electricity generation.

Table 34. Other biomass to be used in bioenergy production in Türkiye

Biomass Types Analyzed in this Study	Other Potential Biomass Types for Bioenergy Production
• Crop residues • Firewood • Animal manure • Organic municipal solid waste • Municipal wastewater treatment sludge	• Other agricultural crops and residues including energy crops, bagasse • Wood industry residues (chips, sawdust, bark) • Wood-based construction and demolition waste • Pellets and briquettes • Food and drink processing wastes (e.g., fruit, vegetable, dairy) • Aquatic biomass such as algae • Paper mill sludge (byproduct of paper production)

4.3.2. Comparison of this study results with global findings

The scope of this study is limited to the projection of biomass potential for electricity generation, with a focus on the most commonly utilized conversion technologies for Türkiye. The results indicate that the total energy potential from solid biomass could reach 1200 PJ by 2050, while the potential for biogas and LFG gas production from wet biomass could reach 11.61 billion cubic meters by the same year.

The potential of biomass as a renewable energy source has received considerable attention worldwide. Table 35 provides a comparative analysis of biomass energy potential across regions and countries, covering a range of biomass types and using different modeling methodologies. In particular, the inclusion of Türkiye's biomass potential, estimated at 120.3 TWh for electricity generation under the highest bioenergy demand scenario by 2050 using the LEAP model, provides valuable insights into the country's renewable energy prospects. By comparing Türkiye's results with global and regional assessments, this table aims to identify potential differences, similarities, and knowledge gaps in biomass energy estimates.

Table 35. Comparison of long-term bioelectricity potential

Region/ Country	**Biomass Type**	**Bioenergy Potential**	**The Modelling Tool used**	**Reference**
World	Energy Crops and biowaste	64-313 EJ/year by 2050	LEAP	[31]
World	Woody Biomass	358 EJ/year by 2050	GLOBIOM	[32]
United Kingdom	Crop and residues, woody biomass, OFMSW, food and drink industry wastes, sewage sludge. Imported dry biomass (pellets and chips), imported bio-oil, bio-ethanol, bio-diesel	More than 1600 PJ/year by 2050	MARKAL	[34]
United Kingdom	Energy crops, crop residues, woody biomass, organic municipal waste, waste fats and oils	1062 TWh/year by 2050	DECC 2050 Calculator	[35]
Switzerland	Domestic biomass resources (woody biomass, food waste, green waste, industrial bio-waste, sewage sludge, animal manure)	6.2 TWh/year for electricity generation by 2050	TIMES	[36]
Australia	Crop straw, woody biomass and bagasse	4.9 GW in 2018	CleanGrid	[37]
China	Crop straw	611 TWh/year for electricity generation by 2030	-	[39]
Pakistan	Agriculture residue, animal manure, municipal waste and forest residue	265 TWh/year for electricity generation by 2050	LEAP	[40]
This study	Crop residues, firewood, animal manure, organic municipal waste, sewage sludge	17 GW capacity and 120.3 TWh/year for electricity generation by 2050	LEAP	

The comparative analysis reveals the significant global potential of biomass as a renewable energy source, with Türkiye emerging as a region with considerable untapped potential. The substantial biomass resources of Türkiye provides a robust foundation for biomass-based electricity generation. However, it is crucial to acknowledge the methodological heterogeneity across studies, which may influence the comparability of results. The accuracy and precision of biomass potential estimates may be influenced by a number of factors, including differing definitions of biomass, the complexities of the modelling employed, and the underlying assumptions made.

To obtain a comprehensive assessment of the biomass potential of Türkiye and its alignment with global trends, further in-depth analysis is necessary. This should include a critical evaluation of the modelling methodologies employed, a detailed characterization of biomass resources, and an exploration of the techno-economic and environmental feasibility of biomass conversion technologies. A comprehensive assessment of this nature will enable policymakers and stakeholders to make well-informed decisions regarding the optimal development and utilization of Türkiye's biomass resources for sustainable energy production.

4.3.3. Comparison of results of this study with other studies for Türkiye

As stated in the section 2.4, there are limited studies carried out in Türkiye match with this study’s scope. Cekinir, S., et al. [48] assumed that bioenergy could contribute up to 390 TWh to electricity generation. This potential is based on the theoretical potential of biomass from all available resources, as taken from other literature carried out for the current year potential estimations. It does not, however, consider future biomass potential estimation results. In a separate study, Senol, H., et al. [49] determined that the generation of electricity from biogas produced from animal manure could contribute up to 19.9 TWh by 2035. Table 36 presents a comparative analysis of the aforementioned studies and this study.

Table 36. Comparison of this study's results with other studies for Türkiye

Biomass Type	Bioenergy Potential	The Projection Period	Reference
All available resources	390 TWh/year by 2050	2020-2050	[48]
Animal Manure	19.9 TWh/year from biogas production by 2035	2022-2035	[49]
This study	28.3 TWh/year from biogas production by 2050	2020-2050	
This study	92 TWh/year from from biomass combustion by 2050	2020-2050	

4.3.4. Comparison of each scenario in terms of electricity capacity by fuel type

In this study, electricity capacity and generation until 2050 are projected under four scenarios. The RS serves as the primary framework, while the other three scenarios (LBDS, MBDS, HBDS) are developed as variations of RS, differing mainly in their bioenergy contributions. For all scenarios, the contributions from solar PV, wind, and nuclear energy are aligned with RS, projecting a total capacity increase to 137.3 GW, which represents 51.8% of the total capacity under RS.

According to the National Energy Plan [18], the country prioritizes capacity increases from solar, wind, and nuclear energy. Specifically, two nuclear plants, one in Akkuyu (Mersin) and another in Sinop, are planned to be fully operational by 2035. Additionally, an average annual increase of 3 GW for solar and 1.4 GW for wind energy is targeted until 2035. These ambitious targets, if achieved, would significantly enhance the country's energy security by reducing reliance on imported fossil fuels.

However, as of 2024, no nuclear plants are operational, and the goal of completing two nuclear plants within the next decade is highly ambitious. In this context, expanding biomass energy using domestic sustainable resources emerges as a more realistic long-term strategy for Türkiye. Biomass expansion could complement solar and wind energy, accelerating the achievement of energy security targets by diversifying the energy mix and reducing fossil fuel dependency.

Therefore, while the primary focus remains on solar, wind, and nuclear energy, integrating biomass energy can offer a pragmatic pathway to meet national energy goals more rapidly. This balanced approach not only addresses the ambitious nature of the current targets but also leverages domestic resources to bolster energy security and sustainability.

Table 37. Projected changes in electricity capacity by fuel type under RS

Fuel Type	2020, MWe	2050, MWe	Capacity increase, %
Biomass	1.1	4.5	304%
Geothermal	1.6	4.5	179%
Hard Coal	10.2	14.0	37%
Hydro	31.0	39.8	28%
Lignite	10.1	15.1	49%
Natural Gas	25.7	49.1	91%
Nuclear	0.0	7.2	-
Oil	0.2	0.0	-100%
Solar	6.7	82.1	1132%
Waste Heat	0.4	0.7	73%
Wind	8.8	48.0	443%
Total	95.8	264.9	177%

Table 38. Projected changes in electricity capacity by fuel type under LBDS

Fuel Type	2020, MWe	2050, MWe	Capacity increase, %
Biomass	1.1	11.2	916%
Geothermal	1.6	4.5	179%
Hard Coal	10.2	14.0	37%
Hydro	31.0	39.8	28%
Lignite	10.1	15.1	49%
Natural Gas	25.7	49.1	91%
Nuclear	0.0	7.2	-
Oil	0.2	0.0	-100%
Solar	6.7	82.1	1132%
Waste Heat	0.4	0.7	73%
Wind	8.8	48.0	443%
Total	95.8	271.6	184%

Table 39. Projected changes in electricity capacity by fuel type under MBDS

Fuel Type	2020	2050	Capacity increase, %
Biomass	1.1	14.1	1178%
Geothermal	1.6	4.5	179%
Hard Coal	10.2	14.0	37%
Hydro	31.0	39.8	28%
Lignite	10.1	15.1	49%
Natural Gas	25.7	49.1	91%
Nuclear	0.0	7.2	-
Oil	0.2	0.0	-100%
Solar	6.7	82.1	1132%
Waste Heat	0.4	0.7	73%
Wind	8.8	48.0	443%
Total	95.8	274.5	187%

Table 40. Projected changes in electricity capacity by fuel type under HBDS

Fuel Type	2020	2050	Capacity increase, %
Biomass	1.1	17.0	1436%
Geothermal	1.6	4.5	179%
Hard Coal	10.2	14.0	37%
Hydro	31.0	39.8	28%
Lignite	10.1	15.1	49%
Natural Gas	25.7	49.1	91%
Nuclear	0.0	7.2	-
Oil	0.2	0.0	-100%
Solar	6.7	82.1	1132%
Waste Heat	0.4	0.7	73%
Wind	8.8	48.0	443%
Total	95.8	277.4	190%

4.3.5. Methodology and Assumptions

This study focused on the potential of sustainable and predictable biomass feedstocks for electricity generation, considering realistic utilization rates. Various statistical methods were employed to estimate long-term biomass and bioenergy potential (Table 20). Population demand and GDP per capita growth were identified as key factors influencing biomass availability. Regression analysis were employed to forecast biomass potentials with strong correlations to these variables. However, certain crop types and animal by-products (e.g., buffalo) exhibiting weak correlations were excluded from long-term estimations. This focus on predictable biomass resources ensures a more reliable assessment of long-term bioenergy potential. However, it is acknowledged that including additional biomass feedstocks could further enhance the projected bioenergy utilization.

Furthermore, as previously stated, the study identified that the selected biomass types can be converted into electricity through two fundamental methods, contingent on their structural composition. These include dry or solid biomass via direct combustion, which is a thermochemical method, and wet biomass via biogas production. Other methods of energy production utilizing biomass in Türkiye include gasification of biomass and electricity generation through syngas production. This is due to the fact that the existing technologies are heavily biased in favour of these two selected technologies. By 2022, biogas and landfill gas will account for 54.5% and direct combustion for 41.1% of the total biomass generating capacity. By the same year, gasification dry power accounted for a mere 1.1% of the total capacity.

Given that certain categories of biomass are compatible with both combustion and biogas production, both of these methods are employed in Türkiye. To illustrate, the animal wastes employed in the production of biomass energy encompass a range of materials beyond those of animal manure. Additionally, other byproducts of animals, such as other parts of the animal's body, are primarily utilized in the poultry sector. As a consequence of their structural composition, these wastes are unsuitable for biogas production; consequently, combustion is the preferred method for their disposal. However, when animal manure and other animal wastes are used in conjunction with forest wastes, they are also subjected to combustion (Table 12). Similarly, sewage sludge is also subjected to combustion after dewatering in some facilities. However, given that animal wastes and sewage sludge are typically employed in biogas production in Türkiye, this study considered the utilization of such wastes in biogas production to be the most appropriate method.

4.3.6. Challenges and limitations in bioenergy production

Türkiye holds a significant position in bioenergy production, as evidenced by the remarkable rate of capacity growth over the last two decades. Bioenergy plants are spread across almost all provinces, indicating the potential for even faster capacity growth. Agricultural residues in particular have significant energy potential, but there are significant challenges to their collection and use for energy production. These challenges include logistical issues arising from Türkiye's large number of small farms and the alternative use of some residues, particularly for purposes such as animal feed.

This study, which estimates the biogas potential of Türkiye from biodegradable municipal waste, assumed a constant average share of 54.5% of this type of waste. However, this assumption may decrease in the future due to increasing zero waste awareness activities, which may limit the total biogas production from this source. On the other hand, the increasing use of integrated waste management facilities with MBT units offers a positive trend. These facilities treat organic waste as a valuable feedstock for biogas production. This can ensure a continuous source of renewable energy even as the overall composition of municipal waste changes.

A major challenge in long-term sludge production estimates lies in predicting the amount generated. This study utilizes the BioWATT tool, which streamlines the process by solely requiring influent wastewater data to determine potential biogas production. However, BioWATT is developed for primarily individual plant assessments. To address this for a nationwide study, assumptions were necessary. This study employed conventional activated sludge technology as the primary system. Additionally, it leveraged average values of critical parameters obtained from a literature review of existing plants across various regions in Türkiye. Furthermore, a visit to the Ankara Central Wastewater Treatment Plant provided valuable data that strengthened the parameters. While plant-based estimations would undoubtedly yield more accurate long-term results, this approach offers a solid framework for national-level projections.

This study avoided making its own long-term forecasts for national population and GDP growth. Instead, it relied on predictions from reputable institutions. However, the study did estimate municipal wastewater potential by forecasting municipal population growth based on national population trends. According to official projections, Türkiye's population is expected to reach 104 million by 2050. However, the inclusion of unrecorded population might lead to a faster population increase. Undoubtedly, a growing population generates more waste and residues, ultimately boosting the country's bioenergy potential.

4.3.7. Opportunities and benefits for further bioenergy production

This study's cost analysis employed current energy source prices without factoring in potential future cost reductions. Consequently, bioenergy scenarios appeared more expensive compared to the reference scenario in cost comparisons. This is primarily due to the high upfront capital costs associated with building bioenergy plants. However, bioenergy offers a significant advantage: its compatibility with existing thermal plants with minor technological upgrades. Utilizing biomass in conjunction with coal (biomass co-firing) or natural gas, after converting it to biomethane, can significantly lower the capital cost of bioenergy implementation.

The benefits of utilizing sustainable biomass potential for energy production go beyond simply reducing emissions by replacing fossil fuels. There are other environmental benefits as well. For example, utilizing animal manure in biogas production not only helps reduce emissions during energy production but also helps reduce emissions associated with manure management. Moreover, the utilization of crop residues for bioenergy production contributes to a reduction in emissions associated with agricultural land management. Traditionally, firewood is used for heating purposes in rural areas. This study promotes the beneficial use of this biomass resource for electricity generation, whether in its traditional form or through conversion into alternative forms such as wood pellet, which is one of the most used biomass resources in electricity generation in worldwide.

This study also promotes advanced waste management through the implementation of integrated waste management plants, where diverse types of waste are systematically sorted and separated for various environmentally friendly purposes. Such practices support the transition to a circular economy and efficient resource management, thereby indirectly contributing to emission reduction by prioritizing waste management in the order of prevention, minimization, re-use, recycling, recovery, and disposal.

The RES scheme plays a crucial role in advancing Türkiye's goal of elevating the share of renewables in electricity generation. Nevertheless, additional incentives and policies focused on biomass-to-energy can enhance the integration of this energy source in future initiatives.

5. CONCLUSIONS AND RECOMMENDATIONS

Building on Türkiye's ambitious renewable energy targets, this study explores the potential of bioenergy to contribute to a sustainable and secure electricity mix. Bioenergy offers a crucial advantage – dispatchability – which complements the variable nature of solar and wind power.

Türkiye's heavy dependence on energy, coupled with a substantial portion of GHG emissions originating from the energy sector, underscores the significance of the country's commitment to achieving a zero-carbon emission target by 2053. In pursuit of this goal, Türkiye has strategically prioritized renewable energy sources over thermal power plants and is actively integrating nuclear energy into its electricity mix.

The country’s official target aims to elevate the share of renewable energy in electricity generation to 55% of the total demand by 2035, with a specific focus on enhancing the capacity of solar and wind electricity generation. Furthermore, nuclear power is expected to have a significant impact on the country's efforts to generate low-carbon electricity, as two power plants are scheduled for operation in the near future. Türkiye does not specify any specific capacity increase for bioenergy due to the complexity of estimating its long-term potential. A comprehensive assessment requires the inclusion of diverse resources. Moreover, long-term energy models tend to categorize bioenergy as a miscellaneous source, prioritizing investments in solar and wind for capacity increases. This is because unlike other renewables, bioenergy's potential relies on the availability of various feedstocks, making it difficult to accurately estimate its long-term potential. This highlights the importance of this study, which offers a more comprehensive analysis by evaluating the potential impact of bioenergy under different long-term scenarios.

The major outcomes of this study can be summarized below:

Biomass and Bioenergy Potential Results

- Crop residues, particularly maize stover and cotton stalk, demonstrate considerable potential for energy growth, with an estimated 673 PJ.
- It is estimated that the total energy potential from crop residues could reach 1140.20 PJ by 2050.
- It is anticipated that the use of firewood will decline because of increased industrialisation of the wood industry. However, the production of roundwood for the purpose of bioenergy generation is projected to reach 7.3 million m^3 by 2050.
- It is estimated that the total energy potential from firewood could reach 56.6 PJ by 2050.
- The growth in animal population presents an opportunity for increased biogas production from manure, with an estimated potential of 7.25 billion m^3 CH_4 by 2050.
- Cattle manure has the highest potential for biogas production, with an estimated 4.85 billion m^3 CH_4 by 2050.
- The MSW management scenarios illustrate a transition towards more sustainable practices, with the HBDS scenario demonstrating a preference for biogas generation through AD plants, which offers environmental and economic benefits.
- It is possible that increasing the capacity of MBT units could result in an increase in the rate of biogas generation from MSW without the necessity for landfilling.
- The highest potential for LFG and biogas production from MSW is estimated to reach 674.9 million m^3 of CH_4 and 3.16 billion m^3 of CH_4, respectively, by 2050.
- The utilization of sewage sludge from wastewater treatment plants represents a significant potential source for biogas, with the highest potential of 525.2 million m^3 CH_4 under a 100% utilization scenario.
- The overall biogas production potential with 100% utilization could reach 11.61 billion m^3 CH_4 by 2050. The largest proportion of the total is

accounted for by animal manure (62.4%), followed by municipal solid waste (33%) and sewage sludge (4.6%).

Electricity Demand and Bioenergy Integration to Electricity Supply

- Türkiye's electricity demand is projected to surge to approximately 642.5 TWh by 2050, necessitating a robust and diversified energy mix.
- The highest electricity demand is projected to be in the industrial sector, reaching 325.6 TWh from 117.5 TWh in 2020.
- RS is developed based on the Türkiye’s National Energy Plan, covers 2020-2035 period. The Plan targets 55% of electricity generation will be provided by renewables and the installed capacity of renewables will be 65% of all energy source by 2035.
- The Plan targets significant expansion of solar and wind energy capacity by 2035. The targeted capacities are 52.9 GW for solar and 29.6 GW for wind energy.
- The Plan also targets a nuclear energy capacity of 7.2 GW by 2035.
- With a 15-year expansion under the RS scenario, the share of renewables in electricity generation could reach 73% in 2050.
- Under the RS scenario, the bioenergy capacity could reach 4.5 GW by 2050, accounting for 4.3% of electricity generation.
- Bioenergy demand scenarios (LBDS, MBDS, HBDS) explored in this study demonstrate the significant potential of biomass resources for electricity generation in Türkiye.
- Under the LBDS scenario, the share of bioenergy could reach a notable 11% in electricity generation by 2050.
- Under the MBDS scenario, the share of bioenergy could reach a 13% in electricity generation by 2050.
- Under the HBDS scenario, the share of bioenergy could reach a notable 16% share in electricity generation by 2050, highlighting the substantial opportunity for biomass to contribute meaningfully to the country's energy mix.

- Under the HBDS scenario, electricity generation from solid biomass could reach 92 TWh by 2050 (12.2% of total generation)
- Under the HBDS scenario, electricity generation from biogas could reach 28 TWh by 2050 (3.8% of total generation)

GHG Emissions Reduction with Bioenergy

- The base year (2020) GHG emissions from electricity generation are estimated at 132 Mt CO_2eq.
- Under the RS, the GHG emission reduction could reach 48% by 2050 and the emissions from electricity generation could be 68 Mt CO_2eq.
- The primary contribution to these emission reductions is the high level of capacity expansion of solar, wind, and nuclear energies.
- Increased bioenergy utilization plays a crucial role in achieving substantial reductions in GHG emissions from electricity generation.
- Bioenergy demand scenarios achieve significantly lower emissions by 2050.
- Under the LBDS, the GHG emission reduction could reach 64% by 2050 and the emissions from electricity generation could be 48 Mt CO_2eq.
- Under the MBDS, the GHG emission reduction could reach 69% by 2050 and the emissions from electricity generation could be 41 Mt CO_2eq.
- Under the HBDS, the GHG emission reduction could reach 73% by 2050 and the emissions from electricity generation could be 35 Mt CO_2eq.

Cost-Effectiveness of Bioenergy

- Bioenergy demand scenarios come with slightly higher total cumulative costs compared to the RS due to the higher capital costs of bioenergy infrastructure.
- The additional cost of electricity generation (compared to the RS) ranges from 408 to 783 million 2020 US$.
- These additional costs are minimal when compared to the substantial GHG savings achieved.

- The cost per ton of avoided GHG emissions remains consistent across all bioenergy scenarios, ranging from 11.1 to 11.5 US$. This highlights the economic viability of bioenergy for achieving climate goals.

Future Considerations for Bioenergy Development

- Future research efforts should explore strategies for optimizing bioenergy production from various biomass resources while ensuring sustainable practices throughout the supply chain.
- Technological advancements to improve the efficiency and cost-effectiveness of bioenergy conversion technologies are also crucial. Additionally, developing effective policies and incentives to encourage wider adoption of bioenergy within the electricity sector can significantly contribute to this goal. By addressing these areas, Türkiye can unlock the full potential of bioenergy and contribute to a cleaner and more sustainable energy future.
- Using both dry and wet biomass resources in CHP plants can increase the energy efficiency compared to traditional heating purposes. The biggest challange is reaching the biomass from the diverse collected locations this can be solved with employing centralized biogas or biomass plants.
- Increasing the share of integrated waste treatment plants in which all different types of waste are utilized for different purposes is the most important and urgent investment for municipalities by leaving these valuable waste from landfilling and low yield LFG production.
- Employing advanced technologies like activated sludge plants can maximize biogas yield from wastewater treatment facilities, contributing to renewable energy production and meeting plant energy needs.
- Integrating bioenergy production with existing power infrastructure offers significant cost benefits. Co-firing biomass with coal in existing thermal plants and upgrading biogas to biomethane for injection into the natural gas grid leverage existing facilities, minimizing the need for expensive dedicated bioenergy plants. This focus on infrastructure integration is key to reducing the overall cost of bioenergy production.

- Future studies can also explore a wider range of biomass resources, conversion technologies, and applications beyond electricity generation. Additionally, prioritizing sustainable practices for sourcing and managing biomass resources is crucial. To ensure efficient utilization, strategies for collecting and transporting biomass from diverse locations to centralized processing facilities are essential.
- This study could be further enhanced by the analysis of regional biomass potential according to biomass type. Furthermore, a more detailed environmental and cost analysis could be conducted.

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7. APPENDICES

APPENDIX 1 – Türkiye’s Electricity Outlook

Table A. 1. Türkiye’s electricity installed capacity by source (MW) [21]

Year	Hard coal + Asphaltite +Imported coal	Lignite	Oil	Natural Gas	Waste Heat	Biomass	Hydraulic	Wind	Geothermal	Solar	Nuclear	Total
2000	480	6,509	1,996	7,044	14	10	11,175	19	18	0	0	27,265
2001	480	6,511	2,455	7,154	14	10	11,673	19	18	0	0	28,334
2002	480	6,503	2,856	9,702	14	14	12,241	19	18	0	0	31,847
2003	1,800	6,439	3,203	11,505	14	14	12,579	19	15	0	0	35,588
2004	1,845	6,451	3,215	12,606	14	14	12,645	19	15	0	0	36,824
2005	1,986	7,131	2,961	13,790	22	14	12,906	20	15	0	0	38,845
2006	1,986	8,211	2,397	14,331	22	20	13,063	59	82	0	0	40,171
2007	1,986	8,211	2,000	14,576	22	21	13,395	146	169	0	0	40,526
2008	1,986	8,205	2,290	15,055	21	38	13,829	364	30	0	0	41,818
2009	2,391	8,110	2,140	16,617	22	65	14,553	792	77	0	0	44,767
2010	3,751	8,199	2,046	18,175	22	86	15,831	1,320	94	0	0	49,524
2011	4,351	8,199	1,778	19,477	22	104	17,137	1,729	114	0	0	52,911
2012	4,383	8,193	1,884	20,399	22	147	19,609	2,261	162	0	0	57,060
2013	4,383	8,223	1,229	24,579	57	178	22,289	2,760	311	0	0	64,009

Year	Hard coal + Asphaltite +Imported coal	Lignite	Oil	Natural Gas	Waste Heat	Biomass	Hydraulic	Wind	Geothermal	Solar	Nuclear	Total
2014	6,533	8,281	1,181	25,508	72	227	23,643	3,630	405	40	0	69,520
2015	6,825	8,697	1,105	24,906	93	277	25,868	4,503	624	249	0	73,147
2016	8,229	9,270	645	25,771	133	364	26,681	5,751	821	833	0	78,498
2017	9,576	9,090	299	26,639	157	477	27,273	6,516	1,064	3,421	0	84,512
2018	9,576	9,421	991	26,109	189	622	28,291	7,005	1,283	5,063	0	88,550
2019	10,183	10,101	312	25,904	372	791	28,503	7,591	1,515	5,995	0	91,267
2020	10,203	10,120	312	25,675	380	1,105	30,984	8,832	1,613	6,667	0	95,891
2021	10,240	10,120	258	25,574	391	1,643	31,493	10,607	1,669	7,816	0	99,811

Table A. 2. Türkiye’s electricity generation by source (GWh) [21]

Year	Hard coal + Asphaltite +Imported coal	Lignite	Oil	Natural Gas	Waste Heat	Biomass	Hydraulic	Wind	Geothermal	Solar	Nuclear	Total
2000	3,819	34,367	9,311	46,217	46	174	30,879	33	76	0	0	124,922
2001	4,046	34,372	10,366	49,549	42	188	24,010	62	90	0	0	122,725
2002	4,093	28,056	10,744	52,497	40	134	33,684	48	105	0	0	129,401
2003	8,663	23,590	9,196	63,536	30	86	35,330	61	89	0	0	140,581
2004	11,998	22,450	7,670	62,242	21	83	46,084	58	93	0	0	150,699
2005	13,246	29,946	5,483	73,445	78	45	39,561	59	94	0	0	161,957
2006	14,217	32,433	4,340	80,691	81	73	44,244	127	94	0	0	176,300
2007	15,136	38,295	6,527	95,025	104	109	35,851	355	156	0	0	191,558
2008	15,858	41,858	7,519	98,685	66	154	33,270	847	162	0	0	198,419
2009	16,596	39,090	4,804	96,095	76	264	35,958	1,495	436	0	0	194,814
2010	19,104	35,942	2,180	98,144	111	347	51,796	2,916	668	0	0	211,208
2011	27,348	38,870	904	104,048	106	364	52,339	4,724	694	0	0	229,397
2012	33,324	34,689	1,639	104,499	112	609	57,865	5,861	899	0	0	239,497
2013	33,524	30,262	1,739	105,116	278	893	59,420	7,558	1,364	0	0	240,154
2014	39,647	36,615	2,145	120,576	338	1,094	40,645	8,520	2,364	17	0	251,961
2015	44,830	31,336	2,224	99,219	408	1,350	67,146	11,653	3,425	194	0	261,785
2016	53,703	38,570	1,926	89,227	713	1,659	67,231	11,653	4,819	1,043	0	270,544
2017	56,782	40,694	1,200	110,490	848	2,124	58,218	17,904	6,127	2,889	0	297,276
2018	68,162	45,087	329	92,483	950	2,673	59,938	19,949	7,431	7,800	0	304,802

Year	Hard coal + Asphaltite +Imported coal	Lignite	Oil	Natural Gas	Waste Heat	Biomass	Hydraulic	Wind	Geothermal	Solar	Nuclear	Total
2019	66,022	46,872	336	57,288	1,101	3,523	88,823	21,731	8,952	9,250	0	303,898
2020	67,874	37,938	323	70,931	1,277	4,460	78,094	24,828	10,028	10,950	0	306,703
2021	60,399	42,983	281	111,181	1,311	6,468	55,927	31,437	10,793	13,943	0	334,723

Table A. 3. Electricity demand of türkiye by sector (GWh)

Year	Residential	Commercial and Services	Industry	Agriculture	Transport	Total Demand, GWh
2000	23,886	21,786	46,694	3,071	720	96,157
2001	23,588	22,478	45,373	3,204	820	95,463
2002	23,575	24,769	48,651	3,491	830	101,316
2003	25,147	26,982	54,091	3,658	890	110,768
2004	27,620	30,027	58,052	3,896	731	120,327
2005	30,872	34,973	58,732	4,114	749	129,439
2006	34,480	35,345	67,184	4,442	790	142,241
2007	36,457	37,947	73,716	4,982	936	154,038
2008	39,515	41,245	72,894	5,808	545	160,007
2009	39,224	41,780	69,339	4,880	556	155,779
2010	41,464	45,095	78,273	5,587	591	171,009
2011	44,292	48,040	86,867	5,148	657	185,004
2012	45,417	50,573	91,175	5,851	799	193,815
2013	44,956	54,114	92,106	4,915	826	196,918
2014	46,245	57,294	96,786	5,162	917	206,403
2015	47,910	59,945	102,058	4,882	1,063	215,857
2016	51,213	63,752	106,533	6,807	1,156	229,461
2017	54,261	70,211	114,649	6,799	1,292	247,213
2018	54,600	75,474	115,985	9,280	1,191	256,531
2019	56,204	74,268	113,365	9,573	1,578	254,988
2020	60,704	69,008	117,430	11,552	1,436	260,130

Table A. 4. Türkiye's bioenergy installed capacity (MW)

Year	RES Licenced Bioenergy Installed Capacity	Unlicensed Installed Capacity	Total, Installed Capacity, MW
2000	-	10.0	10.0
2001	-	10.0	10.0
2002	-	13.8	13.8
2003	-	13.8	13.8
2004	-	13.8	13.8
2005	-	13.8	13.8
2006	-	19.8	19.8
2007	-	21.2	21.2
2008	-	38.2	38.2
2009	-	65.0	65.0
2010	45.3	40.5	85.7
2011	26.8	77.5	104.2
2012	130.1	17.2	147.3
2013	146.9	31.0	178.0
2014	185.2	41.8	227.0
2015	203.7	73.4	277.1
2016	300.0	63.8	363.8
2017	349.2	128.2	477.4
2018	519.1	102.7	621.9
2019	671.2	120.1	791.3
2020	873.3	232.0	1105.3
2021	1273.0	369.7	1642.7

APPENDIX 2 – Key Assumptions Forecast Results

Table A. 5. Population and GDP forecast results

Year	Population	GDP billion US$ (constant 2015 prices)	GDP US$ per capita (constant 2015 prices)
2000	64,729,501	414	6,393
2001	65,603,160	390	5,945
2002	66,401,851	415	6,253
2003	67,187,251	439	6,536
2004	68,010,215	482	7,089
2005	68,860,539	525	7,631
2006	69,729,967	562	8,059
2007	70,586,256	590	8,363
2008	71,517,100	595	8,322
2009	72,561,312	566	7,806
2010	73,722,988	614	8,331
2011	74,724,269	683	9,140
2012	75,627,384	716	9,463
2013	76,667,864	776	10,127
2014	77,695,904	815	10,486
2015	78,741,053	864	10,977
2016	79,814,871	893	11,189
2017	80,810,525	960	11,880
2018	82,003,882	989	12,056
2019	83,154,997	997	11,995
2020	83,614,362	1,016	12,148

Year	Population	GDP billion US$ (constant 2015 prices)	GDP US$ per capita (constant 2015 prices)
2021	84,680,273	1,131	13,357
2022	85,911,035	1,169	13,611
2023	86,907,367	1,233	14,184
2024	87,885,571	1,300	14,792
2025	88,844,934	1,366	15,370
2026	89,784,584	1,427	15,896
2027	90,703,600	1,485	16,372
2028	91,601,117	1,540	16,815
2029	92,476,323	1,594	17,235
2030	93,328,574	1,646	17,640
2031	94,153,776	1,698	18,034
2032	94,951,512	1,749	18,421
2033	95,721,347	1,800	18,802
2034	96,463,090	1,850	19,180
2035	97,176,768	1,900	19,554
2036	97,862,549	1,950	19,929
2037	98,520,720	2,000	20,304
2038	99,151,467	2,051	20,682
2039	99,754,923	2,101	21,064
2040	100,331,233	2,152	21,450
2041	100,882,655	2,203	21,842
2042	101,409,507	2,255	22,238
2043	101,911,980	2,307	22,639

Year	Population	GDP billion US$ (constant 2015 prices)	GDP US$ per capita (constant 2015 prices)
2044	102,390,159	2,359	23,044
2045	102,843,989	2,412	23,453
2046	103,273,571	2,465	23,865
2047	103,679,038	2,517	24,279
2048	104,060,257	2,570	24,694
2049	104,417,089	2,622	25,111
2050	104,749,423	2,674	25,528

Table A. 6. Sectoral gross value added to GDP

Year	Agriculture	Industry	Services	Total
	billion US$ at constant 2015 prices			
2020	67.7	438.3	556.8	1,062.8
2021	75.4	488.3	620.4	1,184.1
2022	78.0	505.1	641.6	1,224.7
2023	82.3	532.5	676.5	1,291.3
2024	86.8	561.7	713.5	1,361.9
2025	91.1	590.0	749.5	1,430.6
2026	95.2	616.6	783.4	1,495.2
2027	99.1	641.6	815.1	1,555.8
2028	102.8	665.5	845.4	1,613.7
2029	106.4	688.6	874.8	1,669.8
2030	109.9	711.3	903.6	1,724.8
2031	113.3	733.6	932.0	1,778.9
2032	116.7	755.7	960.0	1,832.5
2033	120.1	777.6	987.9	1,885.6
2034	123.5	799.4	1,015.5	1,938.3
2035	126.8	821.0	1,043.0	1,990.8
2036	130.2	842.6	1,070.5	2,043.3
2037	133.5	864.3	1,098.0	2,095.8
2038	136.9	886.0	1,125.6	2,148.4
2039	140.2	907.9	1,153.3	2,201.4
2040	143.6	929.9	1,181.3	2,254.8
2041	147.1	952.0	1,209.4	2,308.5
2042	150.5	974.4	1,237.8	2,362.6

Year	Agriculture	Industry	Services	Total
	billion US$ at constant 2015 prices			
2043	154.0	996.8	1,266.3	2,417.1
2044	157.5	1,019.4	1,295.0	2,471.9
2045	161.0	1,042.1	1,323.9	2,527.0
2046	164.5	1,064.9	1,352.8	2,582.1
2047	168.0	1,087.6	1,381.6	2,637.2
2048	171.5	1,110.3	1,410.5	2,692.2
2049	175.0	1,132.9	1,439.2	2,747.0
2050	178.5	1,155.3	1,467.7	2,801.5

Table A. 7. Household size and household number forecast results

Year	Household Size	Household Number (million)
2020	3.4	24.6
2021	3.4	25.0
2022	3.4	25.5
2023	3.3	26.0
2024	3.3	26.4
2025	3.3	26.8
2026	3.3	27.2
2027	3.3	27.6
2028	3.3	28.0
2029	3.3	28.5
2030	3.2	28.9
2031	3.2	29.3
2032	3.2	29.6
2033	3.2	30.0
2034	3.2	30.4
2035	3.2	30.8
2036	3.1	31.2
2037	3.1	31.5
2038	3.1	31.9
2039	3.1	32.3
2040	3.1	32.6
2041	3.1	32.9
2042	3.0	33.3
2043	3.0	33.6

Year	Household Size	Household Number (million)
2044	3.0	33.9
2045	3.0	34.3
2046	3.0	34.6
2047	3.0	34.9
2048	3.0	35.2
2049	2.9	35.5
2050	2.9	35.8

APPENDIX 3 – Biomass Potential Forecast Results

Table A. 8. Arable crop production forecast results (in tons)

Year	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Soybean	Dry bean	Chickpea	Groundnut	Sugarbeet	Cotton
2020	20,489,820	8,300,396	295,353	314,872	6,501,345	980,612	2,069,942	155,294	279,091	629,220	215,812	23,025,141	1,774,547
2021	17,671,024	5,736,072	199,511	276,637	6,748,309	999,666	2,415,090	182,151	305,064	473,249	233,994	18,250,097	2,247,851
2022	23,577,645	7,745,225	346,633	228,620	7,991,947	1,047,731	2,240,486	226,819	255,679	640,250	200,572	19,163,383	2,170,190
2023	23,849,354	7,889,318	350,653	228,199	8,443,689	1,057,136	2,326,616	240,096	258,644	647,676	210,918	19,385,626	2,224,483
2024	24,083,930	8,069,514	354,599	228,147	8,924,092	1,061,550	2,412,184	253,777	261,556	654,966	221,799	19,603,825	2,294,706
2025	24,326,341	8,232,946	358,470	227,864	9,391,823	1,067,653	2,497,525	267,266	264,411	662,115	232,433	19,817,821	2,357,932
2026	24,592,356	8,360,747	362,262	227,142	9,831,644	1,077,812	2,582,650	280,335	267,207	669,118	242,530	20,027,420	2,405,979
2027	24,880,792	8,453,796	365,970	225,998	10,243,481	1,091,882	2,667,389	292,969	269,942	675,967	252,085	20,232,417	2,439,226
2028	25,179,329	8,525,994	369,591	224,598	10,637,286	1,108,069	2,751,453	305,295	272,613	682,656	261,282	20,432,618	2,463,704
2029	25,480,361	8,585,764	373,122	223,045	11,018,803	1,125,278	2,834,610	317,380	275,218	689,178	270,226	20,627,842	2,483,061
2030	25,777,592	8,640,078	376,561	221,425	11,392,717	1,142,598	2,916,651	329,276	277,754	695,530	279,002	20,817,946	2,500,320
2031	26,065,069	8,693,876	379,890	219,812	11,760,765	1,159,282	2,997,047	340,969	280,210	701,679	287,633	21,002,016	2,517,645

Year	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Soybean	Dry bean	Chickpea	Groundnut	Sugarbeet	Cotton
2032	26,339,295	8,750,963	383,109	218,255	12,125,215	1,174,828	3,075,628	352,479	282,584	707,624	296,158	21,179,959	2,536,678
2033	26,598,971	8,812,566	386,215	216,776	12,486,354	1,189,062	3,152,248	363,796	284,876	713,362	304,580	21,351,679	2,557,949
2034	26,841,403	8,881,663	389,208	215,414	12,845,920	1,201,595	3,226,769	374,936	287,083	718,889	312,930	21,517,133	2,582,740
2035	27,067,127	8,957,563	392,087	214,167	13,202,936	1,212,507	3,299,114	385,878	289,207	724,208	321,187	21,676,327	2,610,745
2036	27,272,092	9,045,001	394,854	213,094	13,560,675	1,221,199	3,369,173	396,660	291,248	729,319	329,411	21,829,298	2,644,006
2037	27,457,010	9,143,215	397,510	212,189	13,918,256	1,227,770	3,436,903	407,266	293,207	734,224	337,586	21,976,110	2,682,186
2038	27,619,369	9,255,158	400,055	211,491	14,277,632	1,231,845	3,502,220	417,718	295,084	738,925	345,746	22,116,805	2,726,556
2039	27,758,191	9,381,974	402,490	211,017	14,639,361	1,233,277	3,565,057	428,017	296,880	743,422	353,901	22,251,412	2,777,604
2040	27,873,319	9,523,853	404,815	210,772	15,003,293	1,232,043	3,625,357	438,157	298,595	747,717	362,047	22,379,964	2,835,406
2041	27,964,571	9,682,037	407,040	210,768	15,371,051	1,228,046	3,683,287	448,175	300,236	751,826	370,218	22,502,965	2,900,480
2042	28,033,592	9,854,709	409,166	210,986	15,741,079	1,221,522	3,738,842	458,046	301,804	755,753	378,384	22,620,485	2,972,030
2043	28,079,531	10,042,909	411,193	211,440	16,113,979	1,212,341	3,791,977	467,774	303,299	759,497	386,557	22,732,567	3,050,502
2044	28,103,111	10,245,788	413,122	212,125	16,488,869	1,200,610	3,842,659	477,345	304,723	763,061	394,718	22,839,230	3,135,522
2045	28,104,161	10,463,477	414,953	213,043	16,865,567	1,186,307	3,890,831	486,750	306,073	766,443	402,863	22,940,462	3,227,143
2046	28,083,481	10,695,053	416,687	214,188	17,243,168	1,169,548	3,936,467	495,973	307,352	769,644	410,975	23,036,285	3,324,959

Year	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Soybean	Dry bean	Chickpea	Groundnut	Sugarbeet	Cotton
2047	28,041,926	10,939,544	418,323	215,550	17,620,756	1,150,459	3,979,545	504,998	308,558	772,666	419,035	23,126,728	3,428,544
2048	27,980,186	11,196,045	419,861	217,123	17,997,359	1,129,147	4,020,020	513,807	309,693	775,507	427,024	23,211,763	3,537,503
2049	27,897,294	11,465,584	421,301	218,920	18,373,497	1,105,476	4,057,826	522,402	310,755	778,167	434,951	23,291,359	3,652,278
2050	27,794,842	11,746,217	422,641	220,922	18,747,430	1,079,685	4,092,932	530,754	311,744	780,643	442,781	23,365,489	3,772,025

Table A. 9. Fruits production forecast results (in tons)

Year	Hazelnut	Apricot	Grapes	Apples	Olive	Oranges	Peach	Cherry	Pear	Mandarin	Lemon
2020	665,000	833,398	4,208,908	4,300,486	1,316,626	1,333,975	892,048	724,944	545,569	1,585,629	1,188,517
2021	684,000	800,000	4,493,788	3,955,434	1,738,680	1,742,000	891,857	689,834	530,349	1,819,000	1,550,000
2022	671,702	773,900	4,559,102	3,554,808	1,653,570	1,841,279	826,756	761,750	539,124	1,540,299	985,521
2023	679,492	782,876	4,611,975	3,557,507	1,746,898	1,862,243	854,261	793,592	553,769	1,644,913	997,315
2024	687,140	791,687	4,663,886	3,547,221	1,866,753	1,882,063	882,957	825,374	569,123	1,761,040	1,006,841
2025	694,641	800,329	4,714,797	3,542,605	1,975,650	1,901,784	910,987	857,035	584,057	1,872,367	1,016,985
2026	701,987	808,794	4,764,662	3,549,893	2,060,186	1,921,763	937,660	888,515	598,157	1,972,976	1,028,764
2027	709,173	817,073	4,813,432	3,568,385	2,120,941	1,941,959	962,962	919,751	611,418	2,062,982	1,042,106
2028	716,190	825,158	4,861,061	3,592,977	2,167,720	1,962,071	987,330	950,687	624,114	2,146,488	1,056,226
2029	723,033	833,042	4,907,506	3,620,629	2,206,445	1,981,910	1,011,014	981,265	636,402	2,225,921	1,070,640
2030	729,696	840,719	4,952,733	3,648,885	2,242,007	2,001,319	1,034,215	1,011,430	648,408	2,303,273	1,084,946
2031	736,148	848,152	4,996,525	3,675,897	2,277,867	2,020,098	1,056,979	1,041,006	660,175	2,379,661	1,098,785
2032	742,385	855,338	5,038,859	3,700,392	2,316,664	2,038,161	1,079,399	1,069,943	671,765	2,456,110	1,111,934
2033	748,404	862,273	5,079,712	3,721,989	2,359,216	2,055,471	1,101,483	1,098,189	683,188	2,532,856	1,124,312
2034	754,204	868,955	5,119,075	3,739,778	2,407,577	2,071,962	1,123,305	1,125,704	694,492	2,610,690	1,135,746

Year	Hazelnut	Apricot	Grapes	Apples	Olive	Oranges	Peach	Cherry	Pear	Mandarin	Lemon
2035	759,784	875,384	5,156,948	3,754,018	2,461,209	2,087,649	1,144,819	1,152,455	705,653	2,689,304	1,146,270
2036	765,146	881,562	5,193,341	3,763,254	2,523,413	2,102,438	1,166,169	1,178,417	716,763	2,770,061	1,155,623
2037	770,292	887,490	5,228,269	3,767,807	2,593,605	2,116,352	1,187,317	1,203,572	727,801	2,852,659	1,163,847
2038	775,223	893,172	5,261,741	3,766,803	2,673,830	2,129,334	1,208,348	1,227,897	738,820	2,937,928	1,170,780
2039	779,941	898,608	5,293,765	3,759,940	2,764,857	2,141,365	1,229,287	1,251,371	749,840	3,026,144	1,176,359
2040	784,447	903,800	5,324,348	3,747,217	2,866,780	2,152,442	1,250,126	1,273,973	760,856	3,117,299	1,180,571
2041	788,758	908,767	5,353,611	3,728,399	2,980,448	2,162,594	1,270,954	1,295,767	771,921	3,211,887	1,183,392
2042	792,878	913,513	5,381,570	3,704,130	3,104,540	2,171,866	1,291,701	1,316,745	782,992	3,309,311	1,184,925
2043	796,806	918,039	5,408,235	3,674,092	3,239,761	2,180,240	1,312,395	1,336,893	794,088	3,409,844	1,185,115
2044	800,545	922,347	5,433,611	3,638,606	3,385,481	2,187,735	1,332,994	1,356,196	805,186	3,513,173	1,184,007
2045	804,093	926,435	5,457,695	3,597,644	3,541,763	2,194,346	1,353,490	1,374,632	816,283	3,619,277	1,181,589
2046	807,452	930,305	5,480,492	3,551,488	3,707,927	2,200,094	1,373,840	1,392,188	827,354	3,727,829	1,177,913
2047	810,622	933,957	5,502,009	3,500,460	3,883,258	2,205,001	1,394,005	1,408,853	838,376	3,838,493	1,173,031
2048	813,603	937,392	5,522,239	3,444,808	4,067,092	2,209,081	1,413,937	1,424,605	849,324	3,950,932	1,166,989
2049	816,393	940,606	5,541,175	3,384,212	4,260,132	2,212,311	1,433,657	1,439,424	860,212	4,065,403	1,159,725
2050	818,991	943,600	5,558,812	3,319,234	4,460,979	2,214,725	1,453,087	1,453,291	870,993	4,181,260	1,151,342

Table A. 10. Forecasted crop residue production from arable crops (in tons)

Crop/ Residue	Wheat	Barley	Oat	Rye	Maize		Rice		Sunflower		Soybean	Dry bean	Chickpea	Groundnut	Sugar beets	Cotton
	Straw	Straw	Straw	Straw	Stover	Cob	Straw	Husk (Hull)	Stalk	Head	Stalk (Straw)	Stem and leaves	Straw (Stalk)	Straw (Haulm)	Top (Leaves)	Stalk
2020	49,402	22,043	851	721	126,283	19,056	13,260	3,558	32,538	31,008	3,627	848	1,923	4,778	1,863	145,288
2021	42,606	15,233	747	487	131,080	19,780	13,517	3,627	37,964	36,178	4,254	927	1,447	5,181	1,477	184,040
2022	56,847	20,569	618	846	155,237	23,425	14,167	3,802	35,219	33,563	5,297	777	1,957	4,441	1,551	177,681
2023	57,502	20,951	616	856	164,012	24,749	14,294	3,836	36,573	34,853	5,608	786	1,980	4,670	1,569	182,126
2024	58,068	21,430	616	865	173,343	26,158	14,354	3,852	37,918	36,135	5,927	794	2,002	4,911	1,586	187,876
2025	58,652	21,864	616	875	182,428	27,529	14,437	3,874	39,260	37,413	6,242	803	2,024	5,146	1,604	193,052
2026	59,294	22,203	614	884	190,971	28,818	14,574	3,911	40,598	38,688	6,547	812	2,045	5,370	1,621	196,986
2027	59,989	22,451	611	893	198,971	30,025	14,764	3,962	41,930	39,958	6,842	820	2,066	5,581	1,637	199,708
2028	60,709	22,642	607	902	206,620	31,179	14,983	4,021	43,251	41,217	7,130	828	2,087	5,785	1,654	201,712
2029	61,435	22,801	603	911	214,031	32,297	15,216	4,083	44,558	42,463	7,413	836	2,107	5,983	1,669	203,297
2030	62,151	22,945	598	919	221,294	33,393	15,450	4,146	45,848	43,692	7,690	844	2,126	6,177	1,685	204,710
2031	62,845	23,088	594	927	228,443	34,472	15,676	4,206	47,112	44,896	7,963	851	2,145	6,368	1,700	206,128
2032	63,506	23,240	590	935	235,522	35,540	15,886	4,263	48,347	46,073	8,232	858	2,163	6,557	1,714	207,687
2033	64,132	23,403	586	942	242,537	36,599	16,078	4,315	49,552	47,221	8,497	865	2,180	6,744	1,728	209,428

Crop/ Residue	Wheat	Barley	Oat	Rye	Maize		Rice		Sunflower		Soybean	Dry bean	Chickpea	Groundnut	Sugar beets	Cotton
	Straw	Straw	Straw	Straw	Stover	Cob	Straw	Husk (Hull)	Stalk	Head	Stalk (Straw)	Stem and leaves	Straw (Stalk)	Straw (Haulm)	Top (Leaves)	Stalk
2034	64,716	23,587	582	950	249,521	37,653	16,248	4,360	50,723	48,337	8,757	872	2,197	6,929	1,741	211,458
2035	65,261	23,788	579	957	256,456	38,699	16,395	4,400	51,860	49,421	9,012	878	2,214	7,111	1,754	213,751
2036	65,755	24,021	576	964	263,405	39,748	16,513	4,431	52,961	50,471	9,264	885	2,229	7,293	1,767	216,474
2037	66,201	24,281	573	970	270,350	40,796	16,602	4,455	54,026	51,485	9,512	891	2,244	7,474	1,778	219,600
2038	66,592	24,579	571	976	277,331	41,849	16,657	4,470	55,053	52,464	9,756	896	2,259	7,655	1,790	223,233
2039	66,927	24,915	570	982	284,357	42,910	16,676	4,475	56,041	53,405	9,997	902	2,272	7,836	1,801	227,412
2040	67,204	25,292	569	988	291,426	43,976	16,659	4,470	56,989	54,308	10,233	907	2,285	8,016	1,811	232,145
2041	67,424	25,712	569	993	298,570	45,054	16,605	4,456	57,899	55,176	10,467	912	2,298	8,197	1,821	237,473
2042	67,591	26,171	570	999	305,757	46,139	16,517	4,432	58,772	56,008	10,698	917	2,310	8,378	1,831	243,331
2043	67,702	26,671	571	1,003	313,001	47,232	16,393	4,399	59,608	56,804	10,925	921	2,321	8,559	1,840	249,755
2044	67,758	27,209	573	1,008	320,282	48,331	16,234	4,356	60,404	57,563	11,149	926	2,332	8,739	1,848	256,716
2045	67,761	27,788	576	1,013	327,599	49,435	16,041	4,305	61,162	58,285	11,368	930	2,343	8,920	1,856	264,218
2046	67,711	28,403	579	1,017	334,934	50,542	15,814	4,244	61,879	58,969	11,584	934	2,353	9,099	1,864	272,226
2047	67,611	29,052	582	1,021	342,268	51,649	15,556	4,174	62,556	59,614	11,794	937	2,362	9,278	1,872	280,707
2048	67,462	29,733	587	1,025	349,584	52,752	15,268	4,097	63,192	60,220	12,000	941	2,370	9,455	1,878	289,628

Crop/ Residue	Wheat	Barley	Oat	Rye	Maize		Rice		Sunflower		Soybean	Dry bean	Chickpea	Groundnut	Sugar beets	Cotton
	Straw	Straw	Straw	Straw	Stover	Cob	Straw	Husk (Hull)	Stalk	Head	Stalk (Straw)	Stem and leaves	Straw (Stalk)	Straw (Haulm)	Top (Leaves)	Stalk
2049	67,262	30,449	591	1,028	356,890	53,855	14,948	4,011	63,787	60,787	12,201	944	2,379	9,630	1,885	299,025
2050	67,015	31,194	597	1,031	364,153	54,951	14,599	3,918	64,339	61,313	12,396	947	2,386	9,804	1,891	308,829

Table A. 11. Forecasted crop residue production from fruit trees (in tons)

Crop/ Residue	Hazelnut		Olives		Grapes	Apples	Mandarin	Orange	Lemon	Peach	Apricot	Cherry	Pear
	Shell	Pruning	Pomace	Pruning	Pruning	Pruning	Pruning	Pruning	Pruning	Pruning	Pruning	Pruning	Pruning
2020	1,121	20,256	8,765	8,745	14,001	6,981	3,885	4,045	3,012	3,117	1,524	1,435	1,092
2021	1,153	20,835	11,574	11,548	14,948	6,421	4,456	5,282	3,928	3,117	1,463	1,365	1,062
2022	1,132	20,461	11,008	10,983	15,165	5,771	3,774	5,583	2,498	2,889	1,415	1,508	1,079
2023	1,145	20,698	11,629	11,603	15,341	5,775	4,030	5,647	2,528	2,985	1,432	1,571	1,109
2024	1,158	20,931	12,427	12,399	15,514	5,758	4,314	5,707	2,552	3,085	1,448	1,633	1,139
2025	1,170	21,159	13,152	13,122	15,683	5,751	4,587	5,767	2,577	3,183	1,463	1,696	1,169
2026	1,183	21,383	13,715	13,684	15,849	5,763	4,834	5,828	2,607	3,277	1,479	1,758	1,198
2027	1,195	21,602	14,119	14,087	16,011	5,793	5,054	5,889	2,641	3,365	1,494	1,820	1,224
2028	1,207	21,816	14,431	14,398	16,170	5,833	5,259	5,950	2,677	3,450	1,509	1,881	1,249
2029	1,218	22,024	14,688	14,655	16,324	5,878	5,453	6,010	2,713	3,533	1,523	1,942	1,274
2030	1,230	22,227	14,925	14,891	16,475	5,923	5,643	6,069	2,750	3,614	1,537	2,002	1,298
2031	1,240	22,424	15,164	15,130	16,620	5,967	5,830	6,126	2,785	3,694	1,551	2,060	1,322
2032	1,251	22,614	15,422	15,387	16,761	6,007	6,017	6,181	2,818	3,772	1,564	2,117	1,345
2033	1,261	22,797	15,705	15,670	16,897	6,042	6,205	6,233	2,849	3,849	1,577	2,173	1,368
2034	1,271	22,974	16,027	15,991	17,028	6,071	6,396	6,283	2,878	3,925	1,589	2,228	1,390
2035	1,280	23,144	16,384	16,347	17,154	6,094	6,589	6,331	2,905	4,000	1,601	2,281	1,413

Crop/ Residue	Hazelnut		Olives		Grapes	Apples	Mandarin	Orange	Lemon	Peach	Apricot	Cherry	Pear
	Shell	**Pruning**	**Pomace**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**	**Pruning**
2036	1,289	23,307	16,798	16,761	17,275	6,109	6,786	6,375	2,929	4,075	1,612	2,332	1,435
2037	1,298	23,464	17,266	17,227	17,391	6,117	6,989	6,418	2,950	4,149	1,623	2,382	1,457
2038	1,306	23,614	17,800	17,760	17,503	6,115	7,198	6,457	2,967	4,222	1,633	2,430	1,479
2039	1,314	23,758	18,406	18,364	17,609	6,104	7,414	6,493	2,981	4,296	1,643	2,477	1,501
2040	1,322	23,895	19,084	19,041	17,711	6,083	7,637	6,527	2,992	4,368	1,653	2,521	1,523
2041	1,329	24,026	19,841	19,796	17,808	6,053	7,869	6,558	2,999	4,441	1,662	2,564	1,545
2042	1,336	24,152	20,667	20,620	17,901	6,013	8,108	6,586	3,003	4,514	1,670	2,606	1,568
2043	1,343	24,271	21,567	21,518	17,990	5,964	8,354	6,611	3,004	4,586	1,679	2,646	1,590
2044	1,349	24,385	22,537	22,486	18,074	5,907	8,607	6,634	3,001	4,658	1,687	2,684	1,612
2045	1,355	24,493	23,578	23,524	18,154	5,840	8,867	6,654	2,995	4,730	1,694	2,720	1,634
2046	1,361	24,596	24,684	24,628	18,230	5,765	9,133	6,672	2,985	4,801	1,701	2,755	1,656
2047	1,366	24,692	25,851	25,793	18,302	5,683	9,404	6,686	2,973	4,871	1,708	2,788	1,678
2048	1,371	24,783	27,075	27,014	18,369	5,592	9,679	6,699	2,958	4,941	1,714	2,819	1,700
2049	1,376	24,868	28,360	28,296	18,432	5,494	9,960	6,709	2,939	5,010	1,720	2,849	1,722
2050	1,380	24,947	29,697	29,630	18,491	5,388	10,244	6,716	2,918	5,078	1,725	2,876	1,744

Table A. 12. Forecasted firewood production potential by tree type

Year	Coniferous (stere)	Non-coniferous (stere)	Coniferous (m3)	Non-coniferous (m3)
2020	2,756,402	2,640,278	2,136,212	2,046,215
2021	2,726,426	2,760,942	2,112,980	2,139,730
2022	2,732,890	2,620,078	2,117,990	2,030,561
2023	2,811,879	2,655,679	2,179,206	2,058,152
2024	2,890,850	2,691,282	2,240,409	2,085,744
2025	2,969,805	2,726,887	2,301,599	2,113,337
2026	3,048,744	2,762,493	2,362,776	2,140,932
2027	3,127,666	2,798,102	2,423,941	2,168,529
2028	3,206,571	2,833,712	2,485,092	2,196,127
2029	3,285,460	2,869,323	2,546,231	2,223,726
2030	3,364,332	2,904,937	2,607,358	2,251,326
2031	3,443,188	2,940,552	2,668,471	2,278,928
2032	3,522,028	2,976,169	2,729,572	2,306,531
2033	3,600,852	3,011,788	2,790,660	2,334,136
2034	3,679,659	3,047,408	2,851,736	2,361,742
2035	3,758,450	3,083,031	2,912,798	2,389,349
2036	3,837,224	3,118,655	2,973,849	2,416,957
2037	3,915,983	3,154,280	3,034,887	2,444,567
2038	3,994,725	3,189,908	3,095,912	2,472,179
2039	4,073,451	3,225,537	3,156,925	2,499,791
2040	4,152,161	3,261,168	3,217,925	2,527,405
2041	4,230,855	3,296,800	3,278,913	2,555,020
2042	4,309,534	3,332,435	3,339,888	2,582,637

Year	Coniferous (stere)	Non-coniferous (stere)	Coniferous (m3)	Non-coniferous (m3)
2043	4,388,196	3,368,071	3,400,852	2,610,255
2044	4,466,842	3,403,708	3,461,802	2,637,874
2045	4,545,472	3,439,348	3,522,741	2,665,494
2046	4,624,086	3,474,989	3,583,667	2,693,116
2047	4,702,685	3,510,632	3,644,581	2,720,739
2048	4,781,268	3,546,276	3,705,482	2,748,364
2049	4,859,835	3,581,922	3,766,372	2,775,990
2050	4,938,386	3,617,570	3,827,249	2,803,617

Table A. 13. Animal population forecast by animal type

	Dairy Cattle - Culture	Dairy Cattle-Crossbreed	Dairy Cattle - Domestic	Other Cattle - Culture	Other Cattle-Crossbreed	Other Cattle-Domestic	Sheep	Goats	Chicken-Layer	Chicken-Broiler
2020	3,407,052	2,864,894	601,579	5,431,446	4,729,233	931,278	42,126,781	11,985,845	121,302,869	258,046,340
2021	3,478,396	2,910,769	600,734	5,420,762	4,693,895	926,333	37,775,493	12,499,408	113,323,829	319,458,808
2022	3,590,405	2,989,999	606,508	5,492,606	4,732,744	931,073	38,358,492	12,952,905	111,966,982	333,852,916
2023	3,726,993	3,088,766	615,803	5,622,840	4,820,217	942,123	39,701,130	13,625,416	113,820,136	345,097,482
2024	3,868,345	3,190,440	625,170	5,775,443	4,925,313	953,961	41,185,314	14,325,573	116,228,411	356,315,277
2025	4,005,454	3,287,578	633,161	5,933,367	5,033,530	964,230	42,642,214	15,000,802	118,632,755	367,655,194
2026	4,135,102	3,377,610	639,350	6,089,366	5,138,869	972,171	44,007,452	15,632,933	120,829,104	379,165,021
2027	4,257,402	3,460,723	643,853	6,241,662	5,240,026	977,874	45,275,913	16,223,319	122,804,689	390,838,272
2028	4,374,553	3,538,790	647,092	6,392,014	5,338,523	981,918	46,481,362	16,786,134	124,664,910	402,631,822
2029	4,487,791	3,612,873	649,314	6,540,972	5,434,984	984,615	47,643,144	17,329,727	126,465,457	414,519,081
2030	4,598,141	3,683,844	650,720	6,689,130	5,529,820	986,233	48,777,749	17,860,552	128,251,003	426,478,475
2031	4,705,685	3,751,809	651,365	6,835,805	5,622,604	986,815	49,891,642	18,381,265	130,042,915	438,456,368
2032	4,810,900	3,817,184	651,355	6,981,157	5,713,386	986,499	50,993,087	18,895,012	131,859,604	450,441,827
2033	4,913,830	3,880,037	650,730	7,124,767	5,801,877	985,319	52,083,508	19,402,302	133,701,291	462,428,986
2034	5,014,828	3,940,675	649,571	7,266,755	5,888,210	983,387	53,169,315	19,905,400	135,582,513	474,410,683
2035	5,113,703	3,998,978	647,882	7,406,657	5,971,969	980,699	54,247,323	20,403,406	137,490,593	486,390,982
2036	5,211,133	4,055,502	645,777	7,545,150	6,053,759	977,406	55,329,733	20,900,496	139,458,484	498,360,180

	Dairy Cattle - Culture	Dairy Cattle- Crossbreed	Dairy Cattle - Domestic	Other Cattle - Culture	Other Cattle- Crossbreed	Other Cattle- Domestic	Sheep	Goats	Chicken- Layer	Chicken- Broiler
2037	5,306,958	4,110,144	643,259	7,681,891	6,133,307	973,518	56,413,542	21,395,655	141,474,110	510,324,828
2038	5,401,594	4,163,247	640,401	7,817,357	6,210,999	969,132	57,505,930	21,891,338	143,557,112	522,280,219
2039	5,495,139	4,214,906	637,233	7,951,554	6,286,863	964,294	58,609,312	22,388,247	145,713,493	534,224,849
2040	5,587,580	4,265,126	633,772	8,084,415	6,360,817	959,025	59,723,275	22,886,345	147,939,918	546,159,972
2041	5,679,399	4,314,291	630,089	8,216,583	6,433,416	953,423	60,853,680	23,387,764	150,247,608	558,108,892
2042	5,770,318	4,362,201	626,165	8,347,601	6,504,318	947,466	61,995,238	23,890,375	152,620,823	570,081,573
2043	5,860,433	4,408,944	622,026	8,477,544	6,573,577	941,187	63,150,102	24,395,249	155,064,971	582,076,436
2044	5,949,600	4,454,424	617,670	8,606,246	6,641,055	934,584	64,315,574	24,901,172	157,571,996	594,097,308
2045	6,037,773	4,498,622	613,105	8,733,537	6,706,669	927,670	65,491,220	25,407,582	160,142,438	606,142,555
2046	6,124,763	4,541,412	608,328	8,859,184	6,770,265	920,433	66,673,878	25,913,804	162,767,216	618,215,730
2047	6,210,430	4,582,708	603,337	8,982,985	6,831,686	912,878	67,860,740	26,418,302	165,437,979	630,320,712
2048	6,294,572	4,622,380	598,128	9,104,578	6,890,712	904,993	69,048,323	26,919,891	168,148,512	642,456,832
2049	6,377,261	4,660,500	592,723	9,224,104	6,947,453	896,811	70,239,053	27,419,145	170,905,044	654,617,916
2050	6,458,167	4,696,849	587,106	9,341,051	7,001,551	888,309	71,426,551	27,914,025	173,693,677	666,807,785

Table A. 14. Forecasted collectible manure production potential (in tons)

Year	Dairy - Culture	Dairy - Crossbred	Dairy - Domestic	Other - Culture	Other - Crossbred	Other - Domestic	Sheep	Goat	Chicken-layer	Chicken-broiler
2020	36,148,212	22,783,412	3,185,613	25,018,373	16,600,146	2,235,971	4,797,398	1,356,417	5,698,263	17,716,559
2021	36,905,156	23,148,237	3,181,141	24,969,161	16,476,105	2,224,097	4,301,873	1,414,536	5,323,444	21,932,924
2022	38,093,552	23,778,325	3,211,716	25,300,088	16,612,469	2,235,479	4,368,265	1,465,858	5,259,705	22,921,173
2023	39,542,726	24,563,786	3,260,935	25,899,975	16,919,510	2,262,009	4,521,165	1,541,964	5,346,758	23,693,185
2024	41,042,447	25,372,361	3,310,538	26,602,896	17,288,407	2,290,431	4,690,184	1,621,200	5,459,888	24,463,360
2025	42,497,146	26,144,859	3,352,856	27,330,325	17,668,261	2,315,088	4,856,095	1,697,614	5,572,833	25,241,919
2026	43,872,691	26,860,849	3,385,627	28,048,893	18,038,015	2,334,154	5,011,569	1,769,152	5,676,008	26,032,143
2027	45,170,271	27,521,816	3,409,474	28,750,400	18,393,088	2,347,846	5,156,021	1,835,965	5,768,812	26,833,588
2028	46,413,219	28,142,650	3,426,621	29,442,949	18,738,822	2,357,556	5,293,297	1,899,657	5,856,196	27,643,292
2029	47,614,656	28,731,802	3,438,388	30,129,082	19,077,413	2,364,032	5,425,601	1,961,175	5,940,778	28,459,429
2030	48,785,447	29,296,209	3,445,833	30,811,531	19,410,296	2,367,915	5,554,810	2,021,247	6,024,655	29,280,519
2031	49,926,468	29,836,708	3,449,250	31,487,146	19,735,979	2,369,312	5,681,660	2,080,176	6,108,831	30,102,880
2032	51,042,783	30,356,613	3,449,196	32,156,668	20,054,635	2,368,554	5,807,093	2,138,315	6,194,171	30,925,759
2033	52,134,856	30,856,458	3,445,891	32,818,164	20,365,249	2,365,721	5,931,270	2,195,725	6,280,685	31,748,756
2034	53,206,424	31,338,693	3,439,753	33,472,189	20,668,287	2,361,083	6,054,922	2,252,659	6,369,056	32,571,377
2035	54,255,469	31,802,353	3,430,808	34,116,607	20,962,292	2,354,629	6,177,685	2,309,018	6,458,689	33,393,902
2036	55,289,182	32,251,864	3,419,660	34,754,536	21,249,382	2,346,723	6,300,950	2,365,273	6,551,132	34,215,666

Year	Dairy - Culture	Dairy - Crossbred	Dairy - Domestic	Other - Culture	Other - Crossbred	Other - Domestic	Sheep	Goat	Chicken-layer	Chicken-broiler
2037	56,305,869	32,686,411	3,406,326	35,384,394	21,528,606	2,337,387	6,424,374	2,421,309	6,645,817	35,037,117
2038	57,309,937	33,108,722	3,391,191	36,008,378	21,801,312	2,326,856	6,548,775	2,477,404	6,743,667	35,857,932
2039	58,302,437	33,519,545	3,374,417	36,626,518	22,067,604	2,315,240	6,674,428	2,533,639	6,844,964	36,678,008
2040	59,283,221	33,918,928	3,356,090	37,238,502	22,327,192	2,302,589	6,801,287	2,590,008	6,949,552	37,497,432
2041	60,257,402	34,309,915	3,336,584	37,847,297	22,582,023	2,289,139	6,930,017	2,646,752	7,057,957	38,317,803
2042	61,222,036	34,690,929	3,315,807	38,450,791	22,830,897	2,274,837	7,060,018	2,703,632	7,169,439	39,139,806
2043	62,178,142	35,062,657	3,293,889	39,049,339	23,074,003	2,259,762	7,191,534	2,760,768	7,284,255	39,963,331
2044	63,124,187	35,424,343	3,270,821	39,642,165	23,310,857	2,243,909	7,324,258	2,818,022	7,402,023	40,788,642
2045	64,059,687	35,775,831	3,246,651	40,228,496	23,541,173	2,227,308	7,458,140	2,875,332	7,522,771	41,615,626
2046	64,982,637	36,116,127	3,221,350	40,807,251	23,764,402	2,209,933	7,592,821	2,932,620	7,646,071	42,444,528
2047	65,891,542	36,444,537	3,194,920	41,377,504	23,979,996	2,191,792	7,727,981	2,989,713	7,771,532	43,275,614
2048	66,784,272	36,760,031	3,167,337	41,937,585	24,187,185	2,172,860	7,863,223	3,046,477	7,898,860	44,108,838
2049	67,661,588	37,063,189	3,138,717	42,488,149	24,386,350	2,153,217	7,998,823	3,102,977	8,028,350	44,943,775
2050	68,519,992	37,352,255	3,108,973	43,026,829	24,576,239	2,132,804	8,134,056	3,158,981	8,159,347	45,780,689

Table A. 15. Municipal solid waste production potential forecast (in tons)

	Municipal solid waste, total	Collected municipal solid waste in total waste	Organic fraction of municipal solid waste in collected waste
2020	34,757,760	32,324,472	17,623,302
2021	34,426,851	32,173,558	17,541,024
2022	34,557,694	32,452,771	17,693,251
2023	35,002,686	33,029,115	18,007,473
2024	35,481,507	33,641,059	18,341,105
2025	35,934,225	34,231,950	18,663,259
2026	36,340,609	34,782,055	18,963,176
2027	36,702,583	35,292,585	19,241,517
2028	37,035,909	35,778,157	19,506,251
2029	37,349,885	36,247,400	19,762,083
2030	37,651,950	36,707,296	20,012,818
2031	37,946,138	37,161,628	20,260,520
2032	38,236,177	37,613,947	20,507,124
2033	38,523,027	38,065,137	20,753,113
2034	38,809,472	38,517,909	20,999,964
2035	39,094,587	38,971,326	21,247,167
2036	39,382,974	39,382,974	21,471,597
2037	39,673,683	39,673,683	21,630,092
2038	39,969,470	39,969,470	21,791,355
2039	40,271,246	40,271,246	21,955,883
2040	40,578,998	40,578,998	22,123,669
2041	40,894,382	40,894,382	22,295,617

	Municipal solid waste, total	**Collected municipal solid waste in total waste**	**Organic fraction of municipal solid waste in collected waste**
2042	41,215,525	41,215,525	22,470,704
2043	41,543,336	41,543,336	22,649,427
2044	41,876,882	41,876,882	22,831,276
2045	42,216,170	42,216,170	23,016,256
2046	42,560,267	42,560,267	23,203,858
2047	42,908,240	42,908,240	23,393,572
2048	43,259,176	43,259,176	23,584,903
2049	43,614,011	43,614,011	23,778,359
2050	43,970,907	43,970,907	23,972,939

Table A. 16. Wastewater Production Potential Forecast

Year	Population	Municipal Population	Per capita municipal wastewater amount	Municipal population served by sewerage system	Municipal population served by sewerage and WWTPs	Municipal wastewater amount	Treated municipal wastewater amount	Biologically treated municipal wastewater amount
	of people	of people	litres/capita-day	of people	of people	cubic meter	cubic meter	cubic meter
2020	83,614,362	78,920,614	189.0	71,909,688	61,292,803	4,959,675,016	4,358,270,193	3,390,879,775
2021	84,680,273	79,999,492	192.6	73,265,574	64,649,279	5,150,065,337	4,586,677,596	3,690,055,513
2022	85,911,035	81,236,151	193.7	74,558,953	66,615,307	5,271,324,258	4,731,258,035	3,848,069,366
2023	86,907,367	82,253,121	194.6	75,622,566	68,232,075	5,371,830,706	4,850,636,703	3,987,912,160
2024	87,885,571	83,254,703	195.5	76,670,086	69,824,381	5,471,512,265	4,968,634,793	4,128,711,924
2025	88,844,934	84,240,177	196.4	77,700,759	71,391,078	5,570,264,655	5,085,147,441	4,270,339,011
2026	89,784,584	85,208,669	197.3	78,713,671	72,930,777	5,667,966,633	5,200,050,738	4,412,659,055
2027	90,703,600	86,159,255	198.1	79,707,856	74,442,009	5,764,490,144	5,313,213,746	4,555,512,273
2028	91,601,117	87,091,062	199.0	80,682,401	75,923,386	5,859,710,476	5,424,510,468	4,698,743,514
2029	92,476,323	88,003,263	199.8	81,636,440	77,373,594	5,953,506,264	5,533,819,610	4,842,197,301
2030	93,328,574	88,895,189	200.6	82,569,274	78,791,570	6,045,771,142	5,641,038,036	4,985,729,929
2031	94,153,776	89,762,879	201.4	83,476,761	80,171,015	6,136,054,466	5,745,664,510	5,128,838,697

Year	Population	Municipal Population	Per capita municipal wastewater amount	Municipal population served by sewerage system	Municipal population served by sewerage and WWTPs	Municipal wastewater amount	Treated municipal wastewater amount	Biologically treated municipal wastewater amount
	of people	of people	litres/capita-day	of people	of people	cubic meter	cubic meter	cubic meter
2032	94,951,512	90,605,868	202.1	84,358,413	81,511,189	6,224,263,882	5,847,616,037	5,271,374,410
2033	95,721,347	91,423,669	202.9	85,213,723	82,811,321	6,310,305,215	5,946,807,396	5,413,200,368
2034	96,463,090	92,216,029	203.6	86,042,425	84,071,008	6,394,109,055	6,043,181,695	5,554,185,562
2035	97,176,768	92,982,904	204.3	86,844,473	85,290,178	6,475,628,908	6,136,707,916	5,694,226,728
2036	97,862,549	93,724,382	205.0	87,619,958	86,468,971	6,554,833,980	6,227,372,232	5,833,235,616
2037	98,520,720	94,440,666	205.6	88,369,096	87,607,714	6,631,707,312	6,315,175,978	5,971,137,821
2038	99,151,467	95,131,866	206.2	89,091,997	88,706,576	6,706,223,292	6,400,109,539	6,107,848,537
2039	99,754,923	95,798,038	206.8	89,788,723	89,765,649	6,778,352,348	6,482,158,119	6,243,271,146
2040	100,331,233	96,439,251	207.4	90,459,346	90,459,346	6,848,067,602	6,549,646,331	6,365,994,248
2041	100,882,655	97,057,609	208.0	91,106,065	91,106,065	6,915,565,967	6,614,096,148	6,486,926,921
2042	101,409,507	97,653,354	208.5	91,729,134	91,729,134	6,980,844,850	6,676,341,337	6,606,813,918
2043	101,911,980	98,226,606	209.0	92,328,678	92,328,678	7,043,889,742	6,736,377,496	6,725,592,556
2044	102,390,159	98,777,384	209.5	92,904,718	92,904,718	7,104,676,131	6,794,190,384	6,794,190,384

Year	Population	Municipal Population	Per capita municipal wastewater amount	Municipal population served by sewerage system	Municipal population served by sewerage and WWTPs	Municipal wastewater amount	Treated municipal wastewater amount	Biologically treated municipal wastewater amount
	of people	of people	litres/capita-day	of people	of people	cubic meter	cubic meter	cubic meter
2045	102,843,989	99,305,573	210.0	93,457,132	93,457,132	7,163,165,603	6,849,752,132	6,849,752,132
2046	103,273,571	99,811,207	210.4	93,985,957	93,985,957	7,219,337,368	6,903,051,348	6,903,051,348
2047	103,679,038	100,294,352	210.9	94,491,262	94,491,262	7,273,175,214	6,954,080,584	6,954,080,584
2048	104,060,257	100,754,817	211.3	94,972,846	94,972,846	7,324,635,283	7,002,805,813	7,002,805,813
2049	104,417,089	101,192,403	211.7	95,430,502	95,430,502	7,373,673,809	7,049,192,849	7,049,192,849
2050	104,749,423	101,606,940	212.1	95,864,052	95,864,052	7,420,250,851	7,093,210,885	7,093,210,885

Table A. 17. Sludge production potential forecast

Year	Sludge Production (Dry Solids)	Sludge Production as VS in DS (VS stands for Volatile Solids)	Destruction of VS in Sludge used for Biogas Production
	ton DS /year	ton VS/ year	ton $Vs_{destroyed}$/year
2020	1,144,421,924	858,316,443	429,158,222
2021	1,245,393,736	934,045,302	467,022,651
2022	1,298,723,411	974,042,558	487,021,279
2023	1,345,920,354	1,009,440,266	504,720,133
2024	1,393,440,274	1,045,080,206	522,540,103
2025	1,441,239,416	1,080,929,562	540,464,781
2026	1,489,272,431	1,116,954,323	558,477,162
2027	1,537,485,392	1,153,114,044	576,557,022
2028	1,585,825,936	1,189,369,452	594,684,726
2029	1,634,241,589	1,225,681,192	612,840,596
2030	1,682,683,851	1,262,012,888	631,006,444
2031	1,730,983,060	1,298,237,295	649,118,648
2032	1,779,088,863	1,334,316,647	667,158,324
2033	1,826,955,124	1,370,216,343	685,108,172
2034	1,874,537,627	1,405,903,220	702,951,610
2035	1,921,801,521	1,441,351,141	720,675,570
2036	1,968,717,020	1,476,537,765	738,268,883
2037	2,015,259,015	1,511,444,261	755,722,130
2038	2,061,398,881	1,546,049,161	773,024,580
2039	2,107,104,012	1,580,328,009	790,164,004
2040	2,148,523,059	1,611,392,294	805,696,147

Year	Sludge Production (Dry Solids)	Sludge Production as VS in DS (VS stands for Volatile Solids)	Destruction of VS in Sludge used for Biogas Production
	ton DS /year	ton VS/ year	ton $Vs_{destroyed}$/year
2041	2,189,337,836	1,642,003,377	821,001,688
2042	2,229,799,697	1,672,349,773	836,174,887
2043	2,269,887,488	1,702,415,616	851,207,808
2044	2,293,039,255	1,719,779,441	859,889,720
2045	2,311,791,345	1,733,843,508	866,921,754
2046	2,329,779,830	1,747,334,872	873,667,436
2047	2,347,002,197	1,760,251,648	880,125,824
2048	2,363,446,962	1,772,585,221	886,292,611
2049	2,379,102,587	1,784,326,940	892,163,470
2050	2,393,958,674	1,795,469,005	897,734,503

APPENDIX 4 – LEAP Modelling Results

Table A. 18. Electricity demand forecast by sector (in Terawatt-hours)

Sector	Residential	Services	Agriculture	Industry	Transport	Total
2020	60.4	69.0	11.5	117.5	1.4	259.8
2021	60.1	77.3	13.0	132.2	1.6	284.2
2022	60.6	80.3	13.5	137.9	1.6	293.9
2023	61.3	85.0	14.3	146.3	1.7	308.7
2024	62.1	90.0	15.2	155.1	1.8	324.3
2025	63.0	94.9	16.1	163.6	1.9	339.5
2026	64.0	99.5	16.9	171.6	2.0	354.0
2027	64.9	103.8	17.7	179.0	2.1	367.6
2028	65.9	108.0	18.5	186.0	2.1	380.6
2029	66.8	112.1	19.3	192.8	2.2	393.2
2030	67.8	116.1	20.0	199.4	2.3	405.6
2031	68.7	120.0	20.8	205.9	2.4	417.7
2032	69.7	123.9	21.5	212.3	2.4	429.8
2033	70.6	127.7	22.2	218.6	2.5	441.6
2034	71.5	131.6	23.0	224.8	2.6	453.4
2035	72.4	135.4	23.7	231.0	2.6	465.1
2036	73.2	139.2	24.5	237.2	2.7	476.8
2037	74.1	143.0	25.2	243.3	2.8	488.4
2038	74.9	146.8	25.9	249.5	2.9	500.0
2039	75.8	150.6	26.7	255.7	2.9	511.7
2040	76.6	154.5	27.5	261.9	3.0	523.5
2041	77.4	158.4	28.2	268.2	3.1	535.3

Sector	Residential	Services	Agriculture	Industry	Transport	Total
2042	78.2	162.3	29.0	274.5	3.1	547.1
2043	79.0	166.2	29.8	280.9	3.2	559.0
2044	79.7	170.1	30.6	287.3	3.3	571.0
2045	80.5	174.1	31.4	293.7	3.4	583.0
2046	81.2	178.0	32.1	300.1	3.4	594.9
2047	82.0	182.0	32.9	306.5	3.5	606.9
2048	82.7	185.9	33.7	312.9	3.6	618.8
2049	83.4	189.9	34.5	319.3	3.6	630.7
2050	84.1	193.8	35.3	325.6	3.7	642.5

Table A. 19. Forecasted electricity supply by fuel type under RS (TWh)

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Biomass	Waste Heat Recovery	Total
2020	67.9	37.9	70.9	0.3	78.1	24.8	10.0	11.0	0.0	4.5	1.3	306.7
2021	14.1	13.1	111.0	0.4	115.9	32.5	14.1	18.1	0.0	12.2	3.1	334.3
2022	16.6	13.6	110.6	0.3	117.2	34.3	14.6	22.2	0.0	13.3	3.1	345.8
2023	19.9	16.2	112.1	0.3	118.6	36.1	15.1	27.4	0.0	14.3	3.2	363.1
2024	22.7	18.3	113.1	0.3	120.0	38.1	15.6	33.7	0.0	15.3	3.2	380.3
2025	20.2	16.2	104.2	0.2	121.4	40.2	16.1	41.4	19.1	16.3	3.3	398.5
2026	20.4	17.2	109.0	0.2	122.9	42.8	16.7	46.7	19.1	16.8	3.4	415.1
2027	18.1	15.9	108.3	0.1	124.3	45.7	17.3	52.8	28.7	17.2	3.4	431.7
2028	17.5	16.2	111.5	0.1	125.8	48.7	17.8	59.6	28.7	17.6	3.5	447.0
2029	16.7	16.1	114.0	0.0	127.4	51.9	18.5	67.3	28.7	18.1	3.5	462.0
2030	13.9	14.1	110.0	0.0	128.8	55.4	19.1	75.9	38.2	18.3	3.6	477.2
2031	13.5	13.6	111.1	0.0	128.8	61.1	19.7	83.4	38.2	18.5	3.7	491.5
2032	12.8	12.9	111.3	0.0	128.7	67.3	20.4	91.7	38.1	18.7	3.7	505.7
2033	11.8	11.9	110.5	0.0	128.6	74.2	21.1	100.7	38.1	18.9	3.8	519.6
2034	10.7	10.8	108.4	0.0	128.4	81.8	21.8	110.6	38.0	19.1	3.9	533.5
2035	6.9	7.0	93.1	0.0	127.6	89.7	22.4	120.9	56.7	19.1	3.9	547.2
2036	7.3	7.3	95.9	0.0	128.7	92.6	23.2	125.4	56.7	19.9	4.0	561.0

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Biomass	Waste Heat Recovery	Total
2037	7.6	7.7	98.6	0.0	129.8	95.7	24.0	129.9	56.7	20.6	4.0	574.6
2038	7.9	8.0	101.2	0.0	130.9	98.8	24.9	134.4	56.7	21.4	4.1	588.4
2039	8.2	8.3	103.8	0.0	132.0	102.1	25.7	138.9	56.8	22.2	4.2	602.1
2040	8.5	8.5	106.3	0.0	133.1	105.4	26.6	143.3	56.8	23.0	4.3	615.9
2041	8.7	8.8	108.8	0.0	134.2	108.9	27.6	147.8	56.8	23.9	4.4	629.8
2042	8.9	9.0	111.3	0.0	135.3	112.5	28.5	152.3	56.8	24.8	4.4	643.7
2043	9.1	9.2	113.7	0.0	136.5	116.1	29.5	156.7	56.8	25.7	4.5	657.8
2044	9.2	9.3	116.0	0.0	137.6	119.9	30.5	161.2	56.8	26.6	4.6	671.8
2045	9.4	9.5	118.3	0.0	138.7	123.9	31.6	165.6	56.8	27.6	4.7	685.9
2046	9.5	9.5	120.4	0.0	139.9	127.9	32.7	170.0	56.7	28.6	4.8	700.0
2047	9.5	9.6	122.5	0.0	141.0	132.1	33.8	174.4	56.7	29.6	4.9	714.1
2048	9.5	9.6	124.4	0.0	142.1	136.4	35.0	178.8	56.7	30.7	4.9	728.1
2049	9.5	9.5	126.1	0.0	143.3	140.8	36.2	183.2	56.7	31.8	5.0	742.1
2050	9.3	9.4	127.6	0.0	144.5	145.3	37.5	187.6	56.7	32.9	5.1	755.9

Table A. 20. Forecasted electricity supply by fuel type under LBDS (TWh)

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Waste Heat	Existing Biomass	Biogas CHP	Biomass Combustion CHP	Total
2020	67.9	37.9	70.9	0.3	78.1	24.8	10.0	11.0	0.0	1.3	4.5	-	-	306.7
2021	15.1	14.0	113.1	0.4	115.9	32.5	14.1	18.1	0.0	3.1	-	3.8	4.3	334.3
2022	17.8	14.6	112.8	0.3	117.2	34.3	14.6	22.2	0.0	3.1	-	4.3	4.6	345.8
2023	21.0	17.1	114.3	0.3	118.6	36.1	15.1	27.4	0.0	3.2	-	4.7	5.0	362.8
2024	24.1	19.4	114.9	0.3	120.0	38.1	15.6	33.7	0.0	3.2	-	5.1	5.5	379.9
2025	21.3	17.1	106.4	0.2	121.4	40.2	16.1	41.4	19.1	3.3	-	5.6	6.0	398.2
2026	21.4	18.0	111.0	0.2	122.9	42.8	16.7	46.8	19.1	3.4	-	6.1	6.5	414.9
2027	18.8	16.6	110.1	0.1	124.4	45.7	17.3	52.8	28.7	3.4	-	6.6	7.1	431.4
2028	18.1	16.7	113.1	0.1	125.9	48.7	17.9	59.6	28.7	3.5	-	7.0	7.7	446.8
2029	17.0	16.4	115.2	0.0	127.4	51.9	18.5	67.3	28.7	3.5	-	7.5	8.4	461.9
2030	14.1	14.3	110.7	0.0	128.8	55.4	19.1	75.9	38.2	3.6	-	8.0	9.2	477.2
2031	13.5	13.6	111.1	0.0	128.8	61.1	19.7	83.4	38.2	3.7	-	8.6	10.0	491.5
2032	12.5	12.6	110.5	0.0	128.7	67.3	20.4	91.7	38.1	3.7	-	9.1	10.9	505.7
2033	11.4	11.5	108.9	0.0	128.5	74.2	21.1	100.7	38.1	3.8	-	9.6	11.8	519.6
2034	10.1	10.2	105.8	0.0	128.3	81.7	21.8	110.5	38.0	3.8	-	10.2	12.9	533.5
2035	6.3	6.3	89.6	0.0	127.3	89.5	22.4	120.6	56.6	3.9	-	10.7	14.0	547.2

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Waste Heat	Existing Biomass	Biogas CHP	Biomass Combustion CHP	Total
2036	6.5	6.5	91.7	0.0	128.4	92.4	23.2	125.1	56.6	4.0	-	11.3	15.3	561.0
2037	6.6	6.7	93.6	0.0	129.5	95.4	24.0	129.5	56.6	4.0	-	12.0	16.7	574.6
2038	6.8	6.8	95.3	0.0	130.5	98.5	24.8	134.0	56.6	4.1	-	12.6	18.3	588.4
2039	6.8	6.9	96.9	0.0	131.5	101.7	25.7	138.4	56.6	4.2	-	13.3	20.1	602.1
2040	6.9	7.0	98.3	0.0	132.6	105.0	26.5	142.8	56.5	4.3	-	14.1	22.0	615.9
2041	6.9	7.0	99.5	0.0	133.6	108.4	27.4	147.1	56.5	4.3	-	14.8	24.2	629.8
2042	6.9	6.9	100.4	0.0	134.7	111.9	28.4	151.5	56.5	4.4	-	15.6	26.5	643.7
2043	6.8	6.9	101.1	0.0	135.7	115.5	29.3	155.8	56.4	4.5	-	16.5	29.2	657.8
2044	6.7	6.8	101.6	0.0	136.7	119.2	30.3	160.1	56.4	4.6	-	17.4	32.1	671.8
2045	6.6	6.6	101.8	0.0	137.7	122.9	31.4	164.3	56.3	4.6	-	18.3	35.3	685.9
2046	6.3	6.4	101.7	0.0	138.6	126.8	32.4	168.5	56.2	4.7	-	19.3	38.9	700.0
2047	6.1	6.1	101.3	0.0	139.5	130.7	33.5	172.6	56.1	4.8	-	20.4	42.8	714.1
2048	5.7	5.8	100.6	0.0	140.4	134.7	34.6	176.7	56.0	4.9	-	21.5	47.2	728.1
2049	5.3	5.4	99.5	0.0	141.2	138.8	35.7	180.6	55.9	5.0	-	22.7	52.0	742.1
2050	4.8	4.9	98.0	0.0	142.1	142.9	36.8	184.5	55.7	5.0	-	24.0	57.2	755.9

Table A. 21. Forecasted electricity supply by fuel type under MBDS (TWh)

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Waste Heat	Existing Biomass	Biogas CHP	Biomass Combustion CHP	Total
2020	67.9	37.9	70.9	0.3	78.1	24.8	10.0	11.0	0.0	1.3	4.5	-	-	306.7
2021	15.1	14.0	113.1	0.4	115.9	32.5	14.1	18.1	0.0	3.1	-	4.0	4.3	334.3
2022	17.7	14.5	112.6	0.3	117.2	34.3	14.6	22.2	0.0	3.1	-	4.5	4.7	345.8
2023	20.9	17.0	114.0	0.3	118.6	36.1	15.1	27.4	0.0	3.2	-	5.0	5.2	362.8
2024	23.9	19.3	114.6	0.3	120.0	38.1	15.6	33.7	0.0	3.2	-	5.6	5.7	380.0
2025	21.1	16.9	106.1	0.2	121.4	40.2	16.1	41.4	19.1	3.3	-	6.2	6.2	398.2
2026	21.2	17.8	110.5	0.2	122.9	42.8	16.7	46.8	19.1	3.4	-	6.7	6.9	414.9
2027	18.6	16.4	109.5	0.1	124.3	45.7	17.3	52.8	28.7	3.4	-	7.3	7.5	431.5
2028	17.8	16.4	112.3	0.1	125.9	48.7	17.9	59.6	28.7	3.5	-	7.9	8.3	446.9
2029	16.7	16.2	114.3	0.0	127.4	51.9	18.5	67.3	28.7	3.5	-	8.4	9.1	462.0
2030	13.8	13.9	109.6	0.0	128.8	55.4	19.1	75.9	38.2	3.6	-	9.0	10.0	477.2
2031	13.1	13.2	109.9	0.0	128.8	61.1	19.7	83.4	38.2	3.7	-	9.6	10.9	491.5
2032	12.1	12.2	109.2	0.0	128.7	67.3	20.4	91.7	38.1	3.7	-	10.2	12.0	505.7
2033	11.0	11.1	107.3	0.0	128.5	74.2	21.1	100.6	38.1	3.8	-	10.9	13.2	519.6
2034	9.7	9.8	103.9	0.0	128.3	81.7	21.8	110.5	38.0	3.8	-	11.5	14.5	533.5
2035	5.9	6.0	87.6	0.0	127.2	89.4	22.4	120.5	56.5	3.9	-	12.1	15.9	547.2

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Waste Heat	Existing Biomass	Biogas CHP	Biomass Combustion CHP	Total
2036	6.1	6.1	89.4	0.0	128.2	92.3	23.1	124.9	56.5	4.0	-	12.8	17.5	561.0
2037	6.2	6.3	90.9	0.0	129.3	95.3	23.9	129.4	56.5	4.0	-	13.5	19.4	574.6
2038	6.3	6.3	92.3	0.0	130.3	98.4	24.8	133.8	56.5	4.1	-	14.2	21.4	588.4
2039	6.3	6.4	93.4	0.0	131.3	101.6	25.6	138.1	56.5	4.2	-	15.0	23.7	602.1
2040	6.3	6.4	94.4	0.0	132.3	104.8	26.5	142.5	56.4	4.2	-	15.8	26.2	615.9
2041	6.3	6.3	95.1	0.0	133.3	108.2	27.4	146.8	56.4	4.3	-	16.6	29.1	629.8
2042	6.2	6.2	95.6	0.0	134.3	111.6	28.3	151.1	56.3	4.4	-	17.5	32.3	643.7
2043	6.1	6.1	95.8	0.0	135.2	115.1	29.3	155.3	56.3	4.5	-	18.4	35.8	657.8
2044	5.9	5.9	95.7	0.0	136.2	118.7	30.2	159.5	56.2	4.6	-	19.3	39.8	671.8
2045	5.6	5.7	95.3	0.0	137.0	122.4	31.2	163.6	56.1	4.6	-	20.3	44.2	685.9
2046	5.3	5.3	94.5	0.0	137.9	126.1	32.2	167.6	55.9	4.7	-	21.4	49.1	700.0
2047	4.9	4.9	93.3	0.0	138.7	129.9	33.3	171.6	55.8	4.8	-	22.5	54.5	714.1
2048	4.4	4.4	91.6	0.0	139.4	133.7	34.3	175.4	55.6	4.8	-	23.7	60.6	728.1
2049	4.0	4.0	89.3	0.0	140.0	137.6	35.4	179.1	55.4	4.9	-	25.0	67.3	742.1
2050	3.4	3.4	86.3	0.0	140.7	141.6	36.5	182.7	55.2	5.0	-	26.4	74.8	755.9

Table A. 22. Forecasted electricity supply by fuel type under HBDS (TWh)

Fuel Type	Hard Coal	Lignite	Natural Gas	Oil	Hydro	Wind	Geothermal	Solar	Nuclear	Waste Heat	Existing Biomass	Biogas CHP	Biomass Combustion CHP	Total
2020	67.9	37.9	70.9	0.3	78.1	24.8	10.0	11.0	0.0	1.3	4.5	-	-	306.7
2021	15.0	13.9	113.0	0.4	115.9	32.5	14.1	18.1	0.0	3.1	-	4.1	4.3	334.3
2022	17.6	14.5	112.4	0.3	117.2	34.3	14.6	22.2	0.0	3.1	-	4.8	4.8	345.8
2023	20.7	16.9	113.8	0.3	118.6	36.1	15.1	27.4	0.0	3.2	-	5.5	5.2	362.9
2024	23.7	19.1	114.4	0.3	120.0	38.1	15.6	33.7	0.0	3.2	-	6.2	5.8	380.1
2025	20.9	16.7	105.6	0.2	121.4	40.2	16.1	41.4	19.1	3.3	-	6.8	6.4	398.3
2026	20.9	17.6	110.0	0.2	122.9	42.8	16.7	46.7	19.1	3.4	-	7.5	7.1	415.0
2027	18.3	16.1	108.9	0.1	124.3	45.7	17.3	52.8	28.7	3.4	-	8.1	7.9	431.6
2028	17.5	16.2	111.6	0.1	125.8	48.7	17.8	59.6	28.7	3.5	-	8.8	8.7	447.0
2029	16.5	15.9	113.4	0.0	127.4	51.9	18.5	67.3	28.7	3.5	-	9.4	9.6	462.1
2030	13.5	13.6	108.6	0.0	128.8	55.3	19.1	75.9	38.2	3.6	-	10.1	10.6	477.2
2031	12.7	12.8	108.8	0.0	128.7	61.0	19.7	83.4	38.1	3.7	-	10.7	11.7	491.5
2032	11.8	11.9	107.9	0.0	128.6	67.3	20.4	91.6	38.1	3.7	-	11.4	13.0	505.7
2033	10.6	10.7	105.8	0.0	128.4	74.1	21.1	100.6	38.1	3.8	-	12.1	14.4	519.6
2034	9.3	9.4	102.2	0.0	128.2	81.6	21.8	110.4	38.0	3.8	-	12.8	15.9	533.5
2035	5.6	5.7	85.6	0.0	127.1	89.3	22.3	120.4	56.5	3.9	-	13.4	17.5	547.2
2036	5.8	5.8	87.2	0.0	128.1	92.2	23.1	124.8	56.5	3.9	-	14.1	19.5	561.0
2037	5.9	5.9	88.6	0.0	129.1	95.2	23.9	129.2	56.4	4.0	-	14.7	21.6	574.6

Fuel Type	**Hard Coal**	**Lignite**	**Natural Gas**	**Oil**	**Hydro**	**Wind**	**Geothermal**	**Solar**	**Nuclear**	**Waste Heat**	**Existing Biomass**	**Biogas CHP**	**Biomass Combustion CHP**	**Total**
2038	5.9	6.0	89.8	0.0	130.1	98.2	24.7	133.6	56.4	4.1	-	15.4	24.1	588.4
2039	5.9	6.0	90.7	0.0	131.1	101.4	25.6	137.9	56.4	4.2	-	16.2	26.8	602.1
2040	5.9	5.9	91.3	0.0	132.1	104.6	26.4	142.2	56.3	4.2	-	17.0	29.9	615.9
2041	5.8	5.8	91.7	0.0	133.0	107.9	27.3	146.5	56.2	4.3	-	17.8	33.4	629.8
2042	5.6	5.7	91.7	0.0	133.9	111.3	28.2	150.7	56.2	4.4	-	18.7	37.3	643.7
2043	5.4	5.5	91.4	0.0	134.8	114.7	29.2	154.8	56.1	4.5	-	19.7	41.7	657.8
2044	5.1	5.2	90.8	0.0	135.6	118.2	30.1	158.9	56.0	4.5	-	20.7	46.6	671.8
2045	4.8	4.8	89.8	0.0	136.4	121.8	31.1	162.9	55.8	4.6	-	21.8	52.2	685.9
2046	4.3	4.4	88.4	0.0	137.1	125.4	32.1	166.7	55.6	4.7	-	22.9	58.3	700.0
2047	3.9	4.0	86.1	0.0	137.8	129.1	33.1	170.5	55.4	4.7	-	24.2	65.3	714.1
2048	3.4	3.5	83.4	0.0	138.4	132.8	34.1	174.1	55.2	4.8	-	25.5	73.0	728.1
2049	2.9	3.0	79.9	0.0	138.9	136.5	35.1	177.6	55.0	4.9	-	26.9	81.6	742.1
2050	2.3	2.4	75.6	0.0	139.1	140.0	36.1	180.6	54.6	4.9	-	28.4	91.9	755.9

APPENDIX 5 – Publications Derived from the Thesis

A.E. Ersoy, A. Ugurlu, Bioenergy's role in achieving a low-carbon electricity future: A case of Türkiye, Applied Energy, v 372, (2024), 123799, https://doi.org/10.1016/j.apenergy.2024.123799