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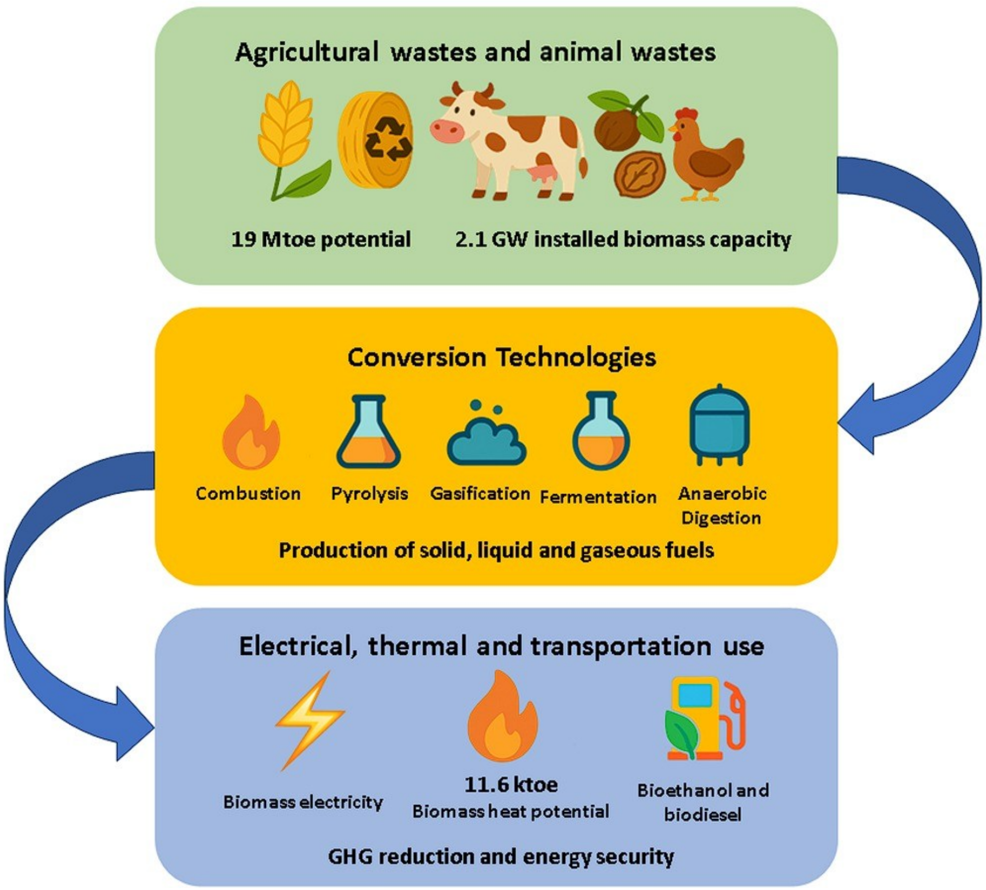
GRAPHICAL ABSTRACT



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Over the past decade, advances in bioenergy technology have enabled the expansion of renewable energy consumption. Projections indicate that roughly 30% of the anticipated increase in renewable energy utilization will stem from modern bioenergy in its solid, liquid, and gaseous fuel manifestations, owing to its substantial role in heat and transportation sectors. At present, fossil fuels account for 60% of global electricity generation, while renewables contribute 30%. Notably, Turkey surpasses this global average, with renewables constituting 36% of its electricity production. In 2002, Turkey's electricity output from renewable sources stood at 34 billion kWh; by 2023, it had surged by 300% to reach 200 billion kWh. Likewise, the installed renewable energy capacity, which was about 12,300 MW in 2002, has more than tripled, exceeding 82,700 MW in 2023. This research delves into biomass, a key pillar of renewable energy, analyzing its potential, technological advancements, significance, and current status in Turkey. Furthermore, it aligns with one of Turkey's foremost energy strategies that focuses on enhancing domestic and renewable energy production.

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Keywords: Biomass; Bioenergy; Renewable energy; Energy efficiency; Sustainability

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INTRODUCTION

Biomass energy can be broadly divided into traditional and contemporary forms of usage. Traditional biomass energy primarily involves the burning of firewood and dried animal dung (Newman *et al.* 2004; Ashworth and Azevedo 2009). The key characteristic of this conventional method is the direct combustion of biomass waste to generate heat energy. In contrast, modern biomass energy stems from a variety of sources, including energy crops, products from energy-focused forestry, agricultural by-products, and urban waste materials (Ahmed and Gupta 2012). These biomass resources are processed through different techniques, transforming them into solid, liquid, and/or gaseous fuels. The range of biomass fuels available is diverse (Arsova 2010). As a result, biomass energy stands out as a more environmentally friendly and sustainable alternative to fossil fuels, as it utilizes organic waste, reduces greenhouse gas emissions, and relies on continuously renewable resources (Eriksson and Prior 1990; Massoud *et al.* 2007; Oladeji 2010; Baskar *et al.* 2012; Rajendran *et al.* 2012; Desideri and Fantozzi 2013).

Bioenergy production and its utilization span a broad range of scales (Rajkumar and Venkatachalam 2013). At one extreme, biomass is used in households primarily for heating and cooking (Stolarski *et al.* 2013). Moving to the middle, various production and distribution models exist, including mixed-scale initiatives, cooperatives, and communitydriven energy projects. At the opposite extreme are large corporations that control both the production and conversion of biomass, as well as the distribution of bioenergy products (Strezov *et al.* 2015). These utility companies capitalize on economies of scale, sourcing substantial amounts of biomass either from their own estates, leased lands, or large suppliers. The biomass is then processed into bioenergy and distributed to thousands of consumers (Sultana and Kumar 2012). Each scale of bioenergy production and consumption presents its own set of advantages and challenges (Sultana *et al*. 2010; Cintas *et al.* 2017). Policymakers should carefully weigh the trade-offs between these benefits and drawbacks, especially when considering the public costs and benefits involved.

Turkey is shifting towards domestic and renewable energy sources to meet increasing energy demand and reduce external dependency. In this context, bioenergy, particularly biomass and biogas technologies, stands out. As of 2023, the installed capacity based on biomass had reached approximately 2.1 GW. Agricultural residues, animal manure, and municipal waste constitute the main bioenergy feedstocks in Turkey. Technically, thermochemical conversion methods (pyrolysis, gasification) and biochemical conversion methods (anaerobic digestion) are commonly employed. However, issues such as sustainability, logistics infrastructure, and financing remain key technical and structural challenges that need to be addressed for the sector's further development.

In Turkey, traditional biomass remains a crucial contributor to energy generation. In rural regions, wood is commonly utilized for cooking and heating, but the adoption of modern biomass for energy purposes is still a relatively recent development (BEPA 2015). As a country deeply rooted in agriculture, Turkey boasts substantial forestry resources, particularly in the regions of Central Anatolia, Cukurova, and Southern Anatolia. While the primary focus in agriculture is the cultivation of cereals and seeds, there is also a growing emphasis on utilizing agricultural waste that would otherwise be discarded. This agricultural waste is a significant biomass source, with considerable potential (FAO 2016). In 2023, agriculture comprised 6% of Turkey's GDP (Kar and Tekeli 2008; OECD 2012; MENR 2014, 2023; MFAL 2017; IEA 2021; IPRAGAZ 2023; TUIK 2023).

Turkey has long been recognized as a leading agricultural powerhouse globally. Various sources consistently rank the country among the top 10 agricultural nations worldwide (Özcan *et al.* 2013). Nearly half of Turkey's land is devoted to farming activities. Agriculture's role is becoming increasingly vital, especially as biomass energy emerges as a significant resource within the country. Biomass waste materials present an opportunity in Turkey to facilitate large-scale, centralized production of process heat for electricity generation. In the near future, biomass-based electricity generation is projected to become a promising and viable method in Turkey (Polat *et al.* 1993; Kaygusuz and Türker 2002; Kaygusuz 2011, 2012).

Biomass energy encompasses a variety of biological fuel sources, including agricultural byproducts, household waste, fuelwood, animal manure, and other materials originating from living organisms. The estimation of recoverable energy potential takes into account the primary agricultural byproducts, livestock waste, forest residues, wood processing scraps, and domestic waste, as referenced in the existing literature (FAO 2016; IEA 2021). The total recoverable bioenergy capacity has been projected to be approximately 19 Mtoe (Kaygusuz and Türker 2002; Bilgen *et al.* 2015). The total recoverable bioenergy capacity is expected to reach approximately 19 Mtoe by 2030 (ETKB 2022). In rural regions, biomass, primarily consisting of wood and animal dung, is predominantly utilized for heating and cooking purposes (Kaygusuz and Şekerci 2016; Toklu 2017).

Agriculture, Energy and GHG Emissions in Turkey

Turkey, occupying a strategic location at the intersection of Europe, Asia, and the Middle East, spans 783,562 square kilometers and features diverse geography including the Anatolian plateau, narrow coastal plains, and mountain ranges. The country has seven geographical regions and a population of about 85 million, with nearly 75% living in urban areas (TUİK 2023). In 2023, Turkey ranked as the world's 17th largest economy, with a GDP of around USD 986 billion and a per capita income over USD 10,200 (TUİK 2023). About 19% of the workforce worked in agriculture in 2022, while industry and services drive the economy (TUİK 2023). With growth averaging 3 to 4% over the last decade, Turkey is expected to reach high-income status, supported by a young population, rising education, and increasing investment. Its open-market economy has also deepened global financial integration (TUİK 2023).

Agriculture Sector

Turkey is the seventh largest producer of agricultural products globally, with agriculture's contribution to GDP decreasing from 11% in 2005 to 6% in 2023 (TUIK 2023). By 2023, the agricultural sector represented 14% of the country's exports and 8% of imports. Between 2010 and 2023, crop production made up 76% of the total agricultural output value, animal products accounted for 20%, and livestock contributed 10%. In 2023, the agricultural workforce comprised around 17% of Turkey's total employment (TUIK 2023). The agricultural exports of the country are varied, with the leading ten products encompassing chicken meat, hazelnuts, tomatoes, raisins, chocolate, tobacco, food preparations, pastries, nuts, and more—each contributing less than 8% of the overall export value. This dispersion of contributions indicates a broad and varied range of export values (Table 1).

Table 1. Agricultural Trade-Key Commodities (2020)

Trade commodity	Export quantity (tons)	Export value (1000 $)	Unit export price (US$/tons)
Hazelnuts	624.124	5.344.624	8.566
Wheat Flour	7.584.212	3.517.896	464
Food Preparations	764.216	2.191.154	2.864
Nuts	420.320	2.584.265	6.142
Pastries	564.720	1.374.568	2.432
Raisins	675.230	1.946.784	2.876
Chocolate	354.169	1.106.424	3.124
Tomatoes	1.876.426	1.424.214	764
Chicken Meat	583.214	1.018.292	1.746
TOTAL	13.446.631	20.508.221	28.978

Note: Adapted from TUIK (2023)

In the context of the country's food security and essential crops, wheat was the dominant staple, accounting for 36.4% of the overall food supply in 2023. Each of the remaining food categories made up less than 9% of the overall food supply for that particular year. To provide greater detail, the typical daily caloric intake per person in 2011 was 3,680 calories, maize, sunflower seed oil, milk, sugar, and wheat together representing over 60% of the total calorie consumption (Table 2) (TUIK 2023).

Table 2. Food Supply and Key Foodstuffs (2023)

Food Commodity	Food Supply (kcal/capita/day)	Share in Total Food Supply
Wheat and products	1.362	36.4%
Sugar (raw equivalent)	300	8.1%
Milk (excluding butter)	275	7.5%
Sunflower Seed Oil	252	6.7%
Maize and products	151	4.1%
Total	2.340	62.8%

Note: Adapted from TUIK (2023)

The country's agricultural sector is predominantly composed of small-scale farms, with approximately 3.1 million farming households distributed across 23 million hectares of arable land. Notably, 58% of these households cultivate plots smaller than 4.9 hectares, which account for only 16.1% of the total agricultural area. In contrast, 40.7% of the farming households operate between 5 and 50 hectares, making up the largest proportion, 63%, of the total agricultural land. Only a small fraction, 2%, of these households control land that exceeds 50 hectares, representing 22% of the entire agricultural area (TUIK 2023). This agricultural structure underscores the critical need to integrate renewable energy solutions, particularly biomass, into the national energy sector to promote sustainability and strengthen energy security.

Energy Sector

Energy plays a pivotal role in contemporary life, yet the current methods of energy production significantly contribute to climate change (MENR 2014). As global development progresses, the need to discover alternative energy routes that can help mitigate the effects of climate change becomes increasingly pressing. Agriculture plays a dual role in this challenge, acting both as an energy consumer and a potential energy supplier (MENR 2014). Specifically, bioenergy—derived from agricultural biomass—offers a viable renewable energy solution. This form of energy can help nations reduce reliance on conventional fossil fuels and shift toward a path of lower energy consumption

Turkey's domestic energy needs are predominantly met through fossil fuels, which constitute roughly 88% of the nation's total primary energy supply (TPES). In addition, a significant portion—around 82%—of the TPES was sourced from imports in 2023, highlighting the country's dependence on external supplies. Approximately 80% of the total imports comprised petroleum and natural gas (Table 3) (MENR 2023).

In the nation, over 70% of the total energy consumed comes from oil products, natural gas, and coal. The industrial sector is the largest consumer of primary energy, using 29%, followed closely by the transportation sector at 22% and the housing sector at 24% (Table 4) (MENR 2023).

Turkey's natural resources are under mounting pressure due to the rising energy demands across various sectors such as industry, transportation, tourism, and agriculture. These growing needs have led to issues like water scarcity, soil degradation, and environmental pollution. As life expectancy continues to rise, the strain on energy infrastructure has intensified. Furthermore, the improvement in living standards has driven up the demand for domestic energy, and projections suggest that this trend will persist in the future (IEA 2021).

Energy Policy

Energy policy constitutes a critical framework guiding the production, distribution, and consumption of energy resources within a country or region. It encompasses a broad spectrum of regulations, strategies, and initiatives aimed at ensuring reliable, affordable, and sustainable energy supply while balancing economic growth, environmental protection, and social welfare. The formulation of energy policy is inherently complex due to the multifaceted nature of the energy sector, which intersects with diverse domains such as technology, economics, geopolitics, and environmental science.

In recent decades, the urgency of addressing climate change has profoundly reshaped energy policy agendas worldwide. The need to reduce greenhouse gas emissions, enhance energy efficiency, and transition towards low-carbon and renewable energy sources has become paramount. Concurrently, concerns about energy security—stemming from geopolitical tensions, resource depletion, and market volatility—have further underscored the importance of resilient and diversified energy systems. Advances in technology, including the development of energy storage, smart grids, and digital energy management systems, present both challenges and opportunities for policymakers seeking to modernize energy infrastructure and promote sustainable development.

Given these evolving dynamics, contemporary energy policies must be adaptive and forward-looking. They require integration of environmental objectives, economic competitiveness, and social inclusiveness, while fostering innovation and international cooperation. The adoption of renewable energy technologies, expansion of decentralized energy generation, and enhancement of energy system flexibility are key elements shaping future energy policy frameworks. Ultimately, the effectiveness of energy policy will depend on its ability to harmonize these diverse priorities and respond to emerging trends in an increasingly interconnected and climate-conscious global landscape.

In the case of Turkey, the country's strategic geographical location, young population, and increasing energy demand further emphasize the importance of energy policies. While increasing investments to ensure energy supply security, Turkey also aims to expand the use of renewable energy sources and improve energy efficiency. National energy policies support renewable energy projects in alignment with climate change goals and accelerate digital transformation processes in the energy sector. Thus, Turkey continues to take the necessary steps toward a sustainable, reliable, and competitive energy system.

Turkey's central goal is to ensure energy security while fostering sustainable development. In pursuit of this, the country seeks to: broaden its energy supply routes and diversify its source nations; maximize the contribution of renewable energy and incorporate nuclear power into its energy portfolio; enhance energy efficiency; and play an active role in bolstering Europe's energy security. Anticipating a substantial rise in energy demand, Turkey aims to address this challenge in a way that is both timely and cost-effective. Additionally, the government is fostering a more favorable investment climate for the private sector by advancing the natural gas markets and electricity liberalization (MENR 2014, 2015, 2023; MFAL 2017).

Energy policies are expected to be reshaped in the future in response to climate change, supply security, and technological advancements. In particular, the widespread adoption of renewable energy sources, energy storage solutions, and digital energy systems will necessitate the updating of current policy frameworks.

Table 3. Turkey's Energy Balance in 2023 (ktoe)

	Coal	Crude Oil	Natural Gas	Hydro	Biomass Wastes	Solar	Wind	Geothermal	Electric	Total
Production	15.646	4.306	703	5.504	10.200	2.770	2.940	12.384	-	54.453
Imports	24.820	32.973	41.650	524	-	-	-	-	524	100.491
Exports	422	4.674	740	179	-	-	-	-	179	6.194
TPES	40.024	32.872	41.560	5.504	10.200	2.768	2.934	12.384	-	138.046

Note: Adapted from MENR (2023). TPES, total primary energy supply

Table 4. Total Final Consumption and Relative Shares in Turkey (2023)

Sector	Final Energy Consumption (TJ: Terajoules)	Share of total consumption (%)
Industry	1,397,570	%39
Transport	126,283	%4
Residential	1,046,145	%28
Commercial & public services	599,400	%17
Agriculture	205,491	%6
Others (excluding the above)	207,381	%6
TOTAL	3,583,464	%100

Note: Adapted from TUIK (2023)

Table 5. Estimated Electricity Installed Capacity and Gross Electricity Generation from Renewable Energy Sources

Renewable Energy Sources	2020		2021		2022		2023	
	Installed (MW)	Generation (TWh)	Installed (MW)	Generation (TWh)	Installed (MW)	Generation (TWh)	Installed (MW)	Generation (TWh)
Hydropower	30.985	78.1	31.493	56.4	31.571	66.3	31.962	63.9
Wind	8.832	24.8	10.607	31.6	11.396	35.3	11.807	34.0
Solar	6.667	11.0	7.816	14.6	9.425	17.4	13.998	18.6
Geothermal	8.832	10.0	1.676	11.2	1.691	11.4	1.692	11.2
Biomass	1.485	5.7	2.035	8.1	2.309	9.6	2.080	9.8
Total	49.582	129.6	53.627	121.9	56.392	140.0	61.539	137.5

Note: Adapted from TUIK (2023)

Additionally, new regulations aimed at reducing carbon emissions, financial incentives, and international collaborations will lead to significant changes in the energy sector. Therefore, energy policies must be designed not only to address current needs but also to respond to potential risks and opportunities that may arise in the future.

Turkey’s energy policy is primarily centered around expanding renewable energy sources and improving energy efficiency. The nation has set an ambitious goal to generate at least 60% of its electricity and 12% of its transportation energy from renewable sources by 2030. Furthermore, Turkey is committed to reducing energy consumption per unit of GDP by at least 40% by the same year. The country has also outlined specific technology-driven targets, including a biomass production target of 2,000 MW by 2023 (MENR 2023). However, biomass’s contribution remains relatively modest compared to wind and hydropower energy. In fact, in terms of the 2023 target for electricity capacity installation, the aim is to incorporate 32 MW from hydropower, 12 MW from wind energy, 14 MW from solar, 1.7 MW from geothermal, and 2.0 MW from biomass (Table 5) (MENR 2023)

Biomass stands as the predominant source driving the REAP's heating and cooling goals; however, it remains unchanged at 3.544 ktoe (Table 6) (MENR 2023). In addition, heat pump technologies that utilize ambient thermal energy for heating and cooling should also be considered.

Table 6. Estimate Energy Shares from Renewable Energy Sources in Heating and Cooling (1000 Ton of Oil Equivalent)

Renewables	2020	2021	2022	2023
Geothermal	446	1.498	3.786	12.384
Solar	766	1.234	1.986	2.770
Biomass & Bioenergy	3.544	6.875	8.764	11.600
Heat pumps	2.364	2.568	2.986	3.136
Total	7.120	12.175	17.522	29.890

Note: Adapted from MENR (2023)

Over the span of a decade, bioenergy’s contribution to the transportation sector is projected to rise consistently. By 2023, the share of biodiesel grows to 1.320 ktoe, up from 33 ktoe in 2013, while the volume of ethanol rises from 127 ktoe in 2013 to 896 ktoe in 2023 (Table 7). Bioenergy will be a crucial component in achieving the transportation sector’s targets (MENR 2014; MENR 2023).

Table 7. Estimate Energy Shares from Renewables in the Transport Sector (1000 Ton of Oil Equivalent)

Renewable liquid fuels	2020	2021	2022	2023
Bioethanol	734	842	862	896
Biodiesel	720	992	1.152	1.320
Renew. Fuel for electricity	24	26	27	28
Renew- Fuel for Transportation	21	22	23	24
Total	1.499	1.882	2.064	2.268

Note: Adapted from MENR (2023)

Greenhouse Gas (GHG) Emissions

Although the section on greenhouse gas (GHG) emissions effectively presents Turkey’s sectoral emission increases over the years, it remains insufficient in evaluating the country's position within the global climate change mitigation context. Including comparative data on Turkey's total GHG emissions and per capita emission levels relative to global averages, OECD countries, EU member states, and G20 countries can provide a more comprehensive perspective on the country's emission profile. For instance, as of 2023, Turkey's per capita emissions stand at approximately 6.5 tons of CO_2-equivalent, which is below the OECD average but above the global average. Similarly, Turkey's carbon intensity (CO_2 emissions per unit of GDP) is another key indicator that invites international benchmarking, particularly in terms of economic structure and energy transition performance. Integrating such comparative data is crucial for assessing Turkey's progress in meeting its global mitigation commitments (*e.g.*, Nationally Determined Contributions under the Paris Agreement) and for informing future policy recommendations.

Table 8 provides a comprehensive breakdown of Turkey's greenhouse gas (GHG) emissions from 1990 to 2014, with a visual representation in Fig. 1. These figures reveal a more than twofold increase in emissions across the analyzed period, with each sector showing an upward trend. Emissions have surged significantly within the energy sector, escalating from 132,477 kt CO_2-eq in 1990 to 339,105 kt CO_2-eq by 2014. This sector stands as the dominant factor behind this increase. The industrial processes sector also saw notable growth, though its impact on the overall emissions remains less significant compared to the energy sector. Emissions from agriculture also experienced a 20% increase between 1990 and 2014; however, the sector's relative share of national emissions has diminished, dropping from 20% in 1990 to 10% in 2023 (TUIK 2023).

Table 8. Aggregated GHG Emissions by Sectors (Mt CO_2-eq) [28]

Sector	1990	2000	2010	2016	2018	2020	2022
Energy	143	220	291	362	375	370	401
IPPU	23	26	49	63	67	67	70
Agriculture	52	46	48	62	69	77	72
Waste	11	15	18	18	18	17	16
LULUCF	-67	-68	-72	-74	-71	-58	-56
Total	162	239	334	431	458	473	503

Adapted from TUIK (2023). IPPU, industrial processes and product use; LULUCF, land-use, land-use change, and forestry

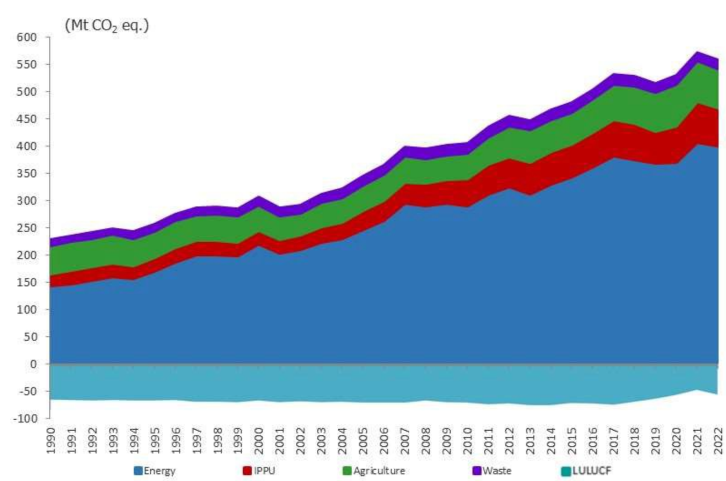

Fig. 1. GHG Emissions and sinks by sector, 1990-2022

BIOMASS CONVERSION PROCESSES FOR HEAT AND FUEL

Vegetable matter is generated through photosynthesis, a process powered by sunlight that enables simple minerals to be transformed into complex organic compounds. During its growth, plant biomass absorbs carbon dioxide (CO_2) from the air, which is subsequently released when it is burned. As a result, the net CO_2 emission of this cycle is neutral, meaning it does not exacerbate the greenhouse effect. Biomass refers to any organic material, such as municipal waste, but for clarity, we limit the term to "plant biomass," focusing on materials derived from the plant kingdom. The conversion of plant biomass into energy occurs through three main processes, which fall into three categories: thermo-chemical, biological, and physical. Figure 2 illustrates the processes by which plant biomass is transformed into heat and fuel (Dahiya 2020).

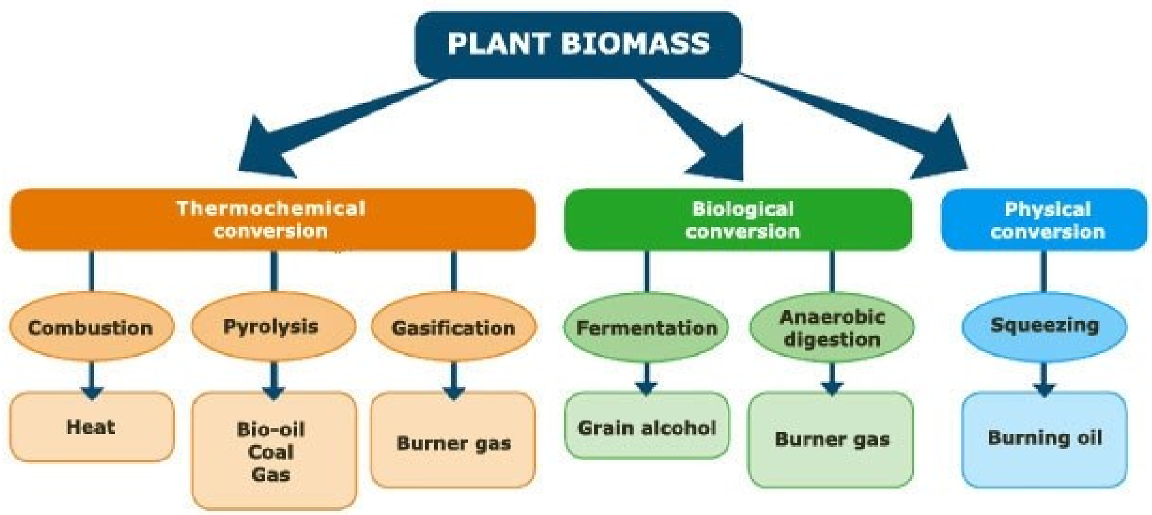

Fig. 2. Plant biomass conversion processes for heat and fuel

Combustion

Biomass combustion remains one of the most conventional methods for converting organic materials into usable energy. For this process to achieve optimal efficiency, it is crucial to lower the water content of the biomass, which is typically done by drying the material under sunlight. These systems are, in essence, co-generation plants, producing both thermal and electrical energy. A portion of the heat generated is used to create steam, which drives turbines linked to electricity generators. The residual heat can be redirected for use in industrial processes or to meet residential heating needs. However, the overall efficiency of these systems is relatively low, typically ranging between 20 and 25%.

Pyrolysis

Pyrolysis refers to the thermochemical breakdown of organic substances, often known as dry distillation, wherein biomass is transformed by heat under conditions of limited oxygen. This method is suitable for any organic material with a moisture content below 15%. The material is heated to temperatures ranging from 200 to 700 °C, and in some cases, a controlled amount of oxygen can trigger partial combustion, causing the temperature to rise (Massoud *et al.* 2007; Strezov and Evans 2015; Dahiya 2020).

Gasification

The process of biomass gasification is a physical-chemical transformation where a solid fuel, such as wood or other forms of biomass, is converted into a gaseous fuel. This transformation occurs through the partial oxidation of carbon-rich compounds under elevated temperatures, typically around 1000 °C, and in an environment where oxygen is limited. The resulting gas, known as syngas, is a blend of nitrogen, methane, hydrogen, carbon monoxide, and other gaseous components. Syngas can be utilized directly in internal combustion engines, which are primarily used for generating electricity (Massoud *et al.* 2007; Strezov and Evans 2015; Dahiya 2020).

Fermentation

Alcoholic fermentation is a biochemical process in which sugars are converted into ethanol. The conversion of biomass with high sugar content into ethanol has been thoroughly tested, particularly in Brazil, where sugarcane fermentation produces ethanol at a cost comparable to gasoline. In contrast, experimental efforts in Italy using sugar beets have yielded disappointing results, as the processing costs were not economically viable (Massoud *et al.* 2007; Strezov and Evans 2015; Dahiya 2020).

Anaerobic Digestion

Anaerobic digestion is a biological transformation process facilitated by bacteria that act on biomass abundant in cellulose. During this process, biogas is produced, containing approximately 65% methane. This methane is then used to power an internal combustion engine linked to an electricity generator. The electricity generated is directly supplied to the grid and sold at a favorable price under the Green Certificate program, classifying it as a renewable energy source. The remaining digested material serves as an effective fertilizer. Such biomass energy plants are prevalent in Northern Europe. To further enhance the efficiency of these plants, it might be beneficial to incorporate specialized equipment to capture the heat generated, as for every kWh of electricity produced, about 1 kWh of thermal energy is also produced (Massoud *et al.* 2007; Strezov and Evans 2015; Dahiya 2020).

EXPERIMENTAL

Methodology for the Assessment

Agricultural residues consist of both crop and livestock byproducts, with the amount produced varying according to the specific crop or breed of livestock. Additionally, the utilization of these residues differs widely, not only between countries but also within regions of a single country. Agricultural waste, such as remnants from harvested plants, finds new purpose in enriching soil and creating biodegradable packaging. Meanwhile, animal-derived waste, particularly dung, plays a crucial role as a natural fertilizer. Consequently, it is essential that agricultural residues used for bioenergy production do not interfere with their current applications. Achieving success in the three stages of analysis hinges on the availability of specific data related to crops or livestock. In the second stage, which involves determining the availability of residues, it is crucial to have access to data detailing the quantities of residues already in use. The following sub-section offers a detailed analysis of the steps involved for crop and livestock residues (OECD 2012; BEPA 2015; FAO 2016; MENR 2023). Using a four-year average yield helps to balance annual climate variability and fluctuations in agricultural production, thereby enabling a more stable and realistic estimation of crop residue quantities.

Crop Residues

Agricultural crop processing and harvesting yield organic remnants known as crop residues, which emerge as secondary products during these activities (Dahiya 2020). These residues can be divided into two main categories: primary and secondary. Primary residues are those produced directly in the field during harvest (Massoud *et al.* 2007). These can be collected on-site, such as cereal straw, sugarcane tops, cotton stalks, and maize stalks. On the other hand, secondary residues are the by-products formed during the processing stage. Examples of these include paddy husks, bagasse, maize cobs, coconut shells, and coconut husks. Figure 3 illustrates the various types of crop residues and their respective locations (Strezov and Evans 2015).

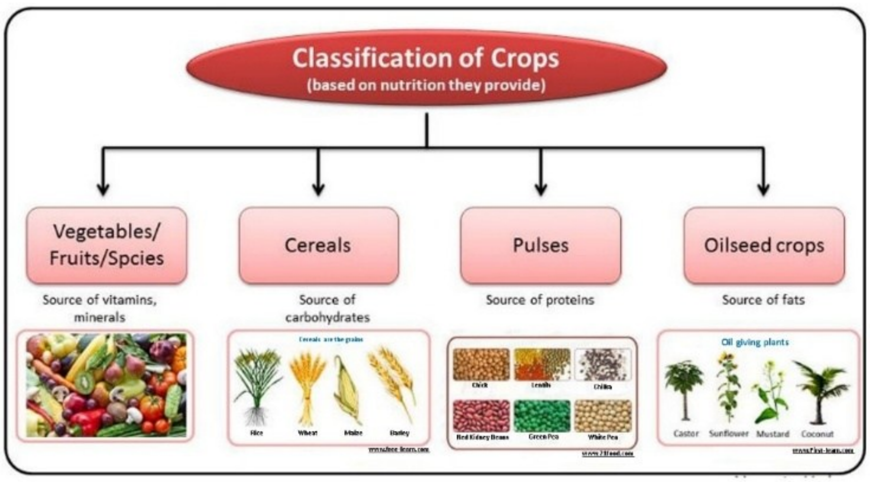

Fig. 3. Crop residue types and location

The total crop residues generated in each province were estimated by applying the following formula, which takes into account the average crop yield over a four-year period at the provincial level (FAO 2016),

$$CR_{total} = \text{Crop production quantity (tons)* RCR} \quad (1)$$

where CR_{total} (t/year) is the total crop residues produced in the area, and RCR (Residue to Crop Ratio) is the residue to crop ratio of the specific crop.

Availability of Crop Residues

The CR_{total} represents the overall volume of crop residues generated. However, not all these residues are suitable for conversion into bioenergy feedstock. Agricultural residues play a critical role as biomass sources, both for domestic and industrial applications. Agricultural residues, forestry by-products, animal waste, municipal solid waste, and energy crops are among the key renewable sources for biomass energy production (Bayraktar 2024). The bioenergy potential of these residues refers to the amount that is actually available for bioenergy production. This potential is calculated using the following formula (FAO 2016),

$$CR_{be} = (CR_{total} – Cr_{soil} - CR_{used}) \quad (2)$$

where CR_{be} (t/year) is the crop residues available for bioenergy production in the area, CR_{total} (t/year) is the total crop residues produced in the area, CR_{soil} (t/year) = amount of residues that should be left in the field, and CR_{used} (t/year) is the amount of crop residues already used.

Accessibility of Crop Residues

Although large quantities of crop residues may be present, gathering and transporting them for bioenergy production can present significant difficulties. Therefore, the notion of accessibility becomes crucial, as it seeks to determine what fraction of the available crop residues can be effectively utilized for bioenergy. The ease of access to these residues is also influenced by the existing logistical framework, including the road and rail systems, which play a crucial role in determining the costs associated with their transportation and collection. The following equation can be used to quantify, in theory, the accessibility of these residues (FAO 2016).

$$CR_{ac} = CR_{be} * k \tag{3}$$

where CR_{ac} (t/year) is the crop residues accessible for bioenergy production in the area, R_{be} (t/year) is the crop residues available for bioenergy production in the area, and k *(%)* is the accessibility coefficient.

Livestock Residues

Livestock farming inherently generates manure as a natural waste product. Unlike the remnants of harvested crops, which are divided into primary and secondary classifications, manure exists as a distinct entity. Its potential for energy generation is notable, requiring minimal refinement before utilization. The livestock species analyzed in this study are primarily cattle and poultry, given their significant role in generating household income across Turkey. To estimate the total manure production, the following formula was applied (FAO 2016).

$$LR_{total} = N_{animal} * \mathrm{Mph} \tag{4}$$

where LR_{total} (t/year) is the total manure produced per year in the area, N_{animal} (t/year) is the number of animal (per cattle and poultry type) in the area, and *Mph* (t/year) is the amount of manure produced per head per year.

The amount of manure produced per head, for each cattle and poultry category, was established by engaging in technical discussions with specialists from TAGEM, alongside utilizing data sourced from the Turkish Biomass Energy Potential Atlas (BEPA 2015).

RESULTS AND DISCUSSION

Crop Residue Assessment Results

The annual production of crop residues is directly influenced by the total crop yield for that specific year. To enhance the precision of our estimate, the average crop production from 2020 to 2023 was determined and utilized. This three-year average then served as the basis for calculating the associated residue generation. Table 9 presents the three-year averages for production volumes, harvested areas, and the outputs from every crop originally selected for examination.

Table 9. Average Production Quantity of Agricultural Crops

Crop	Average Harvest Area (hectares), 2020-2023	Average Production (tons), 2020-2023
Wheat	6,782,542	19,852,624
Barley	3,192,568	7,937,500
Maize	646,324	5,125,678
Sunflower	890,896	2,307,500
Olive	598,864	1,678,944
Rice	124,432	968,564
Cotton	461,746	836,546
Apricot	148,894	696,879
Chickpea	542,246	548,786
Hazelnut	676,768	543,124
Groundnut	51,350	205,392
Pistachio	324,465	196,568
Soybean	37,422	157,500
Walnut	98,886	296,876
Oats	94,642	296,678
Almonds	28,886	86,496
Chestnut	12,678	76,468
Sugar beet	21,323,754	326,524

Adapted from TUIK (2023)

Economic Analysis

Newman *et al.* (2004) outlined the techno-economic framework used for estimating the Net Present Value (NPV). This section illustrates the process followed for that estimation. To illustrate this method, the example focuses on the potential end-use options for briquettes. The NPV calculation served as the foundation for determining the maximum permissible feedstock price and generating profitability zones, which helped establish the conditions under which feedstock production would be profitable in the analysis. The calculations were conducted across three distinct analysis ranges. These ranges include feedstock energy potential (10 to 20 MJ/kg), feedstock costs (0 to 150 $/ton), and plant capacities (4, 40, 400, or 4000 kg/h). The tables provided below show the results obtained at each stage, with each set of results presented according to the three variable ranges.

Total Annual Cost ($/year)

In Table 10, the total annual costs in US$/year for briquette production are detailed. It outlines the overall annual expenses by considering feedstock costs of 20$/ton and energy potential variations ranging from 10 to 22 MJ/kg, alongside four different plant capacities.

Table 10. Total Annualized Cost of Briquettes Production at Different Production Capacities and Energy Potentials of Feedstock

Energy Potential (MJ/kg)	Feedstock Cost (US$/ton)	Total Annual Cost (US$/Year)			
		4 kg/h	40 kg/h	400 kg/h	4000 kg/h
10	$20	$896	$14 642	$146 464	$1 346 264
15	$20	$822	$14 544	$145 485	$1 326 114
17	$20	$794	$14 342	$146 264	$1 314 672
19	$20	$762	$14 312	$146 221	$1 306 761
22	$20	$686	$14 042	$146 178	$1 146 884

The table displays the computed total annualized cost for briquette manufacturing across diverse production capacities and feedstock energy potentials. The 'kg/h' unit indicated in Table 10 refers to the amount of biomass briquettes that the facility can produce per unit of time, and it is understood that this value corresponds to the briquette production capacity of the plant.

Net Present Value (NPV) Calculation

The Net Present Value (NPV) formula reflects the total value adjusted to a specific reference point in time, as follows,

$$NPV = \sum_{i=0}^{n} [(annual\ cash\ flows)/(1+i)n] \tag{5}$$

where the term $(1+i)_n$ represents the discount factor, where "i" is the discount rate. For bioenergy projects, an acceptable range for this rate falls between 9% and 11%. The NPV data is displayed in Table 11.

Table 11. NPV of Briquettes Sold at Their Current Market Price and Discount Rate is Considered as 11%

Energy Potential (MJ/kg)	Feedstock Cost (US$/ton)	Total Annual Cost (US$/Year)			
		4 Kg/h	40 Kg/h	400 Kg/h	4000 Kg/h
10	$20	-$694	$3.986	$284.112	$1.464.768
15	$20	$2.144	$23.612	$576.346	$3.986.789
17	$20	$3.422	$38.462	$964.576	$6.132.658
19	$20	$4.334	$50.112	$1.468.812	$8.986.212
22	$20	$4.986	$60.564	$1.764.864	$11.214.224

Figure 4 provides an overview of the generation with a combined production capacity of 1.012 MW. This capacity is achieved through an effective blend of direct combustion and biogas derived from specific biomass resources throughout Turkey. The western and southern regions of the country exhibit the highest potential for electricity generation. Figure 5 illustrates the energy values associated with the annual crop residue yields across Turkey.

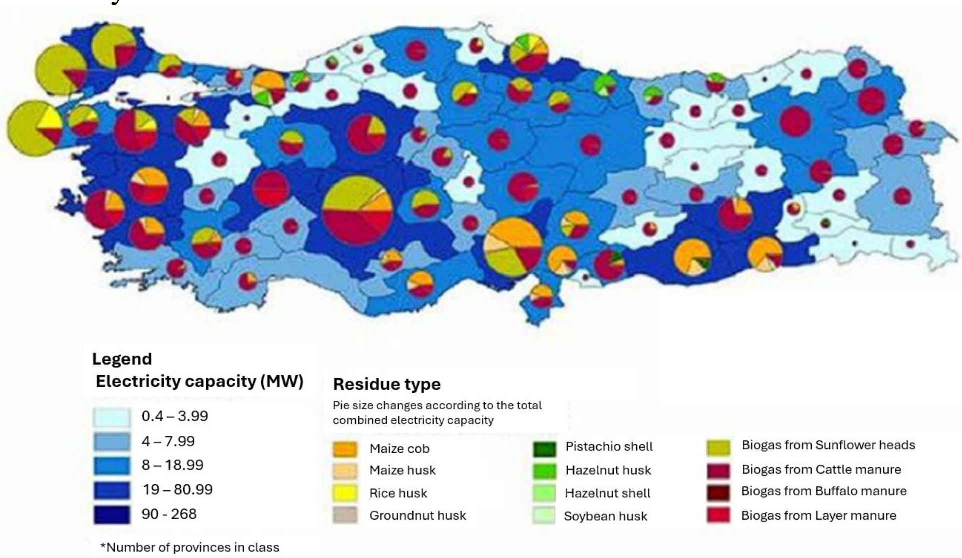

Fig. 4. Electricity capacity generation (MW) from crop residues in Turkey

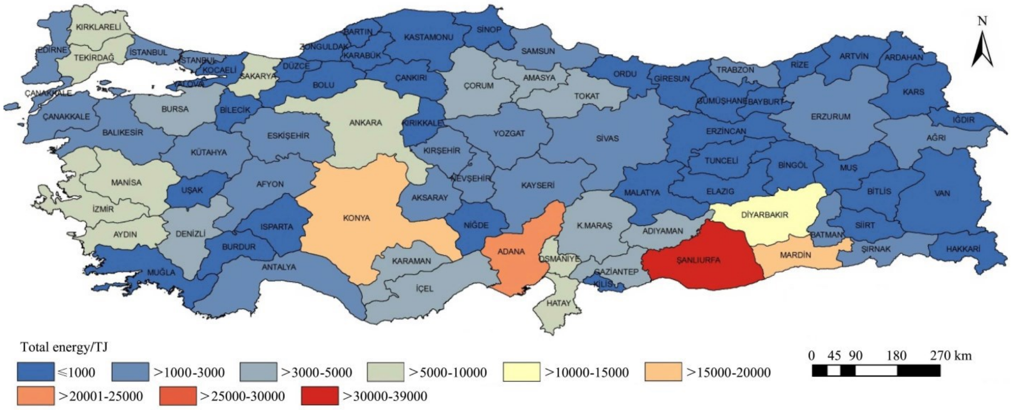

Fig. 5. The map of energy values of annual field crops residues in Turkey

CONCLUSIONS

1. The aim of this analysis for Turkey was to explore how the biomass potential outlined in the Natural Resource Assessment has been recognized and quantified across various provinces could be harnessed for bioenergy production, ensuring both technical feasibility and economic viability. In doing so, the assessment also investigated how agricultural residues can be leveraged for bioenergy generation and its role in helping Turkey meet its renewable energy targets. Agricultural waste can be utilized not only for electricity generation but also for heat production, with both energy applications being evaluated. Given the lack of up-to-date and reliable market data on heat sale prices under current conditions in Turkey—such as pricing, capital investments, and tariffs—it is not possible to accurately assess the financial viability of combined heat and power CHP systems. Due to the lack of up-to-date and reliable market data on heat sale prices, the financial viability of cogeneration CHP systems cannot be accurately assessed. As a result, electricity generation was the sole focus for assessing the profitability of CHP plants. The findings indicated that these plants must operate with high-efficiency technologies, preferably utilizing feedstocks with high energy potential. Moreover, biomass can be effectively employed in cogeneration systems, where steam is initially used to generate electricity, and the resulting low-pressure steam is subsequently utilized for space heating or in various industrial thermal processes. Processing facility-derived biomass ought to be channeled into nearby manufacturing operations, where it would be utilized to generate electricity for grid distribution. Conversely, biomass originating from farmland should be employed in autonomous energy systems, converting heat into electrical power for grid supply.
2. Turkey, with its expansive agricultural sector, faces a notable reliance on imported fossil fuels to fulfill a considerable portion of its energy demands. In response to the dual challenges of energy security and climate change, Turkey has outlined a series of renewable energy goals. Given the scale of its agricultural output, there is growing interest in exploring the potential role of agricultural residues in helping achieve these renewable energy targets, particularly within the bioenergy sector. This research presents an initial evaluation of the availability of both livestock residues and crop, as well as the economical and technical feasibility of harnessing these by-products for heat and power generation. The bioenergy technologies assessed in this study include

pellets, briquettes, large-scale combined heat and power systems utilizing biogas production and direct combustion. The analysis was conducted at the regional level, incorporating specific national data and technical parameters for accuracy and relevance.

3. The findings from the evaluation highlight the bioenergy potential at the provincial level, identifying which regions are most compatible with the bioenergy supply chains under consideration. This study has examined the extent to which the selected supply chains contribute to biomass-based renewable energy targets, as well as the amount of energy that can be supplied to a household through the use of briquettes and pellets. The primary challenge in fully realizing the projected bioenergy potential is the accessibility and mobilization of biomass, which remains a significant barrier to progress.

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