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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Valorization of Livestock Manure and Agricultural Residue for Biogas-Based Circular Economy in Kırklareli Province, Türkiye

Türkiye, Kırklareli İlinde Biyogaz Bazlı Döngüsel Ekonomi İçin Hayvan Gübresi ve Tarımsal Artıkların Değerlendirilmesi

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Abstract

Energy consumption is increasing due to population growth, rising prosperity, and the rapid advancement of technology. The predominant use of fossil fuels, which account for 81% of global energy consumption, has led to significant environmental problems, particularly climate change. Climate change has been a key global issue for the past two decades. The Paris Agreement, adopted at COP21 in 2015, marked the first global commitment to reducing greenhouse gas emissions post-2020. In 2019, the European Union (EU) launched the European Green Deal (EGD), aiming to limit global temperature rise to below 2°C and adapt to climate change. The EU's goal is to become the first climate-neutral continent by 2050, reshaping its policies across sectors like industry, energy, transportation, and agriculture. This study emphasizes the benefits of greenhouse gas (GHG) mitigation, particularly focusing on the generation of bio-methane derived from livestock manure and agricultural residue in the Kırklareli province of Türkiye. This study also examines CH_4 emissions released by the livestock sector due to processes of enteric fermentation and manure management. According to the results obtained, bio-methane has a potential electricity generation capacity of 566 GWh year^{-1}. CO_2 emissions from biogas energy production are calculated as 261492 tons CO_2eq year^{-1}. Accordingly, the CO_2 emission mitigation capacity is determined to be between 310969 and 443799 tons CO_2eq year^{-1} based on the IPCC Guidelines' Middle East, Eastern Europe, and Asia values. This study also examines CH_4 emissions released by the livestock sector due to processes of enteric fermentation and manure management. Enteric fermentation and manure management -based CO_2eq emissions were calculated according to Tier 1 and Tier 2 approaches given in the IPCC Guidelines. This study aims to provide policymakers and relevant stakeholders with comprehensive information regarding the diversification of the energy mix. It emphasizes the benefits of GHG mitigation, particularly focusing on the generation of bio-methane derived from livestock manure and agricultural residues in the Kırklareli province of Türkiye.

Keywords: Waste to energy, Manure management, GHG, CO_2 mitigation, Bio-methane, Circular economy, Energy potential

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Öz

Nüfus artışı, artan refah ve teknolojinin hızla ilerlemesi nedeniyle enerji tüketimi artmaktadır. Küresel enerji tüketiminin %81'ini oluşturan fosil yakıtların baskın kullanımı, özellikle iklim değişikliği olmak üzere önemli çevre sorunlarına yol açmaktadır. İklim değişikliği, son yirmi yıldır önemli bir küresel sorun olmuştur. 2015 yılında COP21'de kabul edilen Paris Anlaşması, 2020 sonrası sera gazı emisyonlarını azaltmaya yönelik ilk küresel taahhüdü temsil etmektedir. Avrupa Birliği (AB), 2019 yılında küresel sıcaklık artışını 2°C'nin altında sınırlamayı ve iklim değişikliğine uyum sağlamayı amaçlayan Avrupa Yeşil Mutabakatı'nı (AYM) başlattı. AB'nin hedefi, sanayi, enerji, ulaştırma ve tarım gibi sektörlerdeki politikalarını yeniden şekillendirerek 2050 yılına kadar ilk iklim nötr kıta olmaktır. Bu çalışma, özellikle Türkiye'nin Kırklareli ilinde hayvan gübresi ve tarımsal artıklardan elde edilen biyometan üretimine odaklanarak sera gazı azaltımının faydalarını vurgulamaktadır. Bu çalışmada ayrıca, hayvancılık sektörü tarafından enterik fermantasyon ve gübre yönetimi süreçleri nedeniyle salınan CH_4 emisyonları da incelenmiştir. Elde edilen sonuçlara göre biyometan, 566 GWh yıl^{-1} potansiyel elektrik üretim kapasitesine sahiptir. Biyogaz enerji üretiminden kaynaklanan CO_2 emisyonları 261492 ton CO_2eq yıl^{-1} olarak hesaplanmıştır. Buna göre, IPCC Kılavuzu'nun Orta Doğu, Doğu Avrupa ve Asya değerleri baz alınarak CO_2 emisyonu azaltma kapasitesi 310969 ile 443799 ton CO_2eq yıl^{-1} arasında olduğu belirlenmiştir. Bu çalışmada ayrıca, hayvancılık sektörü tarafından enterik fermantasyon ve gübre yönetimi süreçleri nedeniyle salınan CH_4 emisyonları da incelenmiştir. Enterik fermantasyon ve gübre yönetimi bazlı CO_2eq emisyonları IPCC Kılavuzunda verilen Tier 1 ve Tier 2 yaklaşımlarına göre hesaplanmıştır. Bu çalışma, politika yapıcılara ve ilgili paydaşlara enerji karışımının çeşitlendirilmesi konusunda kapsamlı bilgi sağlamayı amaçlamaktadır. Özellikle Türkiye'nin Kırklareli ilinde hayvan gübresi ve tarımsal artıklarından elde edilen biyometan üretimine odaklanarak sera gazı azaltımının faydalarına vurgu yapmaktadır.

Anahtar Kelimeler: Atıktan enerji, Gübre yönetimi, SGE, CO_2 azaltımı, Biyo-metan, Döngüsel ekonomi, Enerji potansiyeli

1. Introduction

Energy has become an important indicator that determines the development level of countries around the world. Population growth, rising levels of prosperity and rapid technological development can be determined as the main factors of increasing energy consumption. Accordingly, a significant portion, approximately 81%, of the world's energy supply comes from fossil fuels. (Anonymous, 2024a). This excessive use of fossil fuels leads to a rapid depletion of resources, and environmental problems, particularly climate change pose a threat to the world. On the other hand, one of the important factors that enable countries to progress economically is sustainability in energy. Accordingly, the structure of economies, energy consumption patterns and even lifestyles are changing around the world. Fossil fuels, mentioned as the most responsible for climate change, are being replaced by renewable, sustainable and clean energy sources. Extracting energy from biomass and utilizing its energy potential can be used to generate fossil fuel-free energy while reducing the amount of waste that needs to be disposed of. Climate change has been the most important global issue on the world's agenda, mostly for the past two decades. The Paris Agreement, which forms the framework for the post-2020 climate change regime, was adopted at the Conference of the Parties (COP) 21 in 2015. At COP21, all countries committed for the first time at a global level to reduce greenhouse gas (GHG) emissions after 2020. Accordingly, within the scope of combating global climate change, the EU published the European Green Deal (EGD) declaration in 2019. This initiative launched the transition to a green economy in line with the Paris Climate Agreement, aiming to keep the global temperature increase below 2°C and adapt to the effects of climate change. Consequently, the EU has set the goal of becoming the first climate-neutral continent in 2050 and announced that it will adopt a new growth strategy to achieve this goal and reshape all its policies around climate change. The EGD, envisages comprehensive changes in EU policies in many areas ranging from industry to finance, from energy to transportation and from buildings to agriculture. The green economy refers to the circular economy model with new policies covering all sectors as a solution to the climate crisis with resource efficiency and low carbon emissions (Küçük and Dural, 2022, Arslanhan, 2023). In addition, the transition to a low-carbon economy with the Circular Economy Action Plan envisages radical changes in countries' lifestyles as the basis for growth strategies and sustainable development goals in all sectors, especially in energy, agriculture and food security policies. At the beginning of this radical change is the reduction of CO_2 emission factors (EFs) in the energy sector, especially in electricity generation, which can be achieved through the increased use of renewable energy resources. Biomass energy is one of the most important renewable energy resources to achieve this increase, as it is constantly available and contributes to waste management. The utilization of biomass for energy production plays a significant role in diminishing dependence on fossil fuels and reducing GHG emissions. It facilitates the reintegration of waste into the economy, mitigates global warming and environmental pollution, assists in waste management, and fosters employment opportunities for local communities. Consequently, it contributes significantly to regional development. In recent years, waste from the agriculture and livestock sector has been extensively investigated, especially for its potential to mitigate methane (CH_4) emissions, which is one of the significant GHGs causing climate change (Arslanhan, 2023; Ersoy and Uğurlu, 2020; Kaykıoğlu and Cantekin, 2023; Görmüş, 2018; Köse and Görmüş, 2018; Köse 2017; Özer and Bayar, 2018; Aktaş et. al, 2015). Türkiye possesses substantial potential in terms of biomass resources depending on agriculture and livestock that can be harnessed and utilized as a significant energy source. Biomass energy needs to be utilized near its point of origin, resulting in reduced environmental impacts and costs associated with transportation. Therefore, regional utilization is crucial.

In this study, electricity production based on the bio-methane derived from livestock manure and agricultural residues through anaerobic digestion (AD) technology, along with the corresponding CO_{2e} emission reduction for Kırklareli province, located in the Marmara Region of Türkiye, has been calculated. The aim of this study is to furnish policymakers and relevant stakeholders with comprehensive information regarding the diversification of the energy mix. It emphasizes the benefits of GHG mitigation, particularly focusing on the generation of renewable energy derived from livestock and agricultural wastes in Kırklareli. This study examines also CH_4 emissions released by its livestock sector due to processes of enteric fermentation and manure management (MM). The novelty of this study lies in demonstrating the GHG emissions that will be avoided by obtaining energy from livestock manure and agricultural residues to prevent climate change and in highlighting the contribution of waste to energy production within the circular economy. Previous studies did not reveal the contribution to preventing climate change by calculating the GHG avoided due to supplying energy from bio-methane. This is important because it is the initial study on the mitigation of GHG emissions by using livestock manure and agricultural residues as a renewable energy source instead of fossil fuels, particularly lignite and hard coal, for Kırklareli encompassing all its districts. Additionally, specific CH_4 conversion rates for animal manure, derived from laboratory results, were employed.

Several studies have been conducted on bio-methane production from organic wastes as a renewable energy source both regionally and globally, aiming to reduce dependence on fossil fuels and mitigate GHG emissions. Karaca (2023) investigated the biogas potential of animal manure for Konya Province in Türkiye, resulting in a potential of 266.53 GWh for electricity generation. Altan et al. (2022) mentioned that the AD of livestock wastes could provide approximately 10% of the total electricity consumption for Türkiye in 2018. Şenol et al., (2021) presented Türkiye's bovine manure-based bio-methane potential with a valuation of the spatial distribution by year and province with forecasts extending to 2030. Melikoğlu and Menekşe (2020) forecasted Türkiye's cattle and sheep manure bio-methane potential (BMP) will be 2.14 billion m^3, with 57.9 million animal population and nearly 6600 GWh electricity generation by 2026. Ersoy and Uğurlu (2020) examined GHG emissions from Türkiye's livestock sector due to enteric fermentation and MM by province. Two scenarios were developed for total and realistic manure recovery rates varying by livestock category, with results indicating 8.41 billion m^3 and 4.18 billion m^3 biogas potential for Scenario 1 and Scenario 2 in 2015, respectively. Avcıoğlu et. al., (2019), determined the available annual energy potential of agricultural biomass residues in Türkiye as ranging from 159050 to 482864 TJ, with an average of 298955 TJ for arable agricultural field crops. Hossain et al., (2023) investigated the potential energy resources from livestock manure to evaluate the energy potential of Bangladesh from domestic animals including cows, chickens, sheep, and goats. A comparative analysis of four scenarios including AD, gasification, combustion and direct combustion to heat energy generation is exclusively examined with cogeneration. The gasification process with heat recovery options has the greatest energy estimation with 26564.64 TJ. The CO_2 reduction potentials of the scenarios were evaluated. Liu et al., (2023) evaluated the biogas potential of agricultural waste in Hubei Province, China. The biogas potential was estimated to be 4.67×10^9 m^3, which could result in a carbon emission reduction of 2.33×10^6 tCO_2. A substantial difference was observed between the estimated potential and actual biogas production, with an average discrepancy rate of 96.83%. Additionally, there was regional variation within Hubei, where only 0.5% of the areas with the lowest densities accounted for those with the highest densities. Kapoor et al., (2020) explored the valorization of agricultural waste for a biogas-based circular economy in India. The study evaluated the potential, utilization, and policy frameworks related to biogas production from agricultural waste. Products derived from AD, including high-value outputs like bio-methane, digestate, and by-products such as bio-CO_2, were identified as key contributors to supporting the transition towards a bio-circular economy. Khalil et. al., (2019) investigated the potential of biogas production from animal waste in Indonesia as a waste-to-energy technology through AD. Animal waste, including manure, blood, and rumen contents, was found to have a biogas potential of 9597.4 Mm^3 yea^{-1}r, which could generate over 1.7×10^{10} kWh of electricity annually. Aktaş et al., (2017) investigated the energy potential of rice straw as 100% straw pellet and pellet mixtured with 15% coal powder with a laboratory scale gasifier. Çoban (2023) determined the payback period of a 3 MW electricity production capacity of a biogas plant as 4.24 years by the fertilizer sales obtained from the plant.

Some of the studies in the literature regarding GHG emissions from enteric fermentation and MM in Türkiye are also evaluated in this section. Karaca (2023) studied the energy potential of animal manure (dairy cattle, broilers, and laying hens) in the Konya province, Türkiye. Methane EFs were calculated using the Tier 2 methodology as 67.65 kg CH_4 head^{-1} year^{-1} for dairy cattle, 0.013 kg CH_4 head^{-1} year^{-1} for broilers, and 0.0286 kg CH_4 head^{-1}year $^{-1}$for laying hens. The CH_4 EF for MM from dairy cattle was found to be 67.65 kg CH_4 head^{-1}-year^{-1}, which is very high compared to enteric fermentation EFs. For broilers and laying hens, the results were within the range of values given by IPCC (2006) for developing countries. Kumaş and Akyüz (2023) calculated CH_4 emissions for the period 2016-2020 in the Lake District of Türkiye from enteric fermentation and MM using the IPCC Tier 1 approach. For enteric fermentation, they employed Eastern European methane EFs for cattle (99 kg CH_4 head^{-1} year^{-1} for dairy cattle and 58 kg CH_4 head^{-1} year^{-1} for other cattle) and developed country values for sheep (8 kg CH_4 head^{-1} year^{-1}) and goats (5 kg CH_4 head^{-1} year^{-1}). For MM, they used temperature-based Middle Eastern values for cattle and buffalo, while developing country values were applied for sheep, goats, horses, donkeys, mules, and poultry. The CH_4 emissions from MM were found to be 1.43% of those from enteric fermentation, with 1567000 tons of CH_4 emitted from enteric fermentation and 22450 tons from MM. Yaylı and Kılıç (2021) calculated CH_4 EFs for the enteric fermentation of cattle in Türkiye using the IPCC Tier 2 methodology, finding 47 kg CH_4/head-year for lactating cows and 52.5 kg CH_4 head^{-1} year^{-1}for bulls. The average EF in the cattle/buffalo category was calculated as 34.3 kg CH_4 head^{-1} year^{-1}. Compared to the IPCC (2006) Tier 1 values, which range from 68-47 kg CH_4/head-year for dairy and other cattle in Asia and 46-31 kg CH_4 head^{-1} year^{-1} for dairy cattle and other cattle in the Middle East, the values in the study were similar to those in Asian and the Middle East countries and lower than those in European countries. Kara et al., (2019) estimated GHG emissions from the enteric fermentation of animal manure in Konya Province, Türkiye, using IPCC Tier 1 EFs. They applied Asian values for cattle and developed country values for sheep and goats. The total CH_4 emissions from enteric fermentation in 2017 were determined to be 1110.14 Gg, which included emissions from cattle, buffalo, sheep, goats, camels, horses, mules, and donkeys. Öztürk and Ünal (2011) calculated the CH_4 EF from MM for the Tire-İzmir Region of Türkiye using the IPCC Tier 2 methodology. They identified solid and pit storage, daily spread, and paddock as the main manure storage systems in the region. They assumed an Asian Tier 1 EF for CH_4 from MM as 16 kg CH_4 head^{-1} year^{-1}, whereas their study obtained a value of 2.05 kg CH_4 head^{-1} year^{-1}.

2. Materials and Methods

In this study, the electrical energy that can be produced based on the bio-methane potential in Kırklareli has been calculated, using up-to-date data from the Turkish Statistical Institute (TurkStat) for the year 2023, considering livestock manure and agricultural residue. The bio-methane generation capacity through AD of manure and agricultural residue at the district level is examined. AD is one of the most effective GHG mitigation options for MM. The direct CH_4 emissions from livestock via enteric fermentation and MM are also examined. Kırklareli is located in the Marmara Region of Türkiye on the European Continent, between 41°44′–42°00′ Northern Latitudes and 26°53′–41°44′ Eastern Longitudes, with a land area of 6555 km^2. It shares a border with Bulgaria to the north, and is bordered by the Black Sea along its eastern coastline, Edirne to the west, and Tekirdağ to the south (*Figure 1*). In Kırklareli, the share of the agricultural sector in the city's 2023 Gross Domestic Product (GDP) was 11%, amounting to approximately 536 million USD (Anonymous, 2025).

Figure 1. Kırklareli Province map

2.1 Animal production in Kırklareli

In this study, manure from cattle, small ruminants, and poultry were considered for bio-methane production. The data for the cattle category includes dairy cattle (purebred, crossbred, and domestic) and buffalo. For the small ruminant category, merino sheep, domestic sheep, and Angora goats were included. The poultry category consists of turkey, goose, duck, egg-laying chicken, and broiler (meat) chicken. Since manure generation varies with the age of the animals, age groups for cattle and small ruminants were also taken into account. *Table 1* presents the distribution of the total number of animals in Kırklareli by district (Anonymous, 2024b).

The districts of Central, Lüleburgaz, and Pınarhisar represent the top three in terms of animal population, collectively accounting for approximately 80% of the total animal population in Kırklareli. Conversely, the Pehlivanköy district exhibits the lowest level of animal population. Among all categories, poultry represents the highest population.

Table 1. Animal population for Kırklareli by the district in 2023

District	Cattle		Small Ruminant		Poultry	Total
	Young	Adult	Young	Adult		
Central	13006	32304	477	137521	327805	**511113**
Lüleburgaz	17383	34986	841	50112	201919	**305241**
Pınarhisar	2050	5229	881	55114	64821	**128095**
Babaeski	6245	18957	695	38068	54244	**118209**
Kofçaz	1082	3131	631	32763	15043	**52650**
Vize	2139	8780	790	30452	9323	**51484**
Demirköy	1108	3105	1425	11490	3943	**21071**
Pehlivanköy	687	1832	0	6518	6915	**15952**
Total	**43700**	**108324**	**5740**	**362038**	**684013**	**1203815**

2.2 Agricultural production in Kırklareli

Agricultural crop statistics were the main data source for calculating the agricultural residue biomass potential of Kırklareli. The annual production by cereal type per district is presented in *Table 2* (Anonymous, 2024c). The districts of Lüleburgaz, Central, and Babaeski stand out for their significant agricultural production, collectively constituting 78% of the total production in Kırklareli. Conversely, the Demirköy district has the smallest area dedicated to plant production. Wheat and sunflower cultivation comprise the majority of crops in the city.

Table 2. Agricultural production by cereal types per district, ton year^{-1}

Crops	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Total
Lüleburgaz	144494	8733	12	152	878	1219	61282	**216770**
Central	70571	5608	608	1906	29157	0	57087	**164937**
Babaeski	113356	5076	138	131	4365	7455	33854	**164375**
Vize	44359	1736	0	251	126	0	15478	**61950**
Pınarhisar	32037	1656	140	286	266	0	13754	**48139**
Pehlivanköy	15844	392	0	133	192	5873	4991	**27425**
Kofçaz	10713	902	21	2556	0	0	3862	**18054**
Demirköy	156	88	0	89	0	0	0	**333**
Total	**431530**	**24191**	**919**	**5504**	**34984**	**14547**	**190308**	**701983**

2.3 Direct CH_4 emissions from livestock

2.3.1. Enteric fermentation

CH_4 emissions from livestock refer to those produced through enteric fermentation and manure excretion. Methane is emitted directly by livestock as a by-product of digestion via enteric fermentation. According to Türkiye's total CH_4 emissions for 2021, agriculture accounts for the largest share at 61.43%, with 54.6% resulting from enteric fermentation and 6.23% from MM. Enteric fermentation constitutes approximately 89% of the emissions within the agriculture sector, while MM accounts for 10% (Anonymous, 2024d). Based on the IPCC methodology (IPCC, 2006), CH_4 emissions from enteric fermentation can be estimated using the EFs depending on the animal type and region, as outlined in the Tier 1 approach. Considering the values used in similar studies for Türkiye and the country's geographical location, the EFs for three regions, Eastern Europe, Asia, and the Middle East are applied (*Table 3*). The EFs are given separately for dairy and cattle for the Tier 1 approach. Since cattle population data is available only disaggregated by age, the average values of the separately calculated emissions were utilized.

Table 3. Tier 1 approach enteric fermentation EF, kg CH_4 head^{-1} year^{-1} (IPCC, 2006)

	Eastern Europe	Asia	Middle East
Dairy Cattle	99	68	46
Other Cattle	58	47	31
Small ruminants young and adult (45-65 kg)*	5	5	5

*: developing countries

2.3.2. Manure management (MM)

CH_4 emissions are released into the atmosphere under the anaerobic decomposition of manure during handling, storage, and treatment processes. These emissions are generally much less than those resulting from enteric fermentation. When manure is stored openly or deposited onto pastures, it decomposes under aerobic conditions, resulting in reduced CH_4 production. Consequently, their energy content cannot be evaluated. This leads to both the loss of energy sources and improper waste disposal, which have detrimental effects on the environment. Furthermore, there is a lack of utilization of manure as fertilizer. In Türkiye, animal manure is stored and disposed of using varying methods in different regions and at different rates. These methods include open storage, liquid or solid management systems including lagoons, ponds, pits, pastures, and daily spread. Manure is typically stored in a solid bulk form outside of the barn, in paddocks, and the in pits of dairy farms (Süslü and Seyfi, 2016; Öztürk, 2009; Kayar, 2011; Erkan, 2005).

Tier 1 Approach

CH_4 EFs are classified according to the animal type, the region, and the annual average temperature of the region in the Tier 1 methodology outlined by the IPCC (2006). EFs for cattle are determined by geographical regions, whereas those for small ruminants and poultry are categorized by the classification of developed and developing countries. Since Türkiye is situated in Eurasia, and positioned in Asia, between Eastern Europe and the Middle East, it exhibits similar cattle MM characteristics to these regions. Therefore, the CH_4 emissions resulting from MM were calculated according to these 3 regions, whereas developing country values for small ruminants and poultry were employed. Since the average yearly temperature for Kırklareli is 13.3˚C as obtained from the Turkish Meteorology General Directorate (Anonymous, 2024e), the EF values were taken accordingly (*Table 4*, IPCC, 2006). Given that the cattle population is disaggregated by age in the available dataset, the averages of separately calculated annual CH_4 emission values for dairy and other cattle were used.

Table 4. CH_4 EFs for MM (Tier 1), kg CH_4 head^{-1} year^{-1}

	Eastern Europe	Asia	Middle East
Dairy cow (13˚C)	14	11	2
Other cattle (13˚C)	7	1	1
Small ruminants*		0.1	
Poultry*		0.01	

*: developing countries for <15˚C

Eastern Europe: Solid-based systems are used for the majority of manure. About one-third of livestock manure is managed in liquid-based systems. Asia: About half of the cattle manure is used for fuel with the remainder managed in dry systems.Middle East: Over two-thirds of cattle manure is deposited on pastures and ranges (IPCC, 2006).

Tier 2 Approach

Since site-specific data, such as livestock population characterization, volatile solid matter (VSM) ratios, and methane yields, are obtainable for CH_4 emission estimation from livestock manure in Kırklareli, the IPCC (2006) Tier 2 approach is applied. Methane conversion factor (MCF) and MM systems (MS) usage data were taken from the IPCC Guidelines (2006) for the Eastern Europe, Asia, and Middle East Regions due to the similar values for the related parameters given in studies in the literature (Peypazar and Kılıç, 2021, Süslü and Seyfi, 2016; Öztürk, 2009). MM methane EFs for cattle were calculated by Eq. (1) as given in the IPCC Guideline (2006). Due to the cattle population data being disaggregated by age in the available dataset, the averages of the separately calculated sum of MCFxMS values for dairy and other cattle by region were utilized, while values for small ruminants and poultry from developing countries were employed.

$$EF_i = (VS_i \; x \; 365) x \; [B_{o(i)} \; x \; 0.67 \sum_{(s,k)} \frac{MCF_{s,k}}{100} \; x \; Ms_{(i,s,k)}] \quad \text{(Eq.1)}$$

EF_i: annual methane EF for livestock category i, kg CH_4 animal^{-1} year^{-1}; VS_i: daily volatile solid excreted for livestock category i, kg dry matter animal^{-1} day^{-1}; 365: annual calculation value, days year^{-1}; 0.67: conversion factor of m^3 CH_4 to kilograms CH_4, kg m^{-3}; B_o: CH_4 generating capacity by livestock category i, m$^3CH_4$ kg^{-1} VS; MCF: CH_4 conversion factors for each MM system S by climate region k, %; $Ms_{i,s,k}$: fraction of livestock category i's manure handled using MM system S in climate region k, dimensionless.

2.4 Calculation of bio-methane potential from animal manure by AD

The AD process involves the biological oxidation of organic substrates by specific microorganisms under anaerobic conditions. Organic matter is converted into stable end products while producing biogas, which typically consists of 55-70% CH_4 and 25-45% CO_2. This biogas has significant potential for electricity and heat generation. The main factors affecting bio-methane generation from animal manure are the amount of manure produced, which depends on the number of animals in each species and the waste production rate per animal, along with availability rates. Moreover, the quality and quantity of livestock manure vary depending on the type of animal, type of feed, size of the animal body, type of breeding, ratio of total and volatile solids, and seasonal keeping time. The annual manure generation amount varies depending on the animal species, categorized by the age of cattle as adult (older than 12 months) and young (younger than 12 months), small ruminants adult (older than 6 months) and young (younger than 6 months). In order to determine the amount of livestock manure, the ages of cattle and sheep were taken into consideration. The availability rates of manure generated by cattle, sheep, and poultry as well as CH_4 yields based on solid matter (SM) and VSM ratios were used to determine the amount of bio-methane. The daily amount of manure produced varies between 8-10% of the live weight, depending on the age of the cattle, the content of the ration fed, the way of raising it and the productivity of the cattle. The amount of manure produced for 70-630 kg cattle is 6-51 kg day^{-1} (Anonymous, 2024f; Anonymous, 2024g). Daily manure production for cattle is accepted as: 15 kg head^{-1} assuming a weight of approximately 188 kg for young; 35 kg head^{-1}, assuming a weight of approximately 438 kg for an adult (Anonymous, 2024h). Sheep produce 4-5% of their average live weight per kg of wet manure per day, depending on the production period. Goats produce manure up to 5% of their body weight daily. Daily manure production for small ruminants is accepted as: 1.5 kg head^{-1} assuming a weight of 30 kg for young; 2.5 kg head^{-1} assuming a weight of 50 kg for an adult (Anonymous, 2024i; Anonymous, 2024j; Anonymous, 2024k). Based on the manure values received from the producers as 0.175 kg egg-laying chicken^{-1}, 0.035 kg broiler-chicken^{-1} day^{-1} in the study of Baban et. al., (2001) an average daily value of 0.1 kg chicken^{-1}day^{-1} was taken in this study for poultry manure generation. The manure generation values taken as the basis for the study are compatible with those used in similar literature studies (*Table 5*).

In the study conducted by Aktaş et al., (2015) for Tekirdağ, the availability rates (AR) of animal waste, SM (solid matter) and VSM ratios, and CH_4 yields per unit VSM were obtained as a result of analysis in an accredited laboratory. Due to the similarity of animal waste generated in Kırklareli to Tekirdağ province, the same values were taken in this study for methane potential calculations from livestock manure. The values used in the calculations are given in *Table 6*. Assumptions regarding the rate of collectable wet waste are taken as 41% for small ruminants, 41% for cattle, and 99% for poultry, as the general average of 3 months of pasture months, which are the days spent outside, and 9 months of other months, which are the days spent indoors (Aktaş et al., 2015; DBFZ, 2011). The bio-methane potential that can be generated from livestock manure (BMPl) for all districts was calculated with BMPl, m$^3CH_4$ year^{-1} Eq. (2).

$$BMPl = \sum_{(i,j)} P_{ij} x M_i x AR_i x SM_i x VSM_i x Yl_i \quad \text{(Eq. 2)}$$

i: livestock category; j: district; P: population, head; M: unit manure generation, ton year^{-1}; AR: availability rate, %; SM: solid matter, %; VSM: volatile solid matter, %; Yl: livestock manure CH_4 yield, m^3 CH_4 ton^{-1} VSM

Table 5. Unit manure generation values from the literature, kg head^{-1} day^{-1}

Cattle	Small ruminant	Poultry	Reference
14-39	-	0.155	Tunçez ve Soylu, 2022
22.5	1.6	0.045	Abdeshahian et al., 2016
10-20	2	0.080-0.10	Avcıoğlu ve Türker, 2012
14.5	-	-	Atelge, 2021
37.5	2	0.137	DBFZ, 2011; Özer, 2017
43	2.4	0.180	Köse, 2017

Table 6: The parameters used for bio-methane calculations based on animal species

Animal Type	Unit waste generation, ton animal^{-1} year^{-1}	Availability rate, AR, %*	Solid matter (SM), %*	Volatile solid matter (VSM), %*	Yl, CH_4 yield, m^3CH_4 ton^{-1} VSM*
Cattle	5.48/12.78 (young/adult)	41	14	62	316
Small ruminants	0.55/0.91 (young/adult)	41	36	81	324
Poultry	0.1	99	25	64	436

*: Aktaş et al., 2015

The amount of electrical energy that can be produced from the calculated bio-methane amount was calculated by using Eq. (3) (DBFZ 2011).

$$\text{Epl} = \text{BMPl x EEM x } \eta \qquad \text{(Eq. 3)}$$

Epl: livestock CH_4-based net electricity generation potential in kWh year^{-1}; EEM: energy equivalent of CH_4, 9.97 kWh m$^{-3}CH_4$; η: cogeneration electricity production efficiency, 40%, (DBFZ 2011).

2.5 Calculation of bio-methane potential from agricultural residue by AD

The main factors affecting bio-methane generation from agricultural residue are the agricultural production for each crop type, the residue-to-product ratio, and the availability rates. To calculate the methane potential of agricultural residue, the methane potential was determined based on the amount of waste produced from the most commonly planted agricultural products in Kırklareli, which are wheat, barley, rye, oats, maize, rice and sunflower. The data in *Table 7* was used to calculate the methane potential of these products (BMPa) using Eq. (4), and the net electrical energy that can be obtained with the cogeneration system was calculated using Eq. (5). Similarly to the bio-methane generation from animal manure, the availability of residue, VSM amounts and their corresponding methane yields were taken into account in assessing the bio-methane potential of agricultural residues. The residue-to-product ratio and availability data for the crops were taken from Başçetinçelik et. al., (2006), and the values are within the range of the values given in FAO (2016). VSM ratios and methane yields were taken from DBFZ (2011), and sunflower values from Zhurka et. al., (2020). The values for wheat, barley, rice straw, and maize stalks are within the range of the results presented by the laboratory analysis study of Menardo et. al., (2012). The methane yield values for oat are within the range of the results presented by Murphy et. al., (2011).

Table 7: The parameters used in bio-methane calculations based on plant species

Product type	Actual residue/product ratio	Availability rate (AR, %)	VSM %	Ya, CH_4 yield (m^3 CH_4 ton^{-1} VSM)
Wheat	1.04	15	79.03	295.2
Barley	1.08	15	76.13	351.9
Rye	1.41	15	80.6	273.6
Oat	1.00	15	76.13	290.5
Maize	1.5	60	61.9	250.9
Rice	1.5	70	76.13	260.5
Sunflower	2.7	60	80.6	338*

*: Zhurka et. al., 2020.

$$BMPa = \sum_{(x,j)} Pr_{xj} \; x \; (\tfrac{R}{P})_x \; x \; AR_x \, x \; VSM_x \, x \; Ya_x \qquad \text{(Eq.4)}$$

BMPa, agricultural residue bio-methane potential, m^3CH_4 $year^{-1}$; x: cereal category; Pr: product value, ton/year; R/P: residue-to-product ratio; AR: availability rate, %; VSM: volatile solid matter (%); Ya: agricultural residue CH_4 yield, m^3 CH_4 ton^{-1} VSM;

$$Epa = Mpa \times EEM \times \eta \quad \text{(Eq.5)}$$

Epa = agricultural residue methane-based net electricity generation potential in kWh $year^{-1}$

3. Results and Discussion

3.1 CH_4 emissions from enteric fermentation and MM

The CH_4 emissions that occurred from enteric fermentation are calculated via the Tier 1 approach and given in *Table 8* for three regions Eastern Europe, Asia and the Middle East. The CO_2 equivalent (CO_{2eq}) of CH_4 emission was calculated by multiplying 28, which is the Global Warming Potential (GWP100) of CH_4 over a 100-year time

Table 8: CH_4 emissions from enteric fermentation, kg CH_4 $year^{-1}$

	Animal numbers, head	Eastern Europe		Asia		Middle East	
			Average		**Average**		**Average**
Dairy Cattle	152024	15050376	11933884	10337632	8741380	6993104	5852924
Other Cattle		8817392		7145128		4712744	
Small ruminants young and adult	367778	1838890		1838890		1838890	
Total emission, kg CH4 $year^{-1}$		**13772774**		**10580270**		**7691814**	
ton CO_{2eq} $year^{-1}$		**385638**		**296248**		**215371**	

Table 9: CH_4 Tier 2 EFs for MM kg CH_4 $head^{-1}year^{-1}$

	Eastern Europe	Asia	Middle East
Cattle young	2.35	2.78	1.09
Cattle adult	5.49	6.49	2.54
Small ruminants young and adult **	0.10	0.10	0.10
Poultry**	0.01	0.01	0.01

**: developing countries for 13-14˚C

Table 10: CH_4 emissions from MM, kg CH_4 $year^{-1}$

	Tier 1			Tier 2		
	Eastern Europe	Asia	Middle East	Eastern Europe	Asia	Middle East
Dairy Cows	2128336	1672264	304048	-	-	-
Other cattle	1064168	152024	152024	-	-	-
Average*	1596252	912144	228036	-	-	-
Cattle Young	-	-	-	102756	121603	47628
Cattle adult	-	-	-	594328	703340	275476
Small ruminants young**	36778	36778	36778	574	574	574
Small ruminants adult**				36204	36204	36204
Poultry**	6840	6840	6840	6840	6840	6840
Total	**1639870**	**955762**	**271654**	**740701**	**868561**	**366722**
ton CO_{2eq}	**45916**	**26761**	**7606**	**20740**	**24320**	**10268**

*: average values of dairy and other cattle-originated CH_4 emissions.
**: developing countries for 13-14˚C

horizon (Anonymous, 2024l). Enteric fermentation-based CO_2 emissions are determined as 385638; 296248 and 215371 tons CO_{2eq} $year^{-1}$ for Eastern Europe, Asia and the Middle East, respectively which indicates Middle East value is the least. The methane EFs for MM from cattle, as calculated using Eq. (1), are provided in *Table 9*. The

CH_4 emissions from MM were calculated using the Tier 1 and Tier 2 approaches as presented in *Table 10.* Although the EFs for MM from the Tier 1 approach and the values calculated using the Tier 2 approach for various regions span a wide range (*Table 4* and *Table 9*), the EFs calculated using the Tier 2 approach for the Middle East are similar to those provided by the Tier 1 approach.

3.2 Methane and the electrical energy potential of animal manure

Based on the calculation principles outlined in the Methodology section, the available dry matter, corresponding methane, and net electricity potential by animal type for each district are calculated as specified by Equations 2 and 3 (*Table 11*). The distribution of energy potential across the districts is illustrated in *Figure 2*. *Figure 2* examines the distribution of animal manure-based energy potential in Kırklareli on a district basis. The Central district has the highest potential with 44422762 kWh $year^{-1}$ of net electrical energy, accounting for 33.86%, followed by the Lüleburgaz district with 33477984 kWh $year^{-1}$ representing 25.52%. The electrical energy potential of these two districts from animal waste constitutes 59.38%, more than half of the total potential of the province. Pehlivanköy has the lowest with a 1,68% share. In 2023, Kırklareli province had a total of 152024 cattle, 367778 sheep, and 684013 poultry. Cattle make up the largest share at 56%, followed by small ruminants at 39%, while poultry hold the smallest share at 5% in the CH_4 potential. The total CH_4 potential from animal manure is calculated to be 32895871 m^3 $year^{-1}$, while the electrical energy corresponding to this potential is calculated to be 131188735 kWh $year^{-1}$.

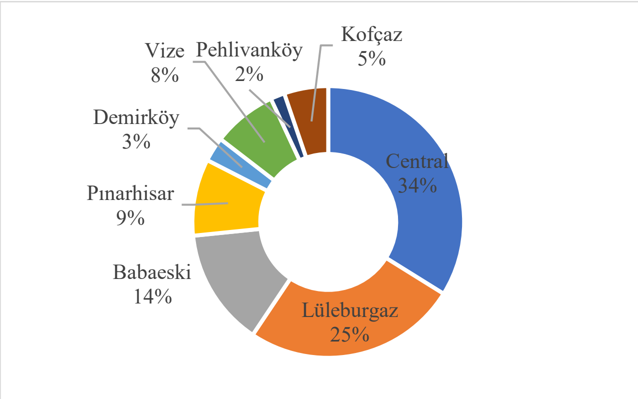

Figure 2. Distribution of animal manure-based energy potential by districts

Table 11. Kırklareli district-based animal methane and energy potential

Districts	Number of Animals				Available dry matter	CH_4 Potential	Net Electrical Energy Potential
	Cattle	**Small ruminants**	**Poultry**	**Total animals**	**ton $year^{-1}$**	**m^3 $year^{-1}$**	**kWh $year^{-1}$**
Central	45310	137998	327805	511113	34150	11139108	44422762
Lüleburgaz	52369	50953	201919	305241	25982	8394680	33477984
Babaeski	25202	38763	54244	118209	14347	4605027	18364847
Pınarhisar	7279	55995	64821	128095	9222	3007629	11994424
Vize	10919	31242	9323	51484	7836	2509715	10008742
Kofçaz	4213	33394	15043	52650	5337	1725803	6882501
Demirköy	4213	12915	3943	21071	2997	960596	3830856
Pehlivanköy	2519	6518	6915	15952	1718	553315	2206620
Total	**152024**	**367778**	**684013**	**1203815**	**101590**	**32895871**	**131188735**

3.3 Methane and the electrical energy potential of agricultural residues

Using the production data by cereal types given in *Table 2* and the values provided in *Table 7*, the CH_4 and electrical energy potential that can be generated from available agricultural residues were calculated as specified by Equations 4 and 5 Annual residue are calculated according to the given methodology and the results are given with *Table 12*, *Table 13* and *Table 14*. *Table 14* gives the net electrical energy potential that can be generated from agricultural residues on a district basis. In Kırklareli province, a CH_4 potential of 109026520 m^3 year^{-1} was calculated from agricultural residues consisting of a total of 1072149 tons year^{-1} residue for 2023. The electrical energy value corresponding to this potential is calculated as 434797762 kWh year^{-1}. Sunflower-originated CH_4 potential ranks first with 84033709 tons year^{-1} (77%), while wheat follows with 15768806 tons year^{-1} (14.5%). When the districts are examined in terms of bio-methane energy potential, Lüleburgaz district has the highest energy potential, with 132006087 kWh year-1 accounting for 30.36%. It is followed by the Central district with, 128510689 kWh year^{-1} representing 29.56%. The energy potential of these two districts from agricultural waste constitutes approximately 60%, more than half of the total potential of the province, depending on total production and corresponding residue. Demirköy has the smallest share, with 0.01% (*Figure 3*).

Table 12. Annual agricultural residues by district, ton year^{-1}

	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Total
Central	73687	6036	860	1897	44027	0	154216	**280723**
Lüleburgaz	150875	9400	17	151	1326	1829	165549	**329146**
Babaeski	118362	5463	195	130	6591	11183	91454	**233378**
Pınarhisar	33452	1782	198	285	402	0	37155	**73274**
Demirköy	163	95	0	89	0	0	0	**346**
Vize	46318	1868	0	250	190	0	41813	**90439**
Pehlivanköy	16544	422	0	132	290	8810	13483	**39680**
Kofçaz	11186	971	30	2543	0	0	10433	**25163**
Total	**450586**	**26037**	**1299**	**5477**	**52826**	**21821**	**514103**	**1072149**

Table 13. Annual agricultural residues methane potential by district, m^3 CH_4 year^{-1}

Districts	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Total CH_4, m^3
Central	2578779	242542	28428	62913	4103956	0	25207728	32224345
Lüleburgaz	5280045	377696	561	5017	123582	253821	27060101	33100824
Babaeski	4142212	219534	6452	4324	614390	1552287	14948805	21488004
Vize	1620950	75081	0	8285	17735	0	6834572	8556623
Pınarhisar	1170684	71621	6546	9440	37440	0	6073311	7369042
Pehlivanköy	578965	16954	0	4390	27025	1222881	2203860	4054076
Kofçaz	391470	39011	982	84368	0	0	1705331	2221162
Demirköy	5700	3806	0	2938	0	0	0	12444
Total	**15768806**	**1046245**	**42969**	**181674**	**4924127**	**3028990**	**84033709**	**109026520**

Table 14. Annual agricultural residues net electrical energy potential by district, kWh year^{-1}

Districts	Wheat	Barley	Rye	Oat	Maize	Rice	Sunflower	Total kWh
Lüleburgaz	21056820	1506253	2238	20008	492844	1012239	107915684	132006087
Central	10284170	967259	113370	250896	16366575	0	100528420	128510689
Babaeski	16519142	875500	25732	17244	2450187	6190520	59615834	85694160
Vize	6464348	299422	0	33040	70727	0	27256274	34123811
Pınarhisar	4668688	285624	26105	37648	149313	0	24220363	29387740
Pehlivanköy	2308914	67612	0	17507	107775	4876851	8788995	16167653
Kofçaz	1561184	155575	3916	336458	0	0	6800861	8857994
Demirköy	22734	15178	0	11715	0	0	0	49627
Total	**62886000**	**4172423**	**171360**	**724517**	**19637420**	**12079610**	**335126431**	**434797762**

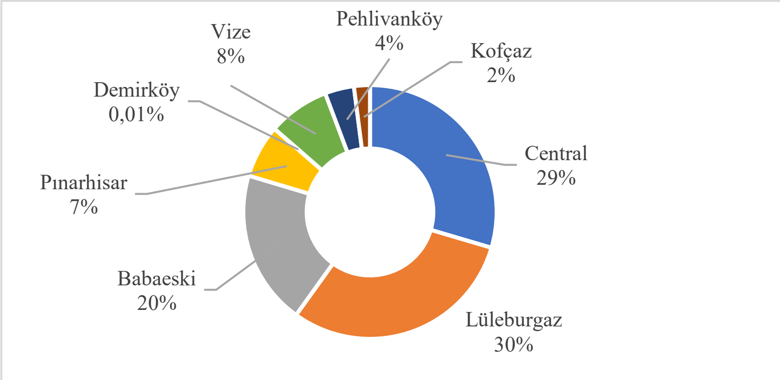

Figure 3. Agricultural residue-based energy potential distribution by district

3.4. Total energy potential of Kırklareli Province

The total CH_4 and energy potentials that can be generated from animal waste and agricultural residues of Kırklareli province for 2023 are presented in *Table 15.* The total methane potential of animal waste-and agricultural residues was calculated to be 141922392 m^3CH_4 $year^{-1}$, while the total net electrical energy potential was calculated to be 565986497 kWh $year^{-1}$. Upon examining the districts, it was revealed that the Central, Lüleburgaz, and Babaeski districts have the highest total electricity potential generated from animal manure and agricultural residues. 78.2% of Kırklareli's total methane potential for 2023 belongs to the Central, Lüleburgaz, and Babaeski districts. This high percentage suggests that investments should be concentrated near these districts. *Figure 4* illustrates the total methane potential from animal waste and agricultural residues by the districts. In all districts except the Demirköy, the methane potential generated from agricultural residues is higher than that from animal manure.

Table 15 The total CH_4 and electrical energy potentials of Kırklareli by the districts in 2023

	Total CH_4 Potential, m^3 $year^{-1}$	**Total electricity, kWh $year^{-1}$**
Central	43363453	172933451
Lüleburgaz	41495504	165484071
Babaeski	26093031	104059006
Vize	11066337	44132553
Pınarhisar	10376671	41382164
Pehlivanköy	4607391	18374274
Kofçaz	3946965	15740495
Demirköy	973040	3880483
Total	**141922392**	**565986497**

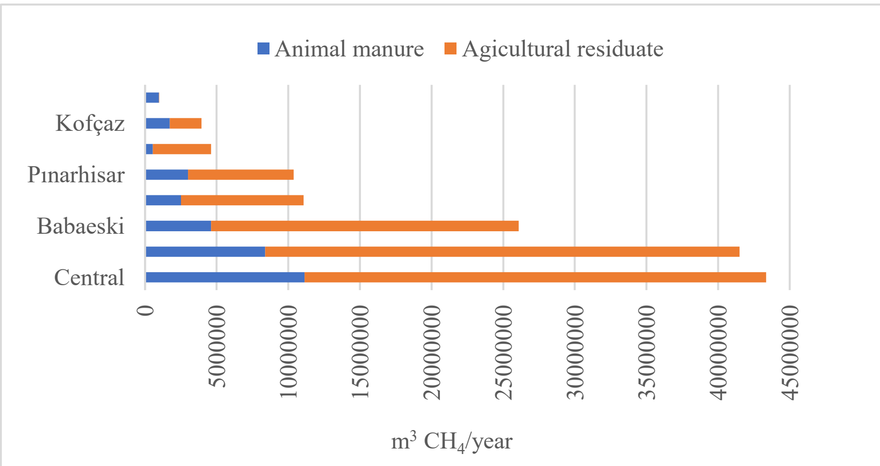

Figure 4. CH_4 potential distribution by districts

3.5. The calculation of CO_2 emission reduction obtained by AD biogas system

The CO_2 emissions resulting from the combustion of bio-methane generated through AD of animal manure and agricultural residue for energy production were calculated as 261492 tons CO_2 year^{-1} using Eq. (6). The calculations were based on the stoichiometric ratio of 2.75 kg CO_2 produced per kg of CH_4.

$$ECO_2 = MV * 0.67 * 2.75/1000 \quad \text{(Eq. 6)}$$

E_{CO2} : ton CO_2 year^{-1}, MV: methane volume, m^3 year^{-1}, 0.67: conversion factor of m^3 CH_4 to kilograms CH_4, kg m^{-3}; 2.75: stoichiometric ratio kg CO_2 formation per kg CH_4

The GHG-reduction effect of biogas generation depends on two factors; mitigation of emissions occurred from MM and reducing emissions by substitution of fossil fuels.

The most significant benefit of a biogas generation system is that it prevents uncontrolled methane emissions. The CO_{2eq} emissions from MM were calculated as outlined in the IPCC (2006) for both Tier 1 EFs and Tier 2 EFs given in *Table 9* for 3 regions. The electricity generation capacity of CH_4 will replace the existing fossil fuel-based electricity in the national grid hence, the equivalent emission avoidance from biogas-based electricity generation was estimated using EFs of 1.165 and 0.998 tCO_{2eq} MWh^{-1} for lignite and hard coal, respectively (Anonymous, 2024m). Accordingly, the CO_2 emission mitigation capacity is determined to be between 310969-443799 tons CO_{2eq} year^{-1} based on the IPCC (2006) Eastern Europe, Asia, and Middle East Tier 1 and Tier 2 values (*Table 16*). Since the evaluation of CO_2 emission reduction was the main goal of the study CH_4 emissions from enteric fermentation were not taken into account. Total CO_{2eq} emission reduction was determined according to the difference between the sum of the CO_{2eq} emissions released through MM and the CO_2 emissions resulting from the same electricity generation from lignite or hard coal between the CO_2 emissions resulting from the combustion of bio-methane (Eq. 7).

$$ERCO_2 = [(MMCO_{2eq} + EECO_{2\ (coal)}) - EECO_{2(BMT)}] \quad \text{(Eq.7)}$$

$ERCO_2$: CO_2 emission reduction, ton year^{-1}; $MMCO_2$: CO_2 emissions from MM; $EECO_{2(coal)}$: CO_2 emissions from electricity production through lignite or hard coal; $EECO_{2(BMT)}$: CO_2 emissions from electricity production through bio-methane

Table 16. The CO_{2eq} emissions, ton year^{-1}

		MM	EE$_{coal}$*		Total CO$_2$eq Emissions from MM + EE$_{coal}$		EE$_{BMT}$*	Reduction	
		CO$_2$eq	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**AD**	**Lignite**	**Hard Coal**
Tier 1	Eastern Europe	45916	659374	564855	**705291**	**610771**	261492	**443799**	**349279**
	Asia	26761			**686136**	**591616**		**424644**	**330124**
	Middle East	7606			**666981**	**572461**		**405489**	**310969**
Tier 2	Eastern Europe	20740			**669643**	**575123**		**408150**	**313631**
	Asia	24320			**683694**	**589174**		**422202**	**327682**
	Middle East	10268			**680114**	**585594**		**418622**	**324102**

*:EE: electricity emissions

4. Conclusions

According to the Türkiye National Energy Plan, the share of renewable energy in primary energy sources, which was 16.7% in 2020, is anticipated to rise to 23.7% by 2035 (ETKB, 2022). Biogas facilities, such as the one in Kırklareli, could significantly contribute to renewable energy production and support Türkiye in meeting its national climate change mitigation targets. Biogas systems support the circular economy and sustainable production via the provision of energy and organic fertilizer. By integrating agricultural and livestock production with energy generation across Türkiye, the country's entire biomass potential can be effectively harnessed as an energy source. While methane potentials fluctuate annually due to changes in livestock numbers and agricultural output, the effective use of these existing potentials can be maximized through a comprehensive plan that encompasses both agricultural and livestock production alongside energy production. Aligning agricultural and livestock production with energy generation through proper planning will promote the use of sustainable energy. By supporting the livestock and agriculture sectors with comprehensive planning, enhancing the potential of renewable energy sources, and facilitating the transition to a circular economy, Türkiye can achieve compliance with the Paris Agreement and the EU Green Deal to address the climate crisis. This approach will contribute to environmental protection, reduce greenhouse gas emissions, and support sustainable development in the country. By setting agricultural and livestock production goals that also consider their waste as an energy source, a continuous and stable supply of energy can be achieved, rather than relying on variable values that fluctuate each year. Consequently, biomass can evolve from a mere potential to a consistently utilized energy source.

Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

The author declares that there are no conflicts of interest with respect to the research, authorship, and/or publication of this article.

Authorship Contribution Statement

Concept: Özer, B.; Design: Özer, B.; Data Collection or Processing: Özer, B.; Statistical Analyses: Özer, B.; Literature Search: Özer, B.; Writing, Review and Editing: Özer, B.

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