


Investigating the Potential for Biogas Production from Animal Manure in Zonguldak Province

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Abstract

Global population growth and technological developments have led to an increase in energy demand and intensification of animal food production. Meeting the growing energy demand with fossil fuels raises environmental issues such as greenhouse gas emissions. Additionally, animal waste from intensive livestock farming activities aimed at meeting food demand is further exacerbating environmental problems. Biogas made from animal waste helps reduce pollution from these wastes and is also an important renewable energy source that helps meet energy needs. In this study, the biogas potential that can be produced from animal waste was calculated based on animal numbers obtained from the 2024 data of the Zonguldak Directorate of Provincial Agriculture and Forestry. The results indicate that the biogas production potential from animal waste in Zonguldak province is estimated at 22.69 million m³. This amount is equivalent to approximately 106.65 GWh of electrical energy, 26.78 million m³ of natural gas energy, and 113.46 × 10⁹ kcal of thermal energy. Based on these results, utilizing the existing biogas potential for electricity generation is expected to provide approximately 276.27 million TL in economic savings. Additionally, this initiative is anticipated to prevent the release of 46819.35 tons of CO₂-equivalent greenhouse gases into the environment.

Keywords

Biogas potential,
Renewable energy,
Animal waste,
Zonguldak

Zonguldak İlinde Hayvan Gübresinden Biyogaz Üretim Potansiyelinin Araştırılması

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Özet

Küresel ölçekte nüfus artışı ve teknolojik gelişmeler, enerji talebinde bir artışa ve hayvansal gıda üretiminin yoğunlaşmasına yol açmıştır. Artan enerji talebinin fosil yakıtlarla karşılanması, sera gazı emisyonları gibi çevresel sorunları gündeme getirmektedir. Bunun yanı sıra, gıda talebini karşılamak amacıyla yoğunlaşan hayvancılık faaliyetlerinden kaynaklanan hayvansal atıklar, çevresel sorunları daha da derinleştirmektedir. Hayvan atıklarından üretilen biyogaz, bu atıkların neden olduğu kirliliği azaltmaya yardımcı olur ve aynı zamanda enerji ihtiyaçlarının karşılanmasına yardımcı olan önemli bir yenilenebilir enerji kaynağıdır. Bu çalışmada, Zonguldak İl Tarım ve Orman Müdürlüğü'nün 2024 verilerinden elde edilen hayvan sayıları temel alınarak, hayvan atıklarından üretilebilecek biyogaz potansiyeli hesaplanmıştır. Sonuçlar; Zonguldak ilinde hayvansal atıklardan biyogaz üretim potansiyelinin 22.69 milyon m³ olduğu tahmin edilmektedir. Bu miktar yaklaşık 106.65 GWh elektrik enerjisine, 26.78 milyon m³ doğal gaz enerjisine ve 113.46 x 10⁹ kcal termal enerjiye eşdeğerdir. Bu sonuçlara dayanarak, mevcut biyogaz potansiyelinin elektrik üretiminde kullanılmasının ekonomiye yaklaşık 276.27 milyon TL tasarruf sağlaması beklenmektedir. Ayrıca, bu hamlenin 46819.35 ton CO₂ eşdeğeri sera gazının çevreye salınmasını engellemesi beklenmektedir.

Anahtar kelimeler

Biyogaz potansiyeli,
Yenilenebilir enerji,
Hayvansal atık,
Zonguldak

1. INTRODUCTION

Energy is obtained from nonrenewable fossil fuels, including coal, oil, and natural gas, as well as from renewable sources such as solar, wind, geothermal, hydropower, and biomass [1–3]. Fossil fuels have been the main source of energy in the world for a long time, but they are running out quickly [3]. Moreover, fossil fuel use results in air pollution via greenhouse gas emissions, global warming, and several environmental issues [3,4]. To find solutions to these issues, renewable energy sources, which are sources of energy that are naturally renewable and favorable to the environment, are becoming an increasingly essential option [2,3,5].

Biomass serves as a prominent renewable energy source, comprising biodegradable materials sourced from agricultural, forestry, livestock, municipal, and industrial waste. These materials can be transformed into electricity, heat, or fuels, including biogas, biodiesel, hydrogen, and bioethanol [1,2]. These properties allow biomass to encourage sustainable development by efficiently using resources in a circular carbon economy while also providing realistic answers to future energy needs [2,6].

Biogas has garnered heightened interest among renewable energy sources owing to its ecological advantages and economic viability [3]. Biogas is generated by the anaerobic digestion of biomass, wherein organic materials, including sewage sludge, animal manure, agricultural wastes, and municipal organic waste, are digested [5,7,8]. In this context, biogas that is created from trash serves as a feasible energy source and helps reduce the environmental repercussions that garbage has. This approach has economic advantages, including the supply of heat and power in both urban and rural regions. Moreover, the fermented manure, a by-product of biogas generation, offers benefits for agricultural use [6,9,10].

Animal manure is regarded as a useful organic waste for biogas generation. Its high buffering capacity and nutritional content, which stimulates bacterial growth, make it a popular substrate for anaerobic digestion [11]. Specifically, high-density populations of livestock, including cattle and poultry, result in the generation of substantial quantities of manure [12]. Conventionally, these wastes are used directly or post-composting for the enhancement of soil in agriculture [13]. Nevertheless, inadequate waste management may result in significant environmental and health issues. In this context, anaerobic digestion presents an efficient approach to mitigate adverse effects on air, soil, and water by transforming manure into sustainable biogas energy, yielding nutrient-dense manure, and diminishing smells and microbial pathogens [13,14].

Subsequent to the manufacturing process, biogas may be refined and used to satisfy diverse energy requirements. It typically comprises around 60% methane (CH_4) and 40% carbon dioxide (CO_2) [15]. It may be used directly as fuel for thermal and electrical generating, or it can be transformed into biomethane and introduced into the

natural gas supply grid [16–18]. It may be transformed into a hydrogen-rich gas mixture by steam reforming, making it a renewable hydrogen source for proton exchange membrane (PEM) fuel cells [15]. Worldwide, more than 90% of biogas is used for energy and heating, and around 9% is employed as biomethane in transportation or natural gas systems. Moreover, methane (CH_4) and hydrogen (H_2) in biogas may be directly transformed into power using fuel cell technology [16–18]. For example, biogas can be effectively used as fuel in solid oxide fuel cells (SOFC), which can achieve high electrical and overall system efficiency, high-quality heat recovery and flexible operating conditions [19].

Türkiye has strong potential for biogas production from its agricultural and livestock sectors. Converting increasing animal waste into biogas can produce clean energy, reduce pollution, and generate high-quality manures, offering environmental and economic benefits [20]. Recently, interest in biogas derived from animal waste has increased, and the biogas capacity of many provinces in our country has been investigated. Some studies in the literature, including the calculation of biogas potential from animal manure, are given below.

S. Işık and S. Yavuz [21] examined the biomass and biogas energy potential of Konya between 2011 and 2020 using Turkish Statistical Institute (TUIK) data. In 2020, 12.74% of Türkiye's biomass resources were produced in Konya, and the amount of dry biomass increased from 13.3 million tons in 2011 to 19.5 million tons in 2020. In terms of districts, the highest biomass energy potential was recorded in Cihanbeyli with 11649 MWh, and the lowest potential was recorded in Derebucaak with 47.7 MWh. The biogas production potential was determined as 98.5 million m^3 in 2011 and 165.6 million m^3 in 2020. S. Atılğan and A. Yılmaz [22] assessed the biogas potential that could be produced from animal manure in the province of Mardin. In the study, data from the Mardin Provincial Directorate of Agriculture and Forestry for 2019 was used to determine the presence of 128897 cattle, 937854 sheep and goats, and 1974809 poultry. Based on these data, it was calculated that approximately 56.78 million m^3 of biogas and 266.86 million kWh of electrical energy could be produced annually from 1163972.8 tons of animal manure. E. El [23] investigated the biogas potential from local animal manure wastes in and around Bitlis city center and calculated the equivalent amounts of thermal and electrical energy. Biogas production between 2019 and 2023 ranged between 20594 and 27486 million m^3 , while the corresponding thermal energy was determined as 102.97-137.43 $\times 10^9$ kcal/year and electrical energy as 96.79 and 129.19 GWh year⁻¹. H. Et Yapılcan and H. Bakırtaş [24] examined the biogas potential that can be obtained from ovine and poultry manure in Aksaray province. In the study, it was determined that 39670717 m^3 of biogas can be produced annually, and this amount is equivalent to 186452372 kWh of electrical energy; this amount can meet the energy needs of approximately 12% of Aksaray's population. İ. Şentürk [25] investigated the biogas potential from animal manure in Manisa province and its districts. The study determined that 153347039.2 m^3 of biogas can be produced annually,

which is equivalent to 720.73 GWh of electrical energy; this amount can meet the domestic electricity needs of approximately 29.7% of the provincial population and prevent 316401 tons of CO₂-equivalent greenhouse gas emissions each year. S. Tırınk [26] examined the biogas energy potential of wastes from animal enterprises in Iğdır province and its districts. According to 2020 data, the number of cattle, ovine, and poultry in the province is 157426, 1279203, and 265173, respectively. It was calculated that 43952304 m³ of biogas can be produced annually from animal manure, which is equivalent to 1032879 GJ of heat energy and 114716 MWh of electricity. It has been determined that approximately 78465 tons of CO₂ emission can be prevented annually by using it instead of fossil fuel. L. Gazigil et al. [27] analyzed the biogas potential that can be obtained from animal wastes in Van province. Using 2023 TUIK data, cattle, sheep, and poultry wastes were calculated, and biogas potential was determined by the Agro-Waste method. According to the results, cattle waste contributes 63.68%, sheep waste 36.11%, and poultry waste 0.22% to biogas production. The total biogas potential of Van province was calculated as 50004441.08 m³, which is equivalent to 59005240.47 m³ of natural gas, 73006483.97 kg of coal, and 235020873.05 kWh of electricity. S. Işık and S. Yavuz [28] calculated the annual biogas potential in Bingöl province between 2015 and 2020 using data on the number of cattle, ovine, goats, and poultry. According to the 2020 data, researchers determined that approximately 754 thousand tons of usable manure can be obtained from a total of 5694302 animals, including 865202 cattle and ovine, which is equivalent to 36.5 million m³ of biogas, 171.4 GWh of electricity, and 171449106 kcal of heat energy.

In this study, the biogas capacity that can be produced from animal wastes was theoretically calculated using the data from Zonguldak province and its districts in 2024. In addition, the electricity and heat energy production capacity that can be provided by using biogas obtained from animal waste sources is examined. The number of animals subject to the study was obtained from the Zonguldak Directorate of Provincial Agriculture and Forestry and the TUIK. The amount of animal manure used in the calculation of the amount of biogas was calculated using the type and number of animals.

2. MATERIAL AND METHOD

2.1. General Information about Zonguldak Province

Zonguldak Province is in the Western Black Sea Region, featuring a coastline along the Black Sea to the west and north. Spanning 3310 km², it constitutes almost six per thousand of Türkiye's land area. The province's territory, commencing at the Black Sea coastline, is delineated by the Black Sea to the north, Bartın to the northeast, Karabük to the east, Bolu to the south, and Düzce to the west. Zonguldak is administratively divided into the Central District, Alaplı, Çaycuma, Devrek, Gökçeşey, and the districts of Kdz. Ereğli, Kilimli, and Kozlu (Figure 1). Zonguldak features a predominantly harsh landscape, with 56% of its territory comprised of mountains, 31% of

plateaus, and 13% of plains. Forested regions constitute 56% of the province's territory, with 88% classed as dense forest and 12% as coppice forest [29].

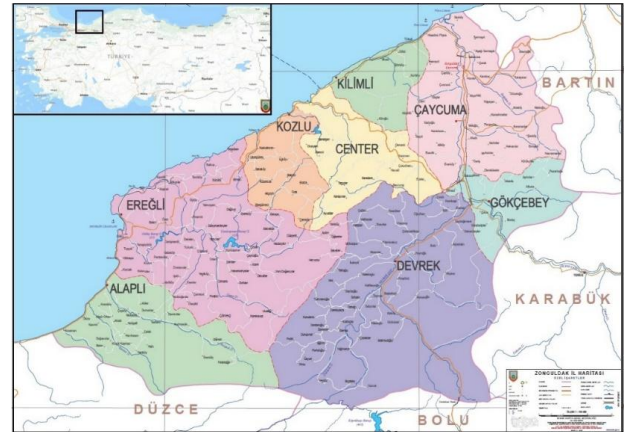


Figure 1. Zonguldak civil administration provincial map [30]

According to the 2024 Address-Based Population Registration System, the population of Zonguldak Province is 586802. Of this population, 373803 people (63.70%) live in urban areas, while 212999 people (36.30%) reside in towns and villages. Table 1 presents the 2024 population of Zonguldak Province and its districts, including the population of provincial/district centers, towns/villages, and the annual population growth rate [31].

Table 1. Population of Zonguldak Province and Its Districts in 2024: District/Provincial Center, Town/Village Population, and Annual Population Growth Rate [31]

Province and district	Population			Annual growth rate of population (%)
	Total	Province and district centers	Towns and villages	
Center	116325	99805	16520	-8.9
Alaplı	43168	20807	22361	-5.8
Çaycuma	90423	31890	58533	-16.9
Devrek	57328	26972	30356	-4.1
Ereğli	174468	121619	52849	-4.7
Gökçeşey	21268	8813	12455	-3.6
Kilimli	33002	19965	13037	-19.1
Kozlu	50820	43932	6888	-1.7

Ereğli has the largest total population at 174468 individuals, followed by the Central District with 116325 individuals and Çaycuma with 90423 individuals, according to the population statistics of Zonguldak Province and its districts presented in Table 1. Gökçeşey has the smallest population, totaling 21268 individuals. There are considerable disparities in urbanization levels throughout the districts. In Kozlu, of the total population of 50820, 43932 inhabit the district center, signifying a substantial urbanization rate. Conversely, in Çaycuma, the district center is home to 31890 inhabitants, while 58533 individuals reside in towns and villages, indicating a majority of rural housing. Similarly, in Alaplı and

Devrek, the village population is close to the urban population. Population growth rates are negative in all districts, with the highest rate of decrease in Kilimli district with 19.1%, followed by Çaycuma district with 16.9%. On the other hand, Kozlu district has the lowest population loss with a decrease rate of -1.7%. These findings reveal that the rural population is decreasing faster than the central population in Zonguldak and that demographic changes related to migration, fertility, or economic factors are being experienced.

2.2. Method

In the study, the amounts of manure per animal determined within the scope of the Agro-Waste project was used. Table 2 shows the commonly acceptable values for calculating biogas energy potential. Additionally, it was assumed that 65% of cattle manure, 13% of ovine manure, and 99% of poultry manure are usable for biogas production [32–34]. The calculations use the equations presented between Eq. 1-11 below.

Table 2. Acceptances for biogas energy potential [32–34]

Animal Species	Annual Manure (Tons years ⁻¹)	Biogas generated from 1 ton of manure (m ³)
Cattle	9.94	33 m ³
Ovine	0.82	58 m ³
Poultry	0.029	78 m ³

Annual amount of liquid manure generated by livestock;

$$M_c = n \times 9.94 \text{ (tons} \times \text{year}^{-1}) \quad (1)$$

$$M_o = n \times 0.82 \text{ (tons} \times \text{year}^{-1}) \quad (2)$$

$$M_p = n \times 0.029 \text{ (tons} \times \text{year}^{-1}) \quad (3)$$

$$M_t = M_c + M_o + M_p \text{ (tons} \times \text{year}^{-1}) \quad (4)$$

In the equations, "n" represents the number of animals. M_c : Amount of liquid manure obtained from bovine animals, M_o : Amount of liquid manure obtained from ovine animals, M_p : Amount of liquid manure obtained from poultry, M_t : It expresses the total amount of liquid manure.

Potential biogas energy (PBE);

$$PBE_c = M_c \times 0.65 \times 33 \text{ (m}^3 \times \text{year}^{-1}) \quad (5)$$

$$PBE_o = M_o \times 0.13 \times 58 \text{ (m}^3 \times \text{year}^{-1}) \quad (6)$$

$$PBE_p = M_p \times 0.99 \times 78 \text{ (m}^3 \times \text{year}^{-1}) \quad (7)$$

$$PBE_t = PBE_c + PBE_o + PBE_p \text{ (m}^3 \times \text{year}^{-1}) \quad (8)$$

In the equations given above, PBE_c : biogas energy obtained from cattle, PBE_o : biogas energy obtained from ovine, PBE_p : biogas energy obtained from poultry, and PBE_t : total potential biogas energy.

Total potential electrical energy (PEEt) per year [28,35,36]

$$PEE_t = PBE_t \times 4.70 \text{ (kWh} \times \text{m}^{-3}) \quad (9)$$

Total potential thermal energy (TPTe) per year is between values given below;

$$TPT_e = PBE_t \times 5000 \text{ (kcal} \times \text{m}^{-3}) \quad (10)$$

Total potential natural gas (TPNg) per year is between values given below;

$$TPN_e = PBE_t \times 1.18 \text{ (m}^3) \quad (11)$$

3. RESULTS

According to the 2024 data of the Zonguldak Provincial Directorate of Agriculture and Forestry, there are a total of 4596293 animals in the province, comprising 58275 cattle, 26530 ovine, and 4511488 poultry. The numbers of animals in the provincial center and districts in 2024 are presented in Table 3. The study classified cattle and buffalo as large ruminants, sheep and goats as ovine, and laying hens, turkeys, geese, ducks, and guinea fowl as poultry.

Table 3. Number of Animals in Zonguldak Province and its Districts in 2024 [37]

Districts/Species	Cattle	Ovine	Poultry
Alaplı	3056	559	195581
Çaycuma	22707	4487	913901
Devrek	10683	9288	663690
Ereğli	8464	5227	600797
Gökçebeş	2846	1091	1744936
Kilimli	567	464	991
Kozlu	5363	2623	23152
Center	4589	2791	368440
Total	58275	26530	4511488

When the 2024 data on livestock in the provincial center and districts are examined, poultry accounts for 98.15% of the total number of animals, while cattle animals account for 1.27% and ovine animals for 0.58% (Figure 2). This distribution demonstrates that poultry farming is the primary focus of livestock activities in Zonguldak.

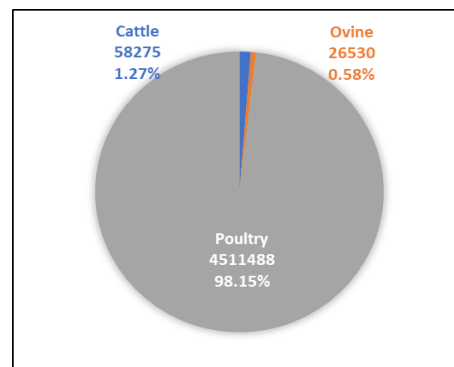
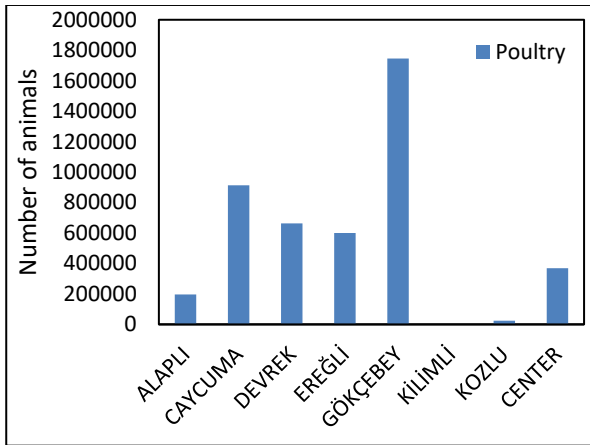


Figure 2. Animal distribution in the province

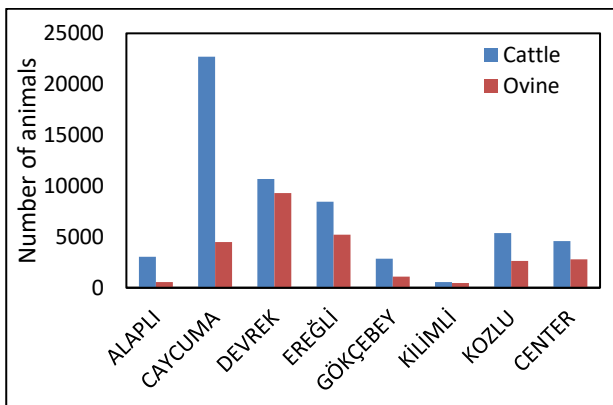
Table 4. Potential for manure from animals

Districts/ Species	Amount of manure obtained (ton year ⁻¹)			Amount of manure available (ton year ⁻¹)		
	Cattle	Ovine	Poultry	Cattle	Ovine	Poultry
Alaplı	30376.64	458.38	5671.85	19744.82	59.59	5615.13
Çaycuma	225707.58	3679.34	26503.13	146709.93	478.31	26238.10
Devrek	106189.02	7616.16	19247.01	69022.86	990.10	19054.54
Ereğli	84132.16	4286.14	17423.11	54685.90	557.20	17248.88
Gökçebeý	28289.24	894.62	50603.14	18388.01	116.30	50097.11
Kilimli	5635.98	380.48	28.74	3663.39	49.46	28.45
Kozlu	53308.22	2150.86	671.41	34650.34	279.61	664.69
Center	45614.66	2288.62	10684.76	29649.53	297.52	10577.91
Total	579253.50	21754.60	130833.15	376514.78	2828.10	129524.82
G. Total	731841.25			508867.7		

Poultry farming is dominant throughout the province. When analyzed on the basis of districts, Gökçebeý ranks first with 1744936 poultry (38.68%), followed by Çaycuma with 913901 (20.26%) and Devrek with 663690 (14.71%). Kilimli ranks last with 991 poultry (0.02%) (Figure 3).

**Figure 3.** Animal distribution in the province

In terms of cattle, Çaycuma leads with 22707 heads (38.97%), followed by Devrek with 10683 and Ereğli with 8464. For Ovines, Devrek ranks first with 9288 animals (35.01%), followed by Ereğli with 5227 and Çaycuma with 4487. Kilimli ranks last in both cattle and ovine livestock, with 567 and 464 animals, respectively (Figure 4).

**Figure 4.** Animal distribution in the province

As of 2024, the total and usable amounts of manure that can be obtained from cattle, ovine, and poultry in Zonguldak province are presented in Table 4. This data is critical in determining the biogas production potential and enables the evaluation of the capacity to convert animal waste into energy. As a result of the calculations made using Equation 4, it was determined that a total of 731841.25 tons of animal waste could be obtained throughout the province. The findings of the analysis revealed that manure generation is highest in the Çaycuma district and lowest in the Kilimli district. In addition, it was calculated that cattle and ovine wastes were generated mostly in the Çaycuma district and poultry wastes were generated mostly in the Gökçebeý district. The total amount of usable manure in the province was determined to be 508967.7 tons, with the highest quantity produced in Çaycuma and the lowest in Kilimli.

The annual biogas potential, calculated based on the amount of available waste, is presented in Table 5. Accordingly, it is observed that the total biogas production from cattle, ovine, and poultry in Zonguldak province and its districts amounts to 22691953.26 m³. The biogas production potential across the province varies by district. According to 2024 data, the highest biogas production potential was determined in the Çaycuma district, with 6915741.44 m³, while the lowest potential was observed in the Kilimli district, with 125979.82 m³. This indicates that both cattle and poultry farming activities are more intensive in Çaycuma compared to other districts, whereas livestock activities are limited in Kilimli. Biogas production from cattle constitutes the largest share in all districts, whereas biogas from ovines remains relatively low. Biogas production from poultry, on the other hand, is considerably high in certain districts, particularly in Gökçebeý, where it amounts to 3907574.78 m³, representing approximately 86% of the total biogas production. While the districts of Çaycuma, Devrek, and Ereğli are characterized by a predominance of cattle farming, Gökçebeý stands out in terms of biogas potential derived from poultry. The districts of Kozlu, Center, and Alaplı exhibit moderate biogas potential, whereas Kilimli represents the region with the lowest potential. The obtained data suggests that districts such as Çaycuma,

Devrek, and Gökçebeý can be considered priority areas for biogas investment.

Table 5. Amount of biogas produced by district (m³)

Districts/ Species	Amount of Biogas Produced (m ³)			
	Cattle	Ovine	Poultry	Total
Alaplı	651578.93	3456.19	437980.18	1093015.29
Çaycuma	4841427.59	27742.22	2046571.62	6915741.44
Devrek	2277754.48	57425.85	1486254.11	3821434.44
Ereğli	1804634.83	32317.50	1345412.79	3182365.11
Gökçebeý	606804.20	6745.43	3907574.78	4521124.41
Kilimli	120891.77	2868.82	2219.23	125979.82
Kozlu	1143461.32	16217.48	51846.13	1211524.93
Center	978434.46	17256.19	825077.17	1820767.82
			Grand total	22691953.26

Biogas production potential in Zonguldak province shows significant variation among districts. Analyses reveal that biogas generation is predominantly concentrated in the districts of Çaycuma, Gökçebeý, Devrek, and Ereğli. Çaycuma accounts for the highest share, with 30% of total production, which can be associated with the district's intensive livestock activities. Gökçebeý ranks second with a 20% share, exhibiting a production level above the regional average. Devrek (17%) and Ereğli (14%) make significant contributions to biogas production, with Devrek particularly benefiting from the organic waste potential associated with its livestock activities. In contrast, the districts of Center (8%), Alaplı, and Kozlu (5%) exhibit limited production shares, which can be attributed to either lower biogas potential or the operation of existing facilities at limited capacity. Kilimli accounts for the lowest production share, only 1%, which may be explained by the district's geographical conditions and the limited extent of agricultural and livestock activities. Figure 5 presents the biogas production percentages for the central district and its surrounding districts.

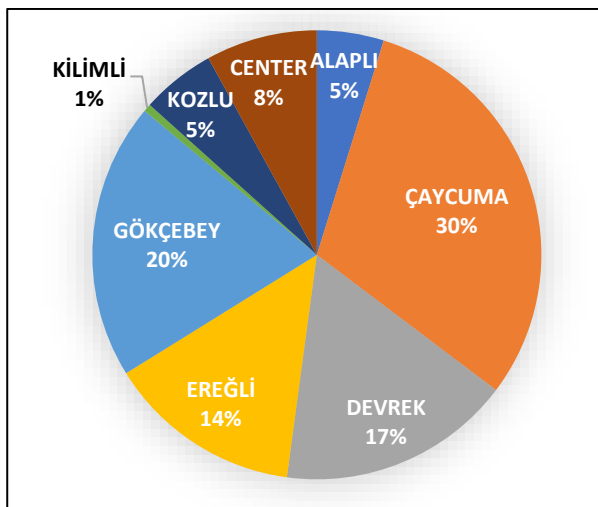


Figure 5. Percentage of biogas production by province and district

The equivalent value of the theoretical biogas potential produced in Zonguldak province and its districts in 2024 compared to other energy sources is given in Table 6. According to this, the theoretical biogas potential

produced in Zonguldak province and its districts has been calculated as approximately 22.69 million m³. From this amount, one can obtain approximately 106.65 GWh of electrical energy, 26.78 million m³ of natural gas equivalent, and 113.46x10⁹ kcal of thermal energy.

Table 6. Equivalent energy sources of biogas produced

Districts/ Species	Biogas (10 ⁶ m ³)	Electricity (GWh)	Natural gas (10 ⁶ m ³)	Heat (10 ⁹ kcal)
Alaplı	1.09	5.14	1.29	5.47
Çaycuma	6.92	32.50	8.16	34.58
Devrek	3.82	17.96	4.51	19.11
Ereğli	3.18	14.96	3.76	15.91
Gökçebeý	4.52	21.25	5.33	22.61
Kilimli	0.13	0.59	0.15	0.63
Kozlu	1.21	5.69	1.43	6.06
Center	1.82	8.56	2.15	9.10
Total	22.69	106.65	26.78	113.46

An examination of biogas-equivalent energy at the district level reveals that the highest potential is observed in Çaycuma, providing 32.50 GWh of equivalent electricity, 8.16 million m³ of equivalent natural gas, and 34.58x10⁹ kcal of equivalent thermal energy. Çaycuma is followed by Gökçebeý and Devrek, while Ereğli and Center exhibit moderate potential. In contrast, the potential in Alaplı, Kozlu, and Kilimli is relatively limited. Figure 6 presents the biogas-equivalent energy values for the central district and its surrounding districts.

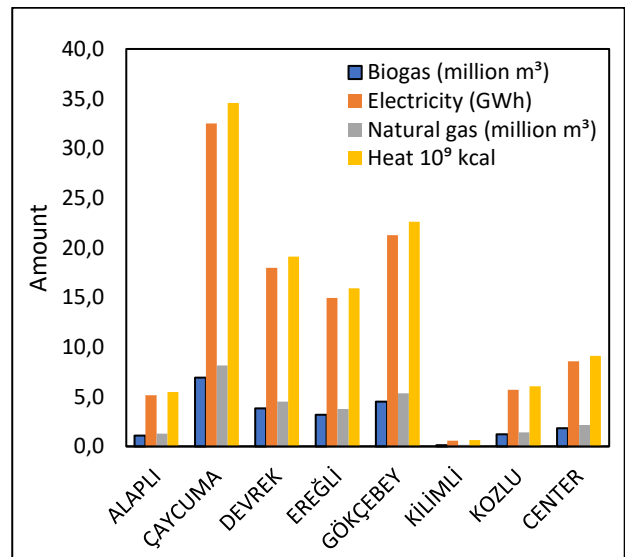


Figure 6. Biogas potential and its equivalent in energy sources in the central district and districts

Biogas production in districts is directly proportional to electricity, natural gas, and thermal energy outputs, with districts possessing high potential emerging as priority areas for regional energy production. Conversely, districts with low potential present a significant opportunity for promoting livestock farming and supporting sustainable energy goals. These findings highlight the need to consider the distribution of Zonguldak's biogas resources across districts in energy planning and policy development processes.

Considering the number of animals in the provincial center and districts, we have calculated that the electricity equivalent of 22.69 million m³ of biogas produced annually is 106.65x10⁶ kWh. According to the single-term, single-time residential (≤ 8 kWh day⁻¹) low-voltage retail sales tariff for September 2024, 1 kWh of electricity costs 2.072342 TL, including taxes. When the daily amount of electricity used in residences exceeds 8 kWh, 1 kWh of electricity costs 3.108511 TL, including taxes [38]. Assuming that residences consume electricity at an average cost of 2.5904265 TL per 1 kWh, estimates suggest that approximately 276.27 million TL could be saved at current prices.

According to calculations, an average of 0.439 tons of CO₂ equivalent greenhouse gas emissions are released per 1 MWh (unit) of gross electricity production across Türkiye [39]. When this potential is realized, it will be possible to prevent the emission of 46819.35 tons of CO₂ equivalent greenhouse gases in Zonguldak province.

4. DISCUSSION AND CONCLUSION

The expansion of the global population and advancements in technology are generating environmental issues by elevating energy use and livestock food production. This research theoretically assessed the biogas potential from animal waste using the Agro-Waste technique, based on data from the Zonguldak Provincial Directorate of Agriculture and Forestry for 2024. Furthermore, the comparable amounts of heat, natural gas, and electrical energy corresponding to the calculated biogas production capacity were established. According to the 2024 data from the Zonguldak Provincial Directorate of Agriculture and Forestry, there are a total of 4596293 animals in the province. Of these animals, 58275 are cattle, 26530 are ovine, and 4511488 are poultry. When examining the distribution within the province, it was determined that 98.15% of the total livestock population consists of poultry, while large and small livestock account for 1.27% and 0.58%, respectively. This situation shows that livestock activities in Zonguldak province are largely focused on poultry farming.

The potential for biogas generation from animal waste in Zonguldak province is estimated to be 22.69 million m³. This quantity is equivalent to about 106.65 GWh of electrical energy, 26.78 million m³ of natural gas energy, and 113.46 x 10⁹ kcal of thermal energy. Given the single-term, single-time residential low-voltage tariff for September 2024, the average unit price of 1 kWh of electricity is 2.5904265 TL. Based on these findings, it is anticipated that using the present biogas potential for power generation might result in an economic benefit of about 276.27 million TL. Additionally, this move is expected to prevent the emission of 46819.35 tons of CO₂ equivalent greenhouse gases into the environment.

The findings indicate that biogas producible from animal waste in Zonguldak province presents significant opportunities in terms of both renewable energy supply and economic gains. Potential differences between

districts illustrate the importance of a strategic approach to local energy planning and sustainable livestock farming practices. In this context, the establishment of biogas facilities would enable the processing of animal manure without causing environmental harm, the generation of clean energy, and the utilization of the materials obtained from anaerobic fermentation as organic fertilizers in agriculture. Thus, by reducing greenhouse gas emissions from fossil fuel use, the negative effects of the carbon footprint can be significantly limited. Additionally, the employment opportunities these facilities will provide will contribute to reducing out-migration by boosting economic vitality in rural areas.

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REFERENCES

- [1] T. Rahimi, R. Babazadeh, A. Doniavi, Designing and planning the animal waste-to-energy supply chains: A case study, *Renew. Energy Focus* 39 (2021) 37–48. <https://doi.org/10.1016/j.ref.2021.07.004>.
- [2] M. Silwadi, H. Mousa, B.Y. AL-Hajji, S.S. AL-Wahaibi, Z.Z. AL-Harrasi, Enhancing biogas production by anaerobic digestion of animal manure, *Int. J. Green Energy* 20 (2023) 257–264. <https://doi.org/10.1080/15435075.2022.2038608>.
- [3] H. Ertop, A. Atilgan, J. Kocięcka, A. Krakowiak-Bal, D. Liberacki, B. Saltuk, R. Rolbiecki, Calculation of the Potential Biogas and Electricity Values of Animal Wastes: Turkey and Poland Case, *Energies* 16 (2023). <https://doi.org/10.3390/en16227578>.
- [4] S. Rasi, J. Lântelä, J. Rintala, Trace compounds affecting biogas energy utilisation - A review, *Energy Convers. Manag.* 52 (2011). <https://doi.org/10.1016/j.enconman.2011.07.005>.
- [5] T.L. Ruwa, S. Abbasoğlu, E. Akün, Energy and Exergy Analysis of Biogas-Powered Power Plant from Anaerobic Co-Digestion of Food and Animal Waste, *Processes* 10 (2022). <https://doi.org/10.3390/pr10050871>.
- [6] A. Fetanat, M. Tayebi, M. Moteraghi, Technology evaluation for biogas production from animal waste in circular carbon economy: A complex spherical fuzzy set-based decision-making framework, *Bioresour. Technol. Reports* 23 (2023). <https://doi.org/10.1016/j.biteb.2023.101521>.
- [7] M.A. Haghghi, M. Feili, H. Ghaebi, H. Athari, Multi-criteria study and machine learning optimization of a novel heat integration for combined electricity, heat, and hydrogen production: Application of biogas-fueled S-Graz plant and biogas steam reforming, *Case Stud. Therm. Eng.* 63 (2024) 105323. <https://doi.org/10.1016/j.csite.2024.105323>.
- [8] M.S. Gaballah, H. Chand, J. Guo, C. Zhang,

- Mixed veterinary antibiotics removal and effects on anaerobic digestion of animal wastes: Current practices and future perspectives, *Chem. Eng. J.* 483 (2024) 149131. <https://doi.org/10.1016/j.cej.2024.149131>.
- [9] A. Golmakani, S. Ali Nabavi, B. Wadi, V. Manovic, Advances, challenges, and perspectives of biogas cleaning, upgrading, and utilisation, *Fuel* 317 (2022) 123085. <https://doi.org/10.1016/j.fuel.2021.123085>.
- [10] K. Archana, A.S. Viskram, P. Senthil Kumar, S. Manikandan, A. Saravanan, L. Natrayan, A review on recent technological breakthroughs in anaerobic digestion of organic biowaste for biogas generation: Challenges towards sustainable development goals, *Fuel* 358 (2024) 130298. <https://doi.org/10.1016/j.fuel.2023.130298>.
- [11] C. Mao, T. Zhang, X. Wang, Y. Feng, G. Ren, G. Yang, Process performance and methane production optimizing of anaerobic co-digestion of swine manure and corn straw, *Sci. Rep.* 7 (2017) 9379. <https://doi.org/10.1038/s41598-017-09977-6>.
- [12] K. Karim, R. Hoffmann, K. Thomas Klasson, M.H. Al-Dahhan, Anaerobic digestion of animal waste: Effect of mode of mixing, *Water Res.* 39 (2005) 3597–3606. <https://doi.org/10.1016/j.watres.2005.06.019>.
- [13] S.A. Gebrezgabher, M.P.M. Meuwissen, B.A.M. Prins, A.G.J.M.O. Lansink, Economic analysis of anaerobic digestion—A case of Green power biogas plant in The Netherlands, *NJAS Wageningen J. Life Sci.* 57 (2010) 109–115. <https://doi.org/10.1016/j.njas.2009.07.006>.
- [14] J.B. Holm-Nielsen, T. Al Seadi, P. Oleskowicz-Popiel, The future of anaerobic digestion and biogas utilization, *Bioresour. Technol.* 100 (2009) 5478–5484. <https://doi.org/10.1016/j.biortech.2008.12.046>.
- [15] T. Guan, P. Alvfors, G. Lindbergh, Investigation of the prospect of energy self-sufficiency and technical performance of an integrated PEMFC (proton exchange membrane fuel cell), dairy farm and biogas plant system, *Appl. Energy* 130 (2014) 685–691. <https://doi.org/10.1016/j.apenergy.2014.04.043>.
- [16] A. Mertins, T. Wawer, How to use biogas?: A systematic review of biogas utilization pathways and business models, *Bioresour. Bioprocess.* 9 (2022). <https://doi.org/10.1186/s40643-022-00545-z>.
- [17] Y. Sayan, Investigation of the effect of a different trapezoidal inclination angle in a reverse trapezoidal cross-section flow channel on the performance of the pem fuel cell with the computational fluid dynamic (cfd) method, *Kahramanmaraş Sütçü İmam Univ. J. Eng. Sci.* 26 (2023) 408–423. <https://doi.org/10.17780/ksujes.1180483>.
- [18] Y. Sayan, Investigating the impact of inverted-trapezoidal cross-section flow channels on the performance of a proton exchange membrane fuel cell with a parallel flow channel configuration, *Renew. Energy* 256 (2026) 124001. <https://doi.org/10.1016/j.renene.2025.124001>.
- [19] L. Pera, M. Gandiglio, P. Marocco, D. Pumiglia, M. Santarelli, Trace contaminants in biogas: Biomass sources, variability and implications for technology applications, *J. Environ. Chem. Eng.* 12 (2024) 114478. <https://doi.org/10.1016/j.jece.2024.114478>.
- [20] S.S. Seyitoglu, E. Avcioglu, M.R. Haboglu, Determination of the biogas potential of animal waste and plant location optimisation: A case study, *Int. J. Energy Res.* 46 (2022) 20324–20338. <https://doi.org/10.1002/er.8523>.
- [21] S. Işık, S. Yavuz, Determination of Biomass Energy Potential That Can Be Obtained from Agricultural and Animal Wastes of Konya Province, *Türk Doğa ve Fen Derg.* 11 (2022). <https://doi.org/10.46810/tdfd.1059408>.
- [22] S. Atılğan, A. Yılmaz, Determination of Biogas Potential from Animal Manure in Mardin Province, *Eng. Mach.* 62 (2021) 429–445. <https://doi.org/10.46399/muhendismakina.874857>.
- [23] E. El, Investigation of Biogas Generation Capacity from Animal Manure in Bitlis Province, *Bitlis Eren Üniversitesi Fen Bilim. Derg.* 14 (2025) 1024–1040. <https://doi.org/10.17798/bitlisfen.1635391>.
- [24] H. Et Yapılcan, H. Bakırtaş, Determination of biogas potential based on ovine and poultry manure in Aksaray province, *Niğde Ömer Halisdemir Univ. J. Eng. Sci.* 13 (2023) 107–115. <https://doi.org/10.28948/ngumuh.1285746>.
- [25] İ. Şentürk, Investigation of the Usability of Manisa Province Livestock Potential for Energy Production, *J. Eng. Fac.* 2 (2024) 144–151.
- [26] S. Tırınk, Calculation of Biogas Production Potential of Animal Wastes: Example of Iğdır Province, *J. Inst. Sci. Technol.* 12 (2022) 152–163. <https://doi.org/10.21597/jist.1026987>.
- [27] L. Gazigil, R. Yetiş, A. Demir Yetiş, Sustainable Energy Future: Investigation of Biogas Production with Livestock Waste and Energy Potential, *Uludağ Univ. J. Fac. Eng.* 30 (2025) 107–122. <https://doi.org/10.17482/uumfd.1610402>.
- [28] S. Işık, S. Yavuz, Investigation of biogas production potential from livestock manure by anaerobic digestion in Bingöl province, *Türk Doğa ve Fen Derg.* 11 (2022). <https://doi.org/10.46810/tdfd.1031911>.
- [29] A. [Internet], General information about Zonguldak province;2025 [cited 2025 September 11], (2025).
- [30] A. [Internet]., Zonguldak civil administration provincial map;2024 [cited 2025 September 11], (n.d.). <http://www.zonguldak.gov.tr/cografya>.
- [31] A. [Internet], Address based population registration system results;2024 [cited 2025 September 11]., (2025). <http://www.zonguldak.gov.tr/>.
- [32] E. Deniz, G. Yeşilören, N.Ö. İşçi, Biomass and

- biofuel potential of food industry in Turkey, *J. Food* 40 (2015) 47–54. <https://doi.org/10.15237/gida.GD14037>.
- [33] M.F. Baran, F. Lüle, O. Gökdoğan, Energy potential can be produced by animal waste of Adiyaman province, *Turkish J. Agric. Nat. Sci.* 4 (2017) 245–249.
- [34] S. Altikat, A. Çelik, Biogas potential from animal waste of Iğdır province, *Iğdır Univ. J. Inst. Sci. Tech* 2 (2012) 61–66.
- [35] H. Nuralan, G. Elden, G. Genç, Investigation of The Biogas and Electric Production Potential and Cost from The Cattle Waste in Kayseri, *Dicle Univ. J. Eng.* 11 (2020) 1175–1185. <https://doi.org/10.24012/dumf.745837>.
- [36] M. Gümüştü, S. Uyanık, Güneydoğu Anadolu Bölgesi hayvansal atıklarından biyogaz ve biyogübre eldesi, *Tesisat Mühendisliği (MMO)* 16 (2010) 59–65.
- [37] Republic of Türkiye Ministry of Agriculture and Forestry, Zonguldak Provincial Directorate of Agriculture and Forestry, “2024 agricultural data,” Zonguldak, Türkiye, data obtained through direct communication, 2024.
- [38] E. Energy Market Regulatory Authority, Electricity market sector report September 2024 [cited 2025 September 29], (2024). <https://www.epdk.gov.tr/Detay/Icerik/5-15713/2024-yili-eylul-ayi-sektor-raporlari>.
- [39] Republic of Türkiye Ministry of Energy and Natural Resources, Türkiye’s Electricity Production and Electricity Consumption Point Emission Factors [cited 2025 October 10], (2025). <https://enerji.gov.tr/evced-cevre-ve-iklim-elektrik-uretim-tuketim-emisyon-faktorleri>.