Biofuels from wastes in Marmara Region, Turkey: potentials and constraints

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Received: 19 February 2021 / Accepted: 12 July 2021 / Published online: 29 July 2021
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Abstract
Turkey, as an energy importing country, is heavily dependent on fossil fuels, bringing about an escalation in environmental problems and raising concerns regarding energy security. However, biowastes offer a potential solution to these woes, especially in Marmara Region of the country. In this study, the region’s potential in terms of the use of waste for energy production is analyzed. Within this context, agricultural and livestock wastes are examined in terms of their amounts, theoretical energy potentials, and associated costs to generate electricity. To evaluate economic costs, collection and feedstock costs for animal and agricultural wastes are used as input in three different scenarios based on FAO’s assessment. Based on the waste volumes and energy potentials thereof, it is found that biowastes can theoretically meet more than half of the electricity demand of the region. The results of the cost analysis demonstrate that both direct combustion of agricultural wastes and conversion of animal wastes to biogas in CHP plants to produce electricity are cost-effective in the context of various scenario options, considering the LCOE and feed-in-tariff values.

Keywords Biowaste · Bioenergy · Biogas · Biomass · Renewable energy · Sustainable energy

Introduction
Biofuels have been drawing increasing attention in recent years, as part of the debate on renewable energy, in terms of energy efficiency and climate change. Shifting energy production from processes based on scarce and environmentally unsustainable resources such as petroleum or coal towards those involving biofuels provides theoretical solutions to these problems in the form of low- or zero-carbon fuel alternatives although no consensus has been reached regarding the sustainability of this approach (Solomon 2010). Yet, biofuel applications, as promising alternatives to fossil fuels, are becoming prevalent worldwide, in the context of energy security and independence (Lehrer 2010; Achinas et al. 2017) and as potential solutions to global climate change, rural development, and environmental conservation issues (Jaeger and Egelkraut 2011; Guo et al. 2015). As most natural resources such as oil reserves are located in politically unstable parts of the world, biofuels (biogas and biomethane) can help reduce dependence on external sources and may replace conventional fuels (Achinas et al. 2017). In this regard, biofuel production is gaining importance as an alternative. Governments in Brazil, the USA, and the EU are subsidizing biofuel production (Mol 2007). According to World Global Bioenergy (2019), in year 2017, 4.7 billion liters of bioethanol was produced in Europe, compared to 74.3 billion liters in the USA. Having produced 15.8 billion gallons in 2019, the USA is the biggest producer of ethanol, which is produced by fermenting the sugar in the biomass. Brazil ranks second with approximately 8.6 billion gallons (statista.com 2020). In terms of biofuel production volume, the USA and Brazil are the two leading countries, having produced 69% of all biofuels worldwide in 2018 (REN21 2019). It is projected that total biofuel output will increase by 25% by the year 2024, compared to its level in 2019 (IEA 2019).
It is also estimated that global electricity consumption will more than double by the year 2030 (World Energy Council 2016). Turkey, as an energy importing country, depends on fossil fuels for 87% of its total energy supply (The World Bank 2015). With a growing population and GDP, Turkey has been investing in renewable energy as a promising alternative, in order to reduce its dependence on foreign energy sources (Acar and Yeldan 2016). The shares of specific primary energy sources in power generation in Turkey as of 2018 are as follows: coal 37%, natural gas 30%, hydroelectric 19.7%, wind 6.5%, solar 2.6%, geothermal 2.4%, and renewable waste 1.2% (Turkish Electricity Transmission Company (TETC) 2020). Oil and natural gas are the leading resources on which Turkey depends for its energy needs. On the other hand, Turkey has set renewable energy targets in line with the Renewable Energy Directive. Accordingly, the renewable energy sources are expected to cover up to 20% of the total energy consumption and 30% of the electricity generation by the year 2023 (Rincon et al. 2019).

Turkey's energy demand in 2030 is projected to be nearly five times the level in the year 2000 (Dumanli et al. 2007). In this context, the use of biomass as an alternative source to meet the rising energy demand and as a means to reduce dependence on foreign and conventional resources deserves a detailed analysis (Dumanli et al. 2007). Rincon et al. (2019) point out that Turkey is the 7th largest agricultural biomass producer in the world and that boosts a significant potential to produce biofuels. The International Energy Agency (IEA) estimates that, in the period 2020–2025, the total installed capacity of biomass power plants in Turkey will increase by 630 MW (IEA 2020a). Considering that Turkey's overall installed capacity connected to the electricity grid was 88550.8 MW in 2018, biomass can potentially provide 0.8% of the total installed electrical power demand (TETC 2020).

According to the Energy Market Regulatory Authority (EMRA) data, through the 4 years preceding 2018, biodiesel production and sales grew by 40%. 2018 also saw 30% waste vegetable oils and 70% vegetable oil seeds used in the production of biodiesel (Biyodizel Sanayi Derneği 2019).

Agricultural and livestock residues have substantial potential in bioenergy production. Besides, their use represents a more environmentally sustainable way of producing energy, compared to using non-renewable resources, as using crop residues left over in the field is not associated with negative impacts on biodiversity, food sovereignty, and ecosystems.

In this paper, we aim to investigate the biowaste potential of Marmara Region, Turkey, in terms of energy production. Since the utilization of wastes as an alternative source of energy may help overcome some concerns such as land and water requirements and environmental problems compared to non-renewable energy sources, utilizing the existing biowaste potential rather than the option of producing oilseeds and crops exclusively for biofuel purposes is addressed here.

To this end, previous studies are reviewed and data made available by government agencies, on biowastes and their potential use in electricity production in Turkey at the national and regional levels, is analyzed. The study is novel in the sense that it estimates and compares the costs of electricity generation based on agricultural wastes versus animal wastes, in order to find out the most cost-effective option for Marmara Region.

The paper is organized as follows: “Literature review” section summarizes the literature on biofuels and biowastes, with special reference to the opportunities they provide in terms of sustainable energy production. Their disadvantages are also discussed. “Data and methodology for calculating Marmara Region's biogas production potential” section presents the data and the methodological approach employed in the study. In this section, we focus on agricultural and livestock wastes as renewable energy sources as potential means to meet the energy demand in Marmara Region, along with their limitations. In “Cost calculation and comparison of costs for various scenarios” section, the costs of electricity production from wastes are calculated and compared with the costs inherent in processes based on other energy sources in various scenarios. “Discussion” section provides a discussion of various aspects of the results, followed by the conclusion of the study in “Conclusion” section.

Literature review

The term biomass refers to a wide range of materials including wood, logging residues, agricultural crops, municipal and food processing wastes, animal wastes, and algae (Demirbas 2009: 1573-1582). Ho et al. (2014) classify biomass in a number of generations. Food crops (sugarcane, cereal, cassava, maize, grass, wheat, rye) are considered the first-generation biomass, the sustainability of which is often questioned because of the possibility of jeopardizing food sovereignty and the potential effects on climate and nature, arising from the need to achieve high levels of productivity in agricultural operations aiming to raise these crops. To overcome this problem, the second-generation biomass is introduced, composed of non-food lignocellulosic materials. Agricultural residues and wastes are also considered second-generation biomass sources. Moreover, municipal and industrial wastes are also used for biofuel production transforming waste to energy in line with waste management practices. These efforts also provide environmental benefits in terms of reducing the amount of waste, greenhouse gas (GHG) emissions, and landfill areas required (Ho et al. 2014).

Özer (2017), in turn, defines biomass as a renewable energy source derived from organic wastes including animal manure, agricultural residues, municipal, and industrial wastes. Primary agricultural residues can be collected after harvesting.
whereas secondary residues are obtained during the processing phase. On the other hand, dedicated energy crops such as miscanthus, poplar, and willow are grown for biomass purposes (Bioenergy Europe 2019). Using (dedicated) energy crops for biomass production, instead of agricultural residues and wastes, accounts for only a small fraction (0.1%) of all biomass production worldwide (Camia et al. 2018). According to Bioenergy Europe (2019), it is estimated that 50 kha was cultivated with these crops to produce energy in 2017 in Europe. Maize, rapeseed, sugarcane, corn, sugar beet, and sweet sorghum are commonly used for energy production.

Yet, biofuel production is also marked with certain limitations in terms of the availability of biomass, such as the limited availability of land, water and nutrient resources, and significant requirements of external energy inputs. Mol (2007) argues that the excessive increase in biofuel production worldwide, especially in Brazil and the USA, poses some sustainability-related risks for different regions and groups. Doubts are raised about biofuels’ worth as a true and cost-effective carbon emission mitigation strategy. In this context, deforestation, loss of biodiversity, monocropping, soil degradation, and water pollution are but a few of the environmental problems associated with biofuel production (Mol 2007; Silva Lora et al. 2011). Furthermore, Jaeger and Egelkraut (2011) argue that biofuel production may lead to an increase in food prices and possible changes in land use, given the need to allocate large areas for the production of the relevant crops.

Given the advantages and potential disadvantages of utilizing biofuels for energy production, wastes offer a viable solution for producing biofuels without the significant sustainability issues and the potential environmental problems involved in conventional processes to produce biofuels. Although using logging residues and municipal solid wastes (MSW) for biofuel production is not completely free from externalities on nature, as forests need logging residues for soil retention and wildlife habitat, and as MSW is used in composting and combustion to generate energy, they are still preferable options as they help restrict the growth of feedstock crops production figures (Jones et al. 2007). The most common wastes that are used for biofuel production are agricultural and municipal wastes, sewage sludge, animal manure, agriculture-related industries’ wastes, food waste, and/or collected municipal waste from households (Achinas et al. 2017). Agricultural residues, which include straws, fruit seeds, and molasses, are commonly used as potential renewable sources (Bhatia 2018). In this sense, Meyer et al. (2018) investigate biogas energy potential of sustainable agricultural residues, animal manure, permanent grasslands, and meadows for projections for year 2030, in the context of EU28. Based on three scenarios which correspond to high, moderate, and low availability, they find that maize is suitable as an option to contribute to the biogas sector throughout EU28 (Meyer et al. 2018).

Agricultural wastes as well as livestock wastes are used as sources for renewable energy, with a view to reducing GHG emissions and facilitating carbon sequestration (Sarmah 2009; Fatima et al. 2021). According to the US Environmental Protection Agency (2000), there are 376000 livestock operations, which generate 58.1 million tonnes of manure each year in the USA (EPA 2000). As Guber et al. (2007) point out, animal feces may be deposited on lands and livestock wastes contain pathogenic bacteria which may be released into the environment, not to mention the risk to cause water pollution and to pose public health risks (EPA 2000; Guber et al. 2007). Sarmah (2009) states that cow manure, as an appropriate biogas source, produces biogas proportionally (for 1 cubic foot of biogas, 1 pound of cow manure is required). A study carried out in Canada found that approximately 7,500 cattle is needed to produce 1 megawatt of electricity. It is estimated that New Zealand has more than 5 million cattle, which produce an enormous amount of waste and thus offer significant biogas production potential. Developing countries have also high, but yet untapped potential in terms of animal wastes and thus biogas production (Sarmah 2009). For instance, Iqbal et al. (2021) state that Pakistan utilizes less than 30% of its biogas potential. The authors demonstrate that biogas investments can play a substantial role in enhancing farm productivity, combatting indoor air pollution, contributing to household hygiene, and household well-being, especially in the rural areas of Pakistan.

Agricultural residues, which can be classified as crop residues and agricultural industrial by-products, can be converted into biofuel, based on their constituents. For instance, according to FAO, approximately 4 billion cubic meters of wood is used each year worldwide. Fifty-five percent of this figure is used as fuel by direct combustion, and 45% of is used as industrial raw material. Forty percent of this latter portion ends up as residues, which are used as raw material for second-generation biofuel production (Food and Agriculture Organization 2009). With respect to another agricultural waste element in the form of sugarcane bagasse and sisal waste, Silayo et al. (2008) state that bioconversion for bioethanol production has gained more attention in recent years, compared to simple incineration given the potential pollution problems.

Renewable energy sources have been receiving increased attention in Turkey as well as within current and future energy generation projections. Even though renewables have only a limited share in energy production, renewable energy markets have been promoted since 1984 through the Electricity Market License Regulation (Erdoğan 2008). According to TETC
(2020), as of 2019, Turkey’s gross electricity generation can be broken down by primary energy resources as follows: 57288 GWh (19%) from natural gas, 88823 GWh (29%) from hydro, 66022 GWh (22%) from hard coal and imported coal, 46872 GWh (15%) from GWh lignite, 39932 GWh (13%) from geothermal/wind/solar, and 4624 GWh (1.5%) from renewable wastes and waste heat. In recent years, substantial investments were made for the installation of additional renewable power capacity in the country. However, the renewable energy market is still mostly dominated by hydropower. Despite the fact that biofuel production from wastes is relatively new and involves some uncertainties, such practices have started to emerge in various regions of Turkey.

Turkey has significant biowaste potential in the form of animal manure. Doruk and Bozdeveci (2017) examine biogas potential of animal manure in Denizli province to the southeast of the Aegean Region. They calculate that as much as 70.16 m³/year of biogas could be produced thanks to 4,370,129 animals which produce 4,578,889 kg/day of manure. Energy equivalent of the biowaste thus produced is calculated to be 46.30 million liters of diesel and 329 million kWh of electricity (Doruk and Bozdeveci 2017). Similarly, animal manure use for biogas production in Düzce, which is located in the Western Black Sea Region, is analyzed in a study by Yürük and Erdöğmuş (2015). They argue that poultry wastes offer considerable biogas potential in the center of the province, to the tune of 5,553,849 m³/year and in Akçaömer district, to the tune of 5,587,289 m³/year (Yürük and Erdöğmuş 2015). Similarly, Thrace Region’s potential with cattle, sheep, and poultry population is calculated as 2,427.81 TJ/year. Methane production volumes and energy potentials of methane derived from animal wastes are calculated using the Turkish Statistical Institute (TurkStat) data. As a result, the energy potential of animal manure in the Thrace Region corresponds to 1.17% of the total energy value derived from petroleum in Turkey (Köse 2017).

Gümüşçu and Uyank (2010) examine data on cattle manure, particularly the number of cattle and waste production volume in the Southeastern Anatolia Region, and find that 1,700 m³/day and 612,000 m³/year of biogas and 2,880,000 kW/year of energy can be obtained from 1,500 cattle. They recommend investments in facilities with a capacity of 500 or more animals in the region. In facilities with 1,000 or more animals, the original investment would be expected to be paid off in around 5 years. In another paper, Marmara Region’s animal waste potential with respect to biogas production from cattle manure is examined, for the period 2005–2014. It is calculated that, by 2014, the region’s biogas potential grew by 15%, reaching to 1,242.17 Mm³ of biogas, compared to 2005, despite the fluctuations in poultry production (Ayhan 2016). Şenol et al. (2017a), in turn, examine biogas production from animal wastes, kitchen wastes, wastewater treatment plant wastes, and agricultural wastes. In a landfill facility in Mamak district of Ankara city, urban solid wastes are utilized to produce 38.6 MWh of electricity, corresponding to 7% of the electricity need of Ankara (Şenol et al. 2017a).

Salihoğlu et al. (2019) analyze the biogas potential of animal (cattle and sheep) waste in Balıkesir province, which is located in Marmara Region. They find that as much as 82,815,600 m³ biogas and 1,879,914,120 MJ energy can be produced per year in Balıkesir, from 5,955,318 tonnes of animal waste. In conclusion, they claim that biogas potential can be taken into consideration to meet the energy demand of the region and transform manure into usable end products. Similarly, Yaşlı and Koç (2019) analyze data on biogas production from animal manure and its energy equivalent in Adana province, based on daily animal manure, wet manure per unit animal (kg/day-animal), solid matter ratio, volatile solids ratio, the proportion of volatile solids in the solid matter, and finally the ratio of methane, and proceed to calculate the amount of methane that can be produced and the corresponding energy value. In conclusion, they find that 88,367,417 m³ of methane can be produced per year, from a total of 3,062,992 animals. The energy equivalent of the total methane gas corresponds to 3,181,227 GJ/year and 75,979 toe/year. When methane gas is burnt in a combined heat and power engine (CHP) with an average electric efficiency of 35%, 309,286 MWhe of electricity can be produced per year. Considering that each kWh of electricity savings corresponds to approximately 0.58 kg reduction in CO₂ emissions, the study shows that 179.4 tonnes of CO₂ emission annually can be avoided by producing biogas from animal wastes, instead of fossil fuel-based processes.

Finally, Ulusoy et al. (2021) analyze the biogas and energy production potential of chicken manure, employing a model biogas plant in Turkey. They conduct a field study in Balıkesir province and find that 110 thousand tonnes of fertilizer per year can be processed in the pilot facility, to obtain 8 million m³/year of biogas. The energy equivalent of this biogas volume is 17.1 GWh/year of electricity and 16 GWh/year of thermal energy. Proceeding with a generalization based on the data they thus obtained, the authors find that, in the whole country each year, 186 million m³/year of biogas could be processed from 2 million tonnes of chicken manure, which would correspond to 198 million kWh/year of electrical energy. An additional benefit to be derived from utilizing this biogas potential is the ability to cut GHG emissions by up to 317 thousand tonnes per year (Ulusoy et al. 2021: 12356).

It should be evident by now that biogas production using animal wastes is a popular topic in the literature. On the other hand, studies on biogas production based on agricultural wastes are not lacking either. Sözer and Yaldız (2011) determined the amount of biogas to be obtained from mixed banana greenhouse wastes and cattle manure. They carried out experiments in a laboratory type biogas generator with a net 15 L
fermentation volume and used supplies from the plastic-covered banana greenhouse located in Akdeniz University Faculty of Agriculture Application Research Farm. They found that the highest biogas production rate is obtained from a mixture of 70% cattle manure and 30% banana greenhouse waste. The amount of biogas produced was 12,044 L per day and the methane ratio in biogas was found to be 51.1%. Görgülü (2019) investigated the biogas potential of animal and agricultural wastes in Burdur province based on TurkStat data for year 2018, and calculated their energy equivalents, reaching to the conclusion that biogas potential of Burdur province and its districts could be obtained 87% from cattle, 11% from sheep, and the remaining 2% from poultry. With reference to the total biomass potential of the selected field crops across the province, Görgülü found that corn offers the highest energy value whereas cabbage and potato have the lowest energy value in terms of biogas production.

Although the literature on biogas production worldwide is vast, more detailed studies on agricultural wastes, livestock residues, and MSWs in the context of biogas production are required to analyze the case of Turkey. Considering agricultural production, animal husbandry, and urbanization rates, one can argue that Turkey has significant potential for biogas production. On the other hand, Marmara Region has both agricultural areas and big cities, making the region a worthwhile case to study the potential of crops and livestock wastes, as well as MSWs. The current study contributes to the literature summarized above with further analysis of the biowaste and bioenergy potential of Marmara Region. It also differs from the previous studies as it offers estimates and comparisons of the costs of electricity generation using agricultural wastes versus animal wastes comprehensively in order to find the most cost-effective option.

Data and methodology for calculating Marmara Region’s biogas production potential

This study aims to assess the amount of biowastes, their energy potential, and the associated costs in the context of electricity generation. The focus is on crop residues (agricultural waste) and livestock residues (animal waste) produced in Marmara Region. Cost assessments are based on three scenarios adapted from FAO’s “BEFS Assessment for Turkey” Report (Maltsooglou et al. 2016). The waste amounts that can be used in biofuel production in Marmara Region at provincial level are taken from the publicly available data at the MENR General Directorate of Energy Affairs website. Data on animal and agricultural production and their wastes were checked against TurkStat data for the year 2019, for verification purposes. The data is used for a projection taking into account the animal count, agricultural production volume, waste amounts, and theoretical energy potentials. Calorific values of the wastes are not calculated from scratch in the current analysis as they have been elaborately analyzed in FAO’s assessment. A methodological flowchart is presented in Figure 1.

The first step taken in the study is to determine the amount of crop residues and animal manure produced in Marmara Region and to calculate theoretical energy equivalents thereof, in terms of megawatt-hours (MWh). Then, applicable costs are calculated, followed by a cost comparison of energy production from biowastes and other sources, based on some elements of the techno-economic analysis provided by Maltsooglou et al. (2016). FAO’s BEFS analysis consists of the assessment of natural resources and biomass potentials at both economic and technical levels, for various provinces of Turkey. The present study, in turn, focuses on Marmara Region’s biomass potential based on agricultural and animal wastes, and the costs per MWh of potential energy production based on such wastes, in accordance with three distinct scenarios, run with FAO’s data. Finally, a comparison with the unit costs of energy production based on other energy sources and the results of the three scenarios is provided. Collection and feedstock costs in FAO’s assessment are used in the case of biomass.

Energy production methods taken into account here consist of direct combustion of crop residues, as well as biogas production from animal manure. Electricity generation in combined heat and power (CHP) or cogeneration systems based on direct combustion or combustion of biogas is analyzed. It is assumed that all crop residues and animal manure produced in Marmara Region are available for energy production.

The share of renewable energy sources (including hydro) in electricity generation was 29.6% in 2017 and 32.4% in 2018 (TurkStat 2019) (see Figure 2). Hydroelectric stands out as the first and foremost source of renewable energy in Turkey. The use of biomass is limited mostly to conventional methods such as burning wood, animal, and vegetable waste for heating purposes, amounting to half of all renewable energy processes in the country (5.4 Mtoe) and there is certainly an untapped potential in agricultural practices. According to EMRA Electricity Market - 2018 Market Development Report, the share of biomass in electricity production was 0.66% with 1,939.72 GWh in 2018, whereas it slightly increased and reached 0.82% with 2,410 GWh (EMRA 2019) in 2019.\(^2\) On the other hand, organic wastes constitute 65% of all waste produced in Turkey, indicating a significant potential for energy production. In addition, 62 million tonnes of agricultural waste (such as barley, wheat, tobacco, paddy, and cotton) is produced each year (Şenol et al. 2017b; MENR 2019).

\(^2\) In 2018, the total capacity of biomass power plants worldwide was 130 gigawatts (GW), 16.2 GW of which was in the USA, 17.8 GW in China, and 10.2 GW in India (REN21 2019).
In the context of Turkey’s animal husbandry and agricultural production sectors, biowastes draw attention as an alternative energy production method. Although a downwards trend is obvious, currently around 25% of Turkey’s population relies on agriculture, livestock, and forestry as its source of income (The World Bank 2018). According to the MENR (2019) General Directorate of Energy Affairs data, the theoretical energy equivalent figures for specific types of waste in Turkey are as follows: 4,385,371 toe/year for animal wastes, 6,009,049 toe/year for agricultural wastes, and 859,899 toe/year for forestry wastes, amounting to a total energy equivalent figure of 11,254,319 toe/year. It is estimated that the amount of biogas that can be produced from such waste in an oxygen-free environment will be around 1.5 to 2 million toe (Yağlı and Koç 2019).

Marmara Region, located in the north-west of Turkey, covers a land area of 67,000 km² and is home to a population of more than 24 million (Ministry of Interior 2019). Industry, tourism, trade, and agriculture sectors are prominent in the region, which consists of 11 provinces — Istanbul, Edirne, Kurklareli, Tekirdağ, Çanakkale, Kocaeli, Yalova, Sakarya, Bilecik, Bursa, and Balıkesir. Together with Istanbul, which is the most densely populated city in the whole country, Bursa and Kocaeli are the main industrial hubs of the region. Other provinces, on the other hand, stand out with their substantial agricultural and livestock potentials. Agricultural and animal wastes produced in the provinces of the region and their biofuel potentials are displayed in Table 1.

Livestock and agricultural production activities reported in Table 1 cover the following: horse, camel, donkey, cattle, goat, sheep, goose, duck, laying hens, and safflower, barley, wheat, sunflower, tare, rye, rice, bean, beet, canola, lentil, corn, chickpea, potato, sorghum, cotton, oat, pear, quince, almond, walnut, strawberry, berry, apple, plum, apricot, hazelnut, fig, cherry, peach, grape, and olive (MENR 2019).

According to Table 1, the amount of the agricultural wastes (crop residues) produced in the region reaches up to 9,375,558.91 tonnes. The theoretical energy equivalents of animal and agricultural wastes in Marmara Region are 890,558.48 toe/year and 3,763,096.69 toe/year, respectively,

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**Fig. 1** Flowchart presenting the authors’ methodological approach

**Fig. 2** Electricity produced from renewable sources including hydropower, 2018 (%) Source: MEU 2019
amounting to a total of 4,653,655.17 toe/year. Considering that Turkey’s total energy equivalent of animal and agricultural wastes is 10,394,420 toe/year (MENR 2019), Marmara Region’s share is substantial (45%) in terms of total theoretical energy amount.

The amount of residues of both crop and livestock can vary depending on the type of crop or animal breed (Maltsoglou et al. 2016). Table 1 reveals that Balikesir and Sakarya provinces have more density in terms of animal population and theoretical energy equivalent. In the case of agricultural production, on the other hand, Balikesir and Bursa rank at the top of the list. Yet Tekirdağ and Edirne have higher waste production capacity levels due to the type of products farmed in these provinces. Since corn and sunflower generate more residues than other species (Başçetinçelik et al. 2006), waste amounts are higher in Tekirdağ and Edirne, where these two crops are widely produced.

Although the waste amount based on animal manure exceeds that of agricultural wastes, Table 1 shows that the equivalent energy values of animal wastes are considerably lower than those of agricultural wastes. This difference might stem from the amount of the organic dry matter, which is comparably low for animal manure (2–10%), and also due to the fact that energy-rich substances in the feed eaten by the animals are digested by the animals (Weiland 2003), leaving less energy in the manure. Dry manure ratios (in percentages) for cows, sheep, and poultry are 12.7%, 25%, and 25%, respectively (Başçetinçelik et al. 2006).

Figure 3 illustrates the amount of animal wastes produced in the region, and their energy equivalents. Balikesir and Sakarya provinces are home to the highest numbers of farm animals with 34,966,167 and 30,153,276 respectively accounting for 6,885,871.04 and 2,230,372.7 tons of animal waste, respectively. However, in spite of the fact that the number of animals in Bursa is less than that of Sakarya, the former province produces more animal manure compared to Sakarya, given the higher numbers of cattle and sheep producing a larger amount of waste, while poultry, in which Sakarya is richer, produces a lesser amount (Başçetinçelik et al. 2006; MENR Energy Potential Atlas 2019). These imbalances also find their reflection on the energy equivalents of the wastes thus produced.

Figure 4 presents the amounts of agricultural wastes produced in individual provinces in the region, along with their energy equivalents. While agricultural production takes place predominantly in Bursa and Balikesir, the amount of agricultural waste produced is higher in Edirne and Tekirdağ, where sunflower and canola production is more common compared to other provinces in the region. According to the MENR data, sunflower, canola, rice, and chickpeas generate more waste than their production volumes. In this context, canola waste in Tekirdağ is truly vast in terms of scale.

Table 1 also shows the energy equivalence of animal and agricultural waste, and the total amount of waste produced in each category, in individual provinces. Total energy equivalent of all animal and agricultural waste produced in the whole region is 4,653,655.17 toe/year (MENR Energy Potential Atlas 2019). As 1 toe is equal to 11.63 megawatt-hours (MWh) (IEA 2020b), the theoretical energy potential of Marmara Region can be calculated as follows:

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4,653,655.17 \times 11.63 = 54,122,009.63 \text{ MWh} = 54,122 \text{ GWh}
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According to the Energy Market Regulatory Authority, in year 2018, the total licensed electricity generation figure was 295,442.15 GWh, while licensed electricity production from biomass was 2,410 GWh (EMRA 2019). That is to say, the share of biomass in overall electricity generation was 0.82%. On the other hand, our assessment on theoretical energy production from biowastes demonstrates that it is possible to generate as much as 54,122 GWh from wastes produced in Marmara Region alone, corresponding to 18.32% of the total electricity generation of the whole country.

According to Turkstat (2018) figures, electricity consumption in Marmara Region stood at 93,324,352 MWh (93,324.35 GWh), 58% of which could theoretically be covered by generating electricity from biowastes produced in the region. These numbers represent theoretical energy potentials and may offer helpful insights for the formulation of regional energy policies. The Ministry of Energy and Natural Resources Energy announced that renewable energy installed capacity is expected to increase to 4,533 GWh by 2023 (Maltsoglou et al. 2016). In line with this target, theoretical energy potential of biowastes of Marmara Region can come in handy.

Cost calculation and comparison of costs for various scenarios

This section of the study analyzes the costs of producing energy using agricultural residues and animal manure, based on FAO’s assessment. The heating values of the agricultural residues available in the region are taken from Maltsoglou et al. (2016). To calculate the costs of producing electricity from agricultural and animal wastes in combined heat and power (CHP) or cogeneration systems, potential energy equivalents in terms of MWh and collection and feedstock costs based on the cost frameworks of the three scenarios envisaged by FAO are used. As a fourth scenario, feedstock costs are assumed to be zero. Furthermore, all agricultural residues and animal manures are assumed to be available for utilization and for energy production. Electricity generation based on crop and livestock residues is usually performed through one of the following two methods (Rincon et al. 2019):

- CHP from direct combustion of biomass
• CHP from biogas (residues first need to be converted into biogas and then fed into the system)\textsuperscript{3,4}

Accordingly, the selected energy pathways are as follows: Crop wastes are used in direct combustion, whereas livestock wastes are used for producing biogas to be eventually burned in CHP systems.

It is noteworthy that accessibility of wastes to be utilized as input for the energy generation processes depends on the locations and can pose a number of problems in the context of the collection of agricultural and livestock residues. In this study, collection and feedstock costs are used as proxies for the price of biomass. Collection can be required if residues are dispersed in the field and thus can involve a collection cost. If there is no need to collect residues, collection cost is taken as zero (Rincon et al. 2019). In line with this, three distinct cost figures in US dollars are assigned to the input, based on FAO’s assessment, agricultural, and livestock residues. Given FAO’s cost assessments, feedstock costs are determined based on collection costs ranging from 0 to 300 USD/t (transport excluded) for agricultural wastes (Table 2).

Collection costs of crop wastes for three alternative price levels at the province level based on the quantity of agricultural waste are summarized in Table 2. Actual collection costs are then calculated per kWh using the unit converter. Given the results for the three scenarios, the costs are found to range between 0 USD/kWh and 0.258 USD/kWh. These values are then used together with the feedstock costs (see Table 3) to calculate the total costs for agricultural wastes (see Table 4). Transport costs are not taken into consideration at this stage. Availability and accessibility of wastes are dependent on several variables such as the location of the field, crop residue type, and the yield (Maltsoglou et al. 2016). In scenario 1, the minimum collection distance value is chosen as 0 km, and thus, collection cost is equal to 0. In scenarios 2 and 3, 150 USD/t and 300 USD/t are selected as the collection cost figures, based on assumed collection distances. However, other indicators are not taken into account and it is assumed that all feedstock residues are available for energy production although crop and animal residues are often used for soil amendment, as animal feed and as fertilizers instead (Rincon et al. 2019).

Feedstock costs are evaluated under four alternative scenarios. Three different cost levels for feedstock are presented in Table 3. In addition to these three, the total cost when the feedstock cost is equal to zero is calculated as the fourth scenario. Feedstock costs are found to be 19 USD/t, 65.5 USD/t, and 112 USD/t with reference to FAO’s assessment. Feedstock costs are calculated based on their weights, as had been the case with collection cost calculation. The wide range of feedstock costs stems from the differences in technology used in CHP facilities and energy potentials of feedstock. Therefore, some feedstock is considered more valuable, while some command lower prices. In this analysis, technology, energy potential (MJ/kg), and efficiencies are not taken into account. Feedstock costs are adapted directly from FAO’s report, which presents input for scenarios based on low, medium, and high prices. The results are shown in Table 3, helping us to infer that feedstock costs are more affordable compared to the case applicable to collection costs in scenarios 2 and 3.

In the case of zero-cost feedstock, collection costs constitute the main expenditure items for bioenergy production, at 0 USD/kWh, 0.129 USD/kWh, and 0.258 USD/kWh, respectively, for the first three scenarios. As one would expect, scenario 4, where feedstock cost is zero, is the most cost-effective option.

The results presenting total costs including collection and feedstock costs are summarized in Table 4. The total costs for agricultural wastes are calculated respectively as 0.016 USD/kWh, 0.186 USD/kWh, and 0.355 USD/kWh for the first three scenarios. Apparently, scenario 1 can be considered as the preferable option compared to other scenarios. Scenario 4, where both collection cost and feedstock cost are zero, on the other hand, is evidently the most cost-effective option.

Similar calculations are applied for biogas use for electricity generation. Livestock wastes that are suitable for conversion into biogas and use in cogeneration facilities instead of direct combustion are accounted for. Since some biomass is not appropriate for direct combustion due to its water content or ash producing potential, some modification may be needed. In this context, animal manure stands as a convenient type of biomass for conversion into biogas for the purpose of generating electrical energy in a CHP plant. The amount of livestock waste may vary with regard to several factors such as animal type, age, and productivity (Maltsoglou et al. 2016). However, these indicators are not taken into account in the assessment here, as they were not available in the database of MENR, covering Marmara Region.

\textsuperscript{3} Biogas production using biomass is possible under various conditions, such as specific temperature ranges, and depends on the biomethane potential of residues, which, in turn, is a function of the physical and chemical properties of manure. In parallel to the methodology adopted for the FAO BEFS study, the following Hashimoto equation is used in order to calculate the potential amount of biogas from biomass: \( \gamma = B_0 \times S_0 \times \left[ 1 - \frac{K}{HRT \times (1 + K)} \right] \)

where \( \gamma \) is the volumetric methane production rate, \( B_0 \) is the biomethane potential, \( S_0 \) is the influent volatile solids concentration, \( K \) is the s kinetic parameter, \( HRT \) is the hydraulic retention time (day), and \( M \) is the maximum specific growth rate (Hashimoto 1986).

\textsuperscript{4} The energy potential of biogas from animal wastes highly depends on the biomass type. For instance, cattle manure and egg-layer chicken manure are observed to be more suitable for biogas production compared to buffalo and broiler manure, and hence, have higher energy potential (Maltsoglou et al. 2016: 38). Theoretical energy equivalence (in toe) of animal wastes produced in Marmara Region are taken from MENR (2019) General Directorate of Energy Affairs and then converted to electricity potential (in MWh) using the equivalence of 1 toe to 11.63 MWh.
### Table 2. Collection costs for cogeneration in the case of agricultural wastes at province level in Marmara Region

| Province      | Amount of agricultural waste (tonne) | Scenario 1: 0 USD/t | Scenario 2: 150 USD/t | Scenario 3: 300 USD/t |
|---------------|--------------------------------------|---------------------|-----------------------|-----------------------|
| Balıkesir     | 1,096,113.83                         | 0                   | 164,417,075           | 328,834,149           |
| Bilecik      | 205,588.10                           | 0                   | 30,838,215            | 61,676,430            |
| Bursa        | 1,512,406.29                         | 0                   | 226,860,944           | 453,721,887           |
| Canakkale    | 865,126.53                           | 0                   | 129,768,980           | 259,537,959           |
| Edirne       | 1,755,665.87                         | 0                   | 263,349,881           | 526,699,761           |
| İstanbul     | 345,642.47                           | 0                   | 51,846,371            | 103,692,741           |
| Kırklareli   | 1,067,270.30                         | 0                   | 160,090,545           | 320,181,090           |
| Kocaeli      | 149,094.91                           | 0                   | 22,364,237            | 44,728,473            |
| Sakarya      | 643,708.91                           | 0                   | 96,556,337            | 193,112,673           |
| Tekirdağ     | 1,706,775.31                         | 0                   | 256,016,297           | 512,032,593           |
| Yalova       | 28,166.39                            | 0                   | 4,224,959             | 8,449,917             |
| Total        | 9,375,558.91                         | 0                   | 1,406,333,837         | 2,812,667,673         |

1 tonne = 1.162 megawatt-hour >>

| Province      | Amount of agricultural waste (tonne) | Scenario 1: 0 USD/MWh | Scenario 2: 258.176 USD/MWh | Scenario 3: 56.368 USD/MWh |
|---------------|--------------------------------------|-----------------------|-----------------------------|---------------------------|

Source: Calculated by the authors using the data from Maltsoglou et al. (2016) and MENR (2019)

*Note: The exchange rate used was 1 USD = 2.47 TL.

### Table 3. Feedstock costs per kWh for agricultural wastes in individual provinces

| Province      | Amount of agricultural waste (tonne) | Scenario 1: 19 USD/t | Scenario 2: 65.5 USD/t | Scenario 3: 112 USD/t |
|---------------|--------------------------------------|----------------------|------------------------|-----------------------|
| Balıkesir     | 1,096,113.83                         | 20,826,162.77        | 71,795,455.87          | 122,764,748.96        |
| Bilecik      | 205,588.10                           | 3,906,173.90         | 13,466,020.55          | 23,025,867.20         |
| Bursa        | 1,512,406.29                         | 28,735,719.51        | 99,062,612.00          | 169,389,504.48        |
| Canakkale    | 865,126.53                           | 16,437,404.07        | 56,665,787.72          | 96,894,171.36         |
| Edirne       | 1,755,665.87                         | 33,357,651.53        | 114,996,114.49         | 196,634,577.44        |
| İstanbul     | 345,642.47                           | 6,567,206.93         | 22,639,581.79          | 38,711,956.64         |
| Kırklareli   | 1,067,270.30                         | 20,278,135.70        | 69,906,204.65          | 119,534,273.60        |
| Kocaeli      | 149,094.91                           | 2,832,803.29         | 9,765,716.61           | 16,698,629.92         |
| Sakarya      | 643,708.91                           | 12,230,469.29        | 42,162,933.61          | 72,095,397.92         |
| Tekirdağ     | 1,706,775.31                         | 32,428,730.89        | 111,793,782.81         | 191,158,834.72        |
| Yalova       | 28,166.39                            | 535,161.41           | 1,844,898.55           | 3,154,635.68          |
| Total        | 9,375,558.91                         | 178,135,619.29       | 614,099,108.61         | 1,050,062,597.92      |

1 tonne = 1.162 megawatt-hour >>

| Province      | Amount of agricultural waste (tonne) | Scenario 1: 16.351 USD/MWh | Scenario 2: 56.368 USD/MWh | Scenario 3: 0.096 USD/kWh |
|---------------|--------------------------------------|----------------------------|-----------------------------|---------------------------|

Source: Calculated by the authors using data from Maltsoglou et al. (2016) and MENR (2019)
As in the case of crop waste costs, livestock manure costs are calculated based on two elements: collection costs (Table 5) and feedstock costs (Table 6). First of all, collection and feedstock costs per kWh are calculated and then added to find the total cost (Table 7). Again, as had been the case with the agricultural waste calculations, costs are calculated solely on the basis of the weight of wastes in the provinces, since other indicators (machinery, labor, capital investment, etc.)

Table 4. Estimated total costs per kWh for agricultural wastes in provinces

| Province | Amount of agricultural waste (tonne) | Direct combustion | Total cost for cogeneration (CHP) |
|----------|--------------------------------------|-------------------|----------------------------------|
|          | ScENARIO 1: 0 USD/t + Scenario 1: 19 USD/t | ScENARIO 2: 150 USD/t + Scenario 1: 65.5 USD/t | ScENARIO 3: 300 USD/t + Scenario 1: 112 USD/t |
| Bahkesir | 1,096,113.83                          | 20,826,162.77     | 236,212,530.37                   | 451,598,898                  |
| Bilecik  | 205,588.10                            | 3,906,173.90      | 44,304,235.55                    | 84,702,297.20                |
| Bursa    | 1,512,406.29                          | 28,735,719.51     | 325,923,555.50                   | 623,111,391.48               |
| Canakkale| 865,126.53                            | 16,437,404.07     | 186,434,767.22                   | 356,432,130.36               |
| Edirne   | 1,755,665.87                          | 33,357,651.53     | 378,345,994.99                   | 723,334,338.44               |
| İstanbul | 345,642.47                            | 6,567,206.93      | 74,485,952.29                    | 142,404,697.64               |
| Kırklareli| 1,067,270.30                          | 20,278,135.70     | 229,996,749.65                   | 439,715,363.60               |
| Kocaeli  | 149,094.91                            | 2,832,803.29      | 32,129,953.11                    | 61,427,102.92                |
| Sakarya  | 643,708.91                            | 12,230,469.29     | 138,719,270.11                   | 265,208,070.92               |
| Tekirdağ | 1,706,775.31                          | 32,428,730.89     | 367,810,079.31                   | 703,191,427.72               |
| Yalova   | 28,166.39                             | 535,161.41        | 6,069,857.05                     | 11,604,552.68                |
| Total    | 9,375,558.91                          | 178,135,619.29    | 2,020,432,945                    | 3,120,713,567                |

1 ton 1.162 megawatt-hour >> 10,894,399.45 MWh 16.351 USD/MWh 185.456 USD/MWh 354.562 USD/MWh
0.016 USD/kWh 0.186 USD/kWh 0.355 USD/kWh

Source: Calculated by the authors using data from Maltsoglou et al. (2016) and MENR (2019)

Table 5. Estimated collection costs per kWh for animal wastes

| Province | Animal waste amount (tonne) | Biogas to electricity |
|----------|-----------------------------|-----------------------|
|          | Scenario 1: 14 USD/t        | Scenario 2: 35 USD/t  | Scenario 3: 55 USD/t |
| Bahkesir | 6,885,871.04               | 96,402,195             | 241,005,486           | 378,722,907 |
| Bilecik  | 614,734.68                 | 8,606,286              | 21,515,714            | 33,810,407  |
| Bursa    | 3,004,653.29               | 42,065,146             | 105,162,865           | 165,255,931 |
| Canakkale| 2,569,039.77               | 35,966,557             | 89,916,392            | 141,297,187 |
| Edirne   | 1,714,313.90               | 24,000,395             | 60,000,987            | 94,287,265  |
| İstanbul | 1,005,106.56               | 14,071,492             | 35,178,730            | 55,280,861  |
| Kırklareli| 1,710,213.94               | 23,942,995             | 59,857,488            | 94,061,767  |
| Kocaeli  | 1,133,270.57               | 15,865,788             | 39,664,470            | 62,329,881  |
| Sakarya  | 2,230,372.77               | 31,225,219             | 78,063,047            | 122,670,502 |
| Tekirdağ | 1,688,142.18               | 23,633,991             | 59,084,976            | 92,847,820  |
| Yalova   | 140,575.46                 | 1,968,056              | 4,920,141             | 7,731,650   |
| Total    | 22,696,294                 | 26,373,093.63 MWh      | 317,748,118 USD       | 794,370,295 USD |

26,373,093.63 MWh 12.048 USD/MWh 30.121 USD/MWh 47.332 USD/MWh
0.012 USD/kWh 0.030 USD/kWh 0.047 USD/kWh

Source: Calculated by the authors using data from Maltsoglou et al. (2016) and MENR (2019)
which can potentially play a part in the cost assessments are excluded in the context of the present study. Thus, the provinces producing more animal wastes are also marked with higher collection and feedstock costs. For the first three scenarios, collection costs are set at USD 14, USD 35, and USD 55 per tonne, leading to 0.012 USD/kWh, 0.030 USD/kWh, and 0.047 USD/kWh, cost levels, respectively (Table 5).

In terms of feedstock costs for animal manure, a similar calculation is applied at prices USD 3, USD 6.5, and USD 10 per tonne for the low, medium, and high scenarios, Table 6.

| Province    | Animal waste amount (tonne) | Scenario 1: 3 USD/t | Scenario 2: 6.5 USD/t | Scenario 3: 10 USD/t |
|-------------|-----------------------------|---------------------|-----------------------|----------------------|
| Bafkirs     | 6,885,871.04                | 20,657,613          | 44,758,162            | 68,858,710           |
| Bilecik     | 614,734.68                  | 1,844,204           | 3,995,775             | 6,147,347            |
| Bursa       | 3,004,653.29                | 9,013,960           | 19,530,246            | 30,046,533           |
| Canakkale   | 2,569,039.77                | 7,707,119           | 16,698,759            | 25,690,398           |
| Edirne      | 1,714,313.90                | 5,142,942           | 11,143,040            | 17,143,139           |
| İstanbul    | 1,005,106.56                | 3,015,320           | 6,533,193             | 10,051,066           |
| Kırklareli  | 1,710,213.94                | 5,130,642           | 11,166,391            | 17,102,139           |
| Kocaeli     | 1,133,270.57                | 3,399,812           | 7,366,259             | 11,332,706           |
| Sakarya     | 2,230,372.77                | 6,691,118           | 14,497,423            | 22,303,728           |
| Tekirdağ    | 1,688,142.18                | 5,064,427           | 10,972,924            | 16,881,422           |
| Yalova      | 140,575.46                  | 421,726             | 913,740               | 1,405,755            |
| Total       | 22,696,294.00               | 68,088,882          | 147,525,912           | 226,962,942          |

| Province    | Animal waste amount (tonne) | Scenario 1: 14 USD/t + | Scenario 2: 35 USD/t + | Scenario 3: 55 USD/t + |
|-------------|-----------------------------|-------------------------|-------------------------|-------------------------|
| Bafkirs     | 6,885,871.04                | 117,059,808             | 285,763,648             | 447,581,618             |
| Bilecik     | 614,734.68                  | 10,450,490              | 25,111,489              | 39,957,754              |
| Bursa       | 3,004,653.29                | 51,079,106              | 124,693,112             | 195,302,464             |
| Canakkale   | 2,569,039.77                | 43,673,676              | 106,615,150             | 166,987,585             |
| Edirne      | 1,714,313.90                | 29,143,336              | 71,144,027              | 111,430,404             |
| İstanbul    | 1,005,106.56                | 17,086,812              | 41,711,922              | 65,331,926              |
| Kırklareli  | 1,710,213.94                | 29,073,637              | 70,973,879              | 111,163,906             |
| Kocaeli     | 1,133,270.57                | 19,265,600              | 47,030,729              | 73,662,587              |
| Sakarya     | 2,230,372.77                | 37,916,337              | 92,560,470              | 144,974,230             |
| Tekirdağ    | 1,688,142.18                | 28,698,417              | 70,057,900              | 109,729,242             |
| Yalova      | 140,575.46                  | 2,389,783               | 5,833,882               | 9,137,405               |
| Total       | 22,696,294.00               | 385,837,001             | 941,896,208             | 1,475,259,120           |

Table 6. Maximum feedstock costs in three scenarios for animal wastes

Table 7. Total costs for biogas production using animal wastes

| Province    | Animal waste amount (tonne) | Biogas to electricity |
|-------------|-----------------------------|-----------------------|
| Bafkirs     | 6,885,871.04                | 26,373,093.63 MWh     |
| Bilecik     | 614,734.68                  | 14.630 USD/MWh        |
| Bursa       | 3,004,653.29                | 0.015 USD/kWh         |
| Canakkale   | 2,569,039.77                | 0.036 USD/kWh         |
| Edirne      | 1,714,313.90                | 0.055 USD/kWh         |
| İstanbul    | 1,005,106.56                | 26,373,093.63 MWh     |
| Kırklareli  | 1,710,213.94                | 14.630 USD/MWh        |
| Kocaeli     | 1,133,270.57                | 0.015 USD/kWh         |
| Sakarya     | 2,230,372.77                | 0.036 USD/kWh         |
| Tekirdağ    | 1,688,142.18                | 0.055 USD/kWh         |
| Yalova      | 140,575.46                  | 26,373,093.63 MWh     |
| Total       | 22,696,294.00               | 26,373,093.63 MWh     |

Source: Calculated by the authors using data from Maltsoglou et al. (2016) and MENR (2019)
respectively, as per FAO’s assessment (Maltosglou et al. 2016). When animal feedstock costs based on scenarios 1, 2, and 3 are compared to those of crop wastes, animal waste option appears to be more cost-effective, with 0.003 USD/t, 0.006 USD/t, and 0.008 USD/t cost levels, respectively (Table 6). Animal feedstock type also affects the biogas yield. Cow, sheep, and poultry manures used for the analysis have different available dry manure ratios — 65%, 13%, and 99%, respectively — and thus have different calorific values (Başçetinçelik et al. 2006) leading to differences in feedstock cost.

Finally, the collection and feedstock costs for specific scenarios are summed up to come up with the total cost figure for that scenario — 0.015 USD/t, 0.036 USD/t, and 0.055 USD/t, respectively (Table 7). Compared to agricultural wastes, animal wastes are found to be slightly less costly in scenario 1. However, scenarios 2 and 3 present a considerably different picture regarding total costs, when feedstock costs are not zero.

On the other hand, as has been the case for crop waste cost calculation, zero feedstock costs for animal manure are also used as the basis of the fourth scenario. In this case, the total costs of producing biogas from animal wastes have been calculated as 0.012 USD/kWh, 0.030 USD/kWh, and 0.047 USD/kWh, respectively. The corresponding costs for crop wastes were 0 USD/kWh, 0.129 USD/kWh, and 0.258 USD/kWh, as shown above. When feedstock costs are set to zero, the results reveal that, under scenario 1, electricity generation based on crop wastes is more cost-effective. In the case of scenarios 2 and 3, on the other hand, animal wastes should only be preferred if the feedstock cost is equal to zero.

**Discussion**

Marmara Region contains both urban and rural areas, which provide plenty of municipal wastes as well as agricultural and animal wastes. The first category — municipal wastes —, however, is not included in the present analysis, even though Istanbul is a major producer of municipal solid wastes. Nevertheless, all provinces in the region have significant waste potential compared to the amounts of waste produced in other parts of Turkey (MENR 2019). The energy potential of wastes can be tapped either through direct combustion in CHP or conversion to biogas in CHP systems. Total costs per kWh for such electricity generation operations are calculated here, using three distinct scenarios. The assessment methodology is adapted from FAO’s BEFS study.

In the light of the results regarding the total costs presented above, electricity production based on biogas obtained from animal wastes can be considered as the most cost-effective option. However, if feedstock costs are equal to zero, energy production from crop wastes based on scenario 1 is the most preferable option mainly due to the zero collection cost involved. In scenarios 2 and 3, energy production from animal wastes appears to be less costly mainly due to the higher collection costs pertaining to crop wastes, when feedstock costs are set to zero. When feedstock costs are taken into consideration (Tables 3 and 6), it can be concluded that energy production from animal wastes is the most cost-effective option for all scenarios. Energy generation through direct combustion of crop wastes in CHP systems, given the challenges of collecting dispersed material, may seem to be the least preferable option (Table 2). While crop residues can be used for soil amendment and animal feeding, animal manure is primarily considered a fertilizer. Remaining parts of crop residues are left in the field, which could then be used for energy production (Başçetinçelik et al. 2006; Rincon et al. 2019). This is one factor which leads to significant variation in collection costs.

The results obtained reveal that energy production from wastes is a preferable option, especially in the light of subsidies provided in Turkey for electricity generation using biomass, in the context of the Renewable Energy Law no. 6094. The law stipulates a price called the feed-in-tariff, which is a fixed cash-per-kWh figure set by the administration and made available for all eligible renewable energy producers. Feed-in-tariff for electricity generation at biomass-based production facilities (including landfill gas) is 13.3 USD cent/kWh. Furthermore, in case the facility uses equipment manufactured locally, this price can be as high as 18.9 USD cent/kWh (see Supplementary Material (Online Source 1) for subsidized prices for renewable energy sources). The results of the analysis demonstrate that the feed-in-tariff would be economically attractive for some of the alternative scenarios discussed here for electricity generation through either direct combustion or conversion to biogas in CHP plants. When feedstock costs are not set to zero, scenarios 1 and 2 appear profitable for crop wastes, while scenarios 1, 2, and 3 appear profitable for animal wastes in the light of feed-in-tariffs. In case feedstock costs are disregarded, scenarios 1 and 2 can be applied for crop wastes; and all scenarios can be applied for animal wastes, with CHP plants.

Energy potential of feedstock and the amount of heat to be converted to electricity are the main variables to determine the efficiency of CHP systems, in terms of electricity output and capacity. Thus, it is possible to produce the maximum amount of electricity with the maximum feedstock figure, using advanced technologies and the highest energy potential levels. Each type of waste is characterized by a unique composition of carbon, hydrogen, oxygen, nitrogen, and sulfur, and hence, generates a specific heat value or thermal energy potential. In addition to the abovementioned factors, agricultural residues are often exposed to a wide range of environmental conditions in terms of temperature and moisture, which also affect their energy potential. Maltosglou et al. (2016) used values in the
range 10 MJ/kg to 20 MJ/kg range as a shorthand for the energy potential of various types of feedstock analyzed in the present study as well. For instance, based on a number of studies including ECN (2012), Desideri and Fantozzi (2013), Durić et al. (2014), and Maltsoglou et al. reported that residues of hazelnut shells and cotton stalk produce higher levels of energy than sunflower stalk or rice husk, regardless of their availability. Our analysis takes these values provided in Maltsoglou et al. (2016) as given and does not apply a change on any crucial assumptions regarding the energy potential of waste analyzed.5

On the other hand, construction costs for the biogas and biofertilizer production systems using animal wastes are significant factors to be taken into account (Gümüşçü and Uyanık 2010). If heat surplus is to be converted into electricity, substantial investments would be required, although the potential profits are also high (Maltsoglou et al. 2016). Within this context, capital investment requirements are discussed in FAO’s BEFS assessment, with respect to different production scenarios based on different plant capacities (kWe). However, capital investment expenditures are not taken into account in the current analysis.

Additionally, “levelized cost of electricity (LCOE)” is used as an indicator of cost-efficiency of energy generation methods, representing “the average revenue per unit of electricity generated,” to recover the building and operational costs during the financial lifetime of the investment (EIA 2013). A number of variables such as investment expenditures, operation and maintenance and fuel costs, discount rate, and lifetime of the facility are taken into consideration to calculate the LCOE value (IRENA 2019; EIA 2013). In the case of renewable energy technologies, the capital cost plays a most significant part regarding the LCOE, given the substantial capital investment requirements involved. However, with the introduction of newer and more advanced technologies, this cost item falls, providing an advantage for renewable energy sources over fossil fuel-based energy sources (Acar et al. 2015).

According to EIA (2013), it is estimated that the total LCOE value will be 94.83 USD/MWh (0.0948 USD/kWh) (in 2019 prices) for biomass-based plants to enter into service in 2025. The LCOE of bioenergy-fired power generation projects varies in different regions due to different installation costs, feedstock, and technologies involved. While this value was 0.06 USD/kWh in China and India in the period 2000–2018, Europe and North America historically faced higher values (0.08 USD/kWh and 0.09 USD/kWh, respectively). Total installation costs depend on the feedstock types to be used and the technology deployed, and thus may vary from country to country, and region to region. While bioenergy plants using rice husks and bagasse have lower installation costs, those using landfill gas, agricultural waste, and MSWs have slightly higher installation costs. Therefore, bioenergy plants using rice husks and bagasse have lower LCOEs (IRENA 2019).

In Turkey, the LCOE values for 2014 are estimated as 120 USD/MWh (0.12 USD/kWh) for onshore wind projects. It is expected to fall to the 60–80 USD/MWh range (0.06–0.08 USD/kWh range) for similar projects as years go by, whereas the LCOE for coal is between 73 and 116 USD/MWh (0.073–0.116 USD/kWh). Similarly, the LCOE values are estimated to be 85–120 USD/MWh for a ground-mounted solar power project, representing a fall from 150 USD/MWh levels in 2014 (WWF 2014). Due to the lack of data on LCOE for biomass in Turkey, an approximation using the LCOE value in Europe (0.08 USD/kWh) can be utilized. In the light of this figure, scenario 1 for crop residues and all scenarios for animal wastes in our analysis appear to be profitable. Similar conclusions are reached when feedstock costs are set to zero.

On the other hand, one cannot help but notice a downward trend in the cost of renewable energy, when comparing 2018 values with 2017 figures. A fall to the tune of 26% is observed in concentrating solar power (CSP), followed by bioenergy with the rate of 14% (IRENA 2019). As feedstock (agricultural, forestry) and technology costs fall, energy production from biomass can come to compete with other energy sources. Global weighted average LCOE based on biomass was 0.062 USD/kWh in 2018, down from 0.071 USD/kWh in 2017 (IRENA 2019). Additionally, the total installation costs of bioenergy projects fell from 2850 USD/kW in 2017 to 2100 USD/kW in 2018. The installation cost figures were 0.072 USD/kWh for geothermal, 0.047 USD/kWh for hydro, 0.085 for solar photovoltaic, 0.185 concentrating solar power, 0.127 for offshore wind, and 0.056 for onshore wind (IRENA 2019).

To sum up, in the light of the results of this study, biowaste has the potential to become a competitive source for energy production, with certain technologies and in specific scenarios. In the current analysis, the energy equivalents and costs of biowastes lead to the conclusion that bioenergy from wastes would be a preferable energy generation method compared to other energy production methods, in terms of LCOEs.

One of the main objectives of Turkey’s energy policies is to increase the use of domestic resources in electricity generation. The use of biowastes for energy production would help achieve this objective and contribute to reducing the level of dependence on energy imports, thereby helping curb the current account deficit. Feed-in-tariffs have been attractive for electricity generation facilities that are based on renewable energy sources including biomass, and have contributed to the expansion of the sector. Those tariffs have been revised and extended to be implemented from July 2021 and onwards as well. Similar policies and subsidies could be introduced or

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5 Further details regarding the energy potential of the selected agricultural residues can be found in Maltsoglou et al. (2016: 60), table 23.
developed in order to trigger further investments in the field. Moreover, Turkey also pursues waste management strategies as well a zero-waste target with the goal of decreasing the amount of waste generation and reducing the use of natural resources, with the help of a number of methods such as reuse and recycling of wastes.

**Conclusion**

In this study, it has been suggested that animal and agricultural wastes in Marmara Region can be considered as economically attractive options for generating electrical energy. The amounts of agricultural and animal wastes and their energy equivalents in Marmara Region have been evaluated using MENR’s data. Then, costs of producing electricity in CHP plants using wastes have been calculated based on FAO’s assessment. It is concluded that agricultural and animal wastes have a substantial potential. Cultivating energy crops or other conventional energy production methods are not included in this analysis, due to environmental and energy security concerns.

Calculations to determine energy equivalents and costs at provincial level in Marmara Region led to the conclusion that biowastes can theoretically provide more than half of the electricity consumption of the region. Besides, it appears that energy generation using wastes also stands out as an economical option under various scenarios. On the other hand, using agricultural and livestock wastes come with certain challenges in terms of logistics including collection and transportation from the fields. Agricultural production with a specific focus on energy poses yet another problem, as it tends to lead to increases in food prices, thus jeopardizing food security. It may also lead to environmental problems such as loss of biodiversity, monocropping, soil degradation, and water pollution. Within this context, utilizing wastes as emphasized in this study, instead of producing crops for energy in arable lands, appears an ever more preferable option. Moreover, various subsidies provided for renewable energy projects can make it easier to devise a strategy for effective energy generation techniques using wastes, and thus contributing to the development of the renewable energy market. Besides, biowaste-based energy generation systems can help alleviate crucial environmental and climate concerns.

**Abbreviations**

BEFS, Bioenergy and food security approach of FAO; CSP, Concentrating solar power; CHP, Combined heat and power; EIA, U.S. Energy Information Administration; EMRA, Energy Market Regulatory Authority, Turkey; FAO, Food and Agriculture Organization of the United Nations; GHG, Greenhouse gas; GW, Gigawatt; GWh, Gigawatt-hours; IEA, International Energy Agency; IRENA, International Renewable Energy Agency; kha, Kilohectares; kWe, Kilowatt-electric; kWh, Kilowatt-hours; LCOE, Levelized cost of electricity; m³, Cubic meter; MENR, Ministry of Energy and Natural Resources, Turkey; MJ, Megajoules; MSW, Municipal solid wastes; Mtoe, Million tonne(s) of oil equivalent; MWh, Megawatt-hours; t, Tonnes; TETC, Turkish Electricity Transmission Company; TL, Turkish Lira; toe, Tonne(s) of oil equivalent; TurkStat, Turkish Statistical Institute; USD, US dollar

**Author contribution**

SO and SA both contributed to the study conception and design. Material preparation, data collection, and analysis were performed by SO and SA. The first draft of the manuscript was written by SO and SA and both authors commented on previous versions of the manuscript. Both authors read, worked in the final revisions of, and approved the final manuscript.

**Data availability**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests**

The authors declare no competing interests.

**References**

Acar S, Kitson L, Bridle R (2015) Subsidies to coal and renewable energy in Turkey. Manitoba. International Institute for Sustainable Development. Canada

Acar S, Yelden AE (2016) Environmental impacts of coal subsidies in Turkey: a general equilibrium analysis. Energy Policy 90:1–15. https://doi.org/10.1016/j.enpol.2015.12.003

Achinas S, Achinas V, Jan G, Euverink W (2017) A technological overview of biogas production from biowaste. Engl J 3:299–307. https://doi.org/10.1016/J.ENG.2017.03.002

Ayhan A (2016) Biogas potential from animal waste of Marmara Region—Turkey biogas potential from animal waste of Marmara Region-Turkey. Celal Bayar Üniversitesi Fen Bilimleri Dergisi. 15(2):171-174. https://doi.org/10.18466/cbayarfbe.492880

Başçentinelik A, Öztürk HH, Karaca C, Kaçır M, Kayd A, Baban A, Güneş K, Komitti N, Barnes I. et al (2006) A guide on exploitation of agricultural residues in Turkey. EU Life Program Project, Project No: LIFE03 TCY/TR/000061

Bhatia SK (2018) Biowaste-to-bioenergy using biological methods—a mini-review. Energy Convers Manag 177:640–660. https://doi.org/10.1016/j.enconman.2018.09.090

Bioenergy Europe (2019) Biomass for energy: agricultural residues and energy crops. Bioenergy Explained https://bioenergyeurope.org/article/204-bioenergy-explained-biomass-for-energy-agricultural-residues-energy-crops.html. Accessed 20 April 2020

Biyodizel Sanayi Derneği (2019) Biyodizel Endüstrisi Raporu 1 Biodiesel Industry Report 1. http://www.biyodizel.org.tr/asset/pdf/biyodizel.pdf. Accessed 4 April 2020

Camia A, Robert N, Jonsson K, Pilli R, Garcia Condado S, Lopez Lozano R, Van Der Velde M, Ronzon T, Guiria Albucap P, M’harek R, Tamosiunais S, Fiore G, Dos Santos Fernandes De Araujo R, Hoeffinher N, Marelli L, Giuntoli J (2018) Biomass production, supply, uses and flows in the European Union: first results from an integrated assessment, EUR 28993 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-77236-8
Silayo DA, Katani JZ, Maliondo SMS, Tarimo MCT (2008) Forest plantation for biofuels to serve natural forest resources. Working Papers of the Finnish Forest Research Institute 98:115–124

Silva Lora EE, Escobar Palacio JC, Rocha MH, Grillo Renó ML, Venturini OJ, Almazán del Olmo O (2011) Issues to consider, existing tools and constraints in biofuels sustainability assessments. Energy 36:2097–2110. https://doi.org/10.1016/j.energy.2010.06.012

Solomon BD (2010) Biofuels and sustainability. Ann N Y Acad Sci 1185:119–134. https://doi.org/10.1111/j.1749-6632.2009.05279.x

Sözer S, Yaldiz O (2011) Muz serası biyogaz üretimi için Ankara’nın başlıca organik atık kaynakları [Major organic waste sources in Ankara for biogas production]. Bitlis Eren Üniversitesi Ziraat Fakültesi Dergisi 24:75–78

Statista.com (2020). Fuel ethanol production worldwide in 2019, by country (in million gallons). https://www.statista.com/statistics/281606/ethanol-production-in-selected-countries/. Accessed 12 April 2020

Şenol H, Elibol E.A, Açıkel Ü, Şenol M (2017a) Biyogaz üretim için Ankara’nın başlıca organik atık kaynakları [Major organic waste sources in Ankara for biogas production]. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi 6:2:15-28.

Şenol H, Elibol E.A, Açıkel Ü, Şenol M (2017b) Türkiye’de Biyogaz Üretimi İçin Başlıca Biyokütle Kaynakları [Primary biomass sources for biogas production in Turkey]. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi 6:81–92

The World Bank (2015) Fossil fuel energy consumption (% of total) – Turkey https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?locations=TR. Accessed 15 March 2020

The World Bank (2018) Rural population (% of total population) – Turkey. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?display=graph&%2D%2D%3E&end=2018&locations=TR&start=1960. Accessed 18 April 2020

Turkish Electricity Transmission Company (TETC) (2020) Türkiye Elektrik Üretim-Tüketim istatistikleri [Electricity production-consumption statistics for Turkey]. https://www.teias.gov.tr/tr-TR/turkiye-elektrik-uretim-tuketim-istatistikleri. Accessed 15 May 2020

TurkStat (2018) https://biruni.tuik.gov.tr/bolgeselistedistik/degiskenlerUzerindenSorgula.do#. Accessed 15 March 2020

Ulusoys Y, Ulukardesler AH, Arslan R, Tekin Y (2021) Energy and emissions benefits of chicken manure biogas production: a case study. Environ Sci Pollut Res 28:12351–12356. https://doi.org/10.1007/s11356-018-3466-0

Weiland P (2003) Production and energetic use of biogas from energy crops and wastes in Germany. Appl Biochem Biotechnol 109:263–274. https://doi.org/10.1385/ABAB:109:1-3:263

World Energy Council (2016) 23rd World Energy Congress, Turkish Energy Market Outlook Achievements, Overview and Opportunities, October, 2016, Istanbul. https://www.dunyaenerji.org.tr/wp-content/uploads/2017/10/turkish-energy-market-outlook.pdf. Accessed 9 April 2020

WWF (2014) Turkey’s renewable power: alternative power supply scenarios for Turkey. http://awsassets.wwftr.panda.org/downloads/wwf_turkey___bnef___turkey_s_renewable_power___alternative_power_supply_scenarios_until_.pdf. Accessed 20 April 2020

Yağlı H, Koç K (2019) Hayvan Gübresinden Biyogaz Üretim Potansiyelinin Belirlenmesi: Adana İlinden Mezofilik Fermantasyon Sonucu Üretilebilecek Biyogaz Miktarının Belirlenmesi Üzerine Bir Araştırma [A research on determination of biogas production from mixture of banana greenhouse wastes and cattle manure]. Akdeniz Üniversitesi Ziraat Fakültesi Dergisi 34(1):47–56

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