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District heating and electricity production based on biogas produced from municipal WWTPs in Turkey: A comprehensive case study

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ABSTRACT

In this paper, district heating (DH) potentials of the wastewater treatment plants (WWTPs) based on their biogas, electricity, and heat productions are considered. Two district heating scenarios are developed: *(i) DH Scenario I* which is based on both excess biogas storage of the WWTP and exhaust gas of the cogeneration with the actual power output, *(ii) DH Scenario II* which is based on the exhaust gas of the cogeneration with the increased power output using all the biogas produced. In DH Scenario I, it is found that 458 dwellings can be heated via the DH system proposed considering only the waste heat of the cogeneration. In addition, the natural gas consumption of 1112 dwellings with the same annual heating load can also be met using the purified biogas. In DH Scenario II, the electricity production could be increased to 1643 kWh by burning all the biogas produced in the cogeneration plant. In this scenario, the annual heating load of 755 dwellings in Gaziantep province can be covered using the waste heat in the DH system. The payback period for the DH Scenario I is calculated as 2.5 years, while for the DH Scenario II, it is obtained as 2 years.

Credit author statement

A.Abusoglu: Methodology, Conceptualization, Writing – review & editing, Supervision. A.Tozlu: Resources, Conceptualization, Methodology, Investigation, Editing. A.A-Moghaddam: Review & Editing.

1. Introduction

Products derived from renewable sources such as biogas, landfill gas, and pyrolysis gas are secondary energy sources. They are converted into end-point energy, which is the energy provided in the form of, for example, district heating and electricity for the final users. Biogas is rich in carbon but is not yet a fossil material. The most common method in a wastewater treatment facility is to transform biomass, which is in the form of sewage sludge, into a gaseous secondary energy source (biogas) using anaerobic decomposition. The anaerobic digestion process was reported to be a well-established technology used to thermally stabilize the sewage sludge allowing the recovery of energy to provide self-generated renewable electricity and heat [1]. A large proportion of the studies available in open-access literature on removing sewage sludge, a by-product of the wastewater treatment plants that are generally regarded as useful, focused on energy recovery using sludge [2–5]. The stabilization of sewage sludge in anaerobic digestion tanks at different temperature ranges, enrichment of the methane content and purification of the produced biogas, and optimization of the total biogas production through the use of anaerobic digestion systems were discussed in several published studies [6–10].

1.1. Anaerobic sludge digestion process and biogas production in wastewater treatment plants

The biogas production of a WWTP consists of a series of steps, in brief, starting with tertiary treatment of sewage (flotation and sludge thickening), followed by the anaerobic digestion process and biogas production, and ending with dewatering of the digested sludge (see Fig. 1).

Anaerobic digestion is composed of four consecutive sub-

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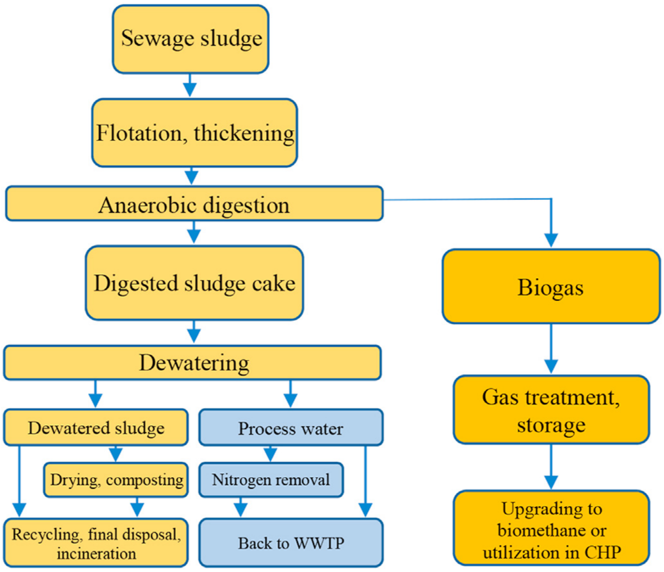


Fig. 1. Schematic of sludge stabilization in a WWTP.

processes that are realized by different population of microorganisms: Hydrolysis (conversion of insoluble biopolymers into soluble organic compounds), acidogenesis (conversion of soluble organic compounds into volatile fatty acids (VFA) and carbon dioxide (CO_2)), acetate formation (conversion of volatile fatty acids into acetate and hydrogen (H_2)) and methane production (conversion of acetate, carbon dioxide and hydrogen into methane) [11,12]. The sludge putrefaction process occurs at two different temperature ranges: Mesophilic (20–40 °C) and thermophilic (50–60 °C). While mesophilic putrefaction requires relatively smaller reactor volumes, thermophilic putrefaction is preferred in processes in which the removal of infectious pathogens is preferred from the waste since the process takes place at higher temperatures. Sludge residence time is one of the most critical parameters in the anaerobic sludge putrefaction process in principle. A sludge residence time of 15–30 days at 25 °C was reported to be required to allow for the methane formation, hydrolysis, and acidification of the fats [13,14]. Lower temperatures reduce the rate of methane production, and therefore longer residence times would be required.

Biogas is a volumetric gaseous mixture of 50–75% methane (CH_4), 25–45% carbon dioxide (CO_2), 0.1–1.5% hydrogen sulphide (H_2S) and 0.01–0.05% ammonia (NH_3). Biogas is saturated with water vapor, and it may contain dust particles, hydrogen (H_2), nitrogen (N_2), and carbon monoxide (CO) in trace amounts depending on the content of the waste sludge and due to the nature of the anaerobic putrefaction process. The upper and lower calorific value of biogas containing 50–75% methane by volume varies between 22 and 30 MJ/m^3 and 19–26 MJ/m^3, respectively [15]. The biogas produced via the anaerobic sludge putrefaction process may either be used in heat and electricity generation in cogeneration plants or used to enhance the contents of the natural gas [16].

1.2. District heating based on biogas and waste heat in the European Union

In large-scale DH implementations designed for the cities, hot water or saturated steam obtained during the cooling of the working fluid in thermal power plants or waste heat obtained from local industrial sites are generally used. In smaller DH applications, the waste heat of combined heat and power production systems is utilized [17–19]. The use of renewable energy possibilities in DH has been investigated in many studies [20–33]. A large proportion of the studies available in the open-access literature focused on geothermal energy use in DH applications [28–33]. The main reason for this is that the temperatures of some geothermal sources are suitable for space heating rather than power generation.

As of the end of 2018, biomass-dependent energy production contributed an estimated 12% (approximately 45.2 EJ) to total global final energy consumption [34]. Excluding conventional biomass, the energy generated from biomass with high technology aid as a requirement of urban infrastructure services was around 19.3 EJ, which meets 5.1% of the total global energy demand. Energy obtained from biomass and biogas provided approximately 13.2 EJ of heat to buildings in 2018, approximately 0.7 EJ of this amount belonged to heating supply by DH [35]. Bioenergy use in DH increased by an average of 5.7% annually between 2013 and 2018, and bio-heat accounted for 95% of the heat supplied to DH systems from renewable sources in 2018. It was reported that as of the end of 2017, there were around 6000 DH networks in the EU countries, and they met 12% of the total heat demand [36]. Holzleitner et al. [37] stated that in the EU's strategy for heating and cooling, two significant subjects are considered: The carbon emission reduction potential of DH with increased energy efficiency and the use of renewable energy sources. Thus, with this strategy, the EU accepts that DH will be a premise solution for supplying renewable and sustainable heat and that waste heat sources should be utilized effectively. According to one of the recent studies by the United Nations, more than half of the world's population lives in cities [38]; in the EU, this corresponds to about 75% of the population [39]. Residential buildings in the urban areas are the principal consumers of district heating and cooling. Heating and cooling needs in buildings vary according to the type of houses, energy standards for buildings, and of course, the climatic conditions. Buildings built before 1960, when the residences were regulated by a certain standard set by the EU, constitute approximately half of the total estimated 250 million residences in the union [39]. Heating requirements differ significantly in the countries within the union, both due to the renovation of the old buildings for efficient heating and cooling and the different climate zones of the EU countries. The heat supplied to residential buildings through district heating is approximately half of the total heat consumed in the residential sector (see Fig. 2) [40].

One of the technology cooperation and implementation programs that the International Energy Agency (IEA) is currently actively conducting is the bioenergy program, and in Task 37, the economic and environmental sustainability of biogas production via anaerobic digestion is investigated [36]. In the Task 37 report [41], biogas production is classified according to the following plant types: Wastewater treatment plants (WWTPs), landfill, bio-waste, agricultural, and industrial. Table 1 presents, as of 2019, the numbers of wastewater treatment plants in Task 37 member countries in the European Union and the total amounts of energy produced from biogas, which is obtained anaerobically from sewage sludge. In this table, the ratio of the amounts of energy obtained from biogas from wastewater treatment plants of member countries within the biogas resources classified by the IEA under Task 37 is also given.

Since the biogas obtained from wastewater treatment systems for electricity and heat generation are discussed in this study, only these productions of the countries listed in Table 1 are focused. The EU strongly supports the use of DH systems that work in integration with combined heat and power (CHP), cogeneration, and trigeneration cycles to encourage renewable energy sources and reduce the use of fossil fuels and associated emissions. According to the EU "Energy Efficiency Directive" (2012/27/EU) [42], within the

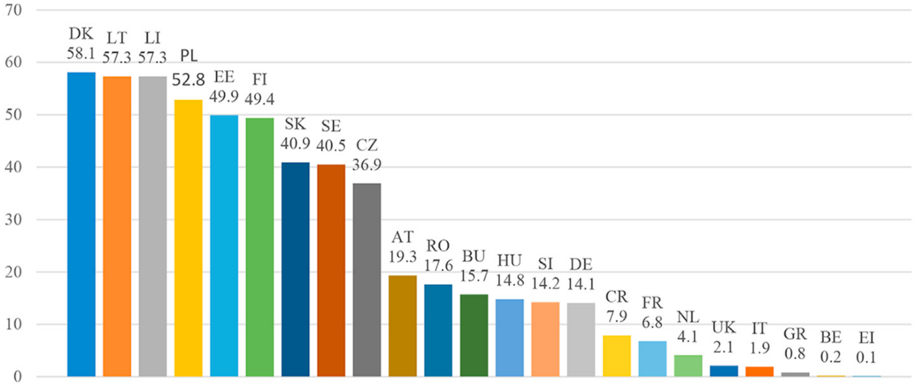


Fig. 2. Percentages of residential heat supply from DH in EU countries and UK (Adapted from Ref. [40]).

Table 1
Status of biogas production in WWTPs and energy utilization in Task 37 member states in the EU and United Kingdom based on IEA Bioenergy [41].

Task 37 Member States in EU	Number of WWTP plants	Energy (electricity + heat) production based on biogas obtained in WWTPs (GWh/year)	Share (%)
Austria	80	158.06	28.00
Denmark	51	308.00	8.30
Estonia	4	0.30	3.34
Finland	16	162.00	23.00
France	88	442.00	12.00
Germany	1,274	3,657.00	7.00
Ireland	15	No data	No data
Sweden	138	715.00	35.00
Switzerland	473	633.00	43.50
Netherlands	80	640.00	18.00
United Kingdom[a]	163	1,483.00	15.09

[a] United Kingdom left the EU on January 31, 2020.

framework of the 20-20-20 targets of the EU (20% increase in energy efficiency, 20% reduction in carbon dioxide emissions, 20% of the use of renewable energy sources by 2020) member states must set indicative energy efficiency targets based on their primary and final energy consumption, energy savings and energy intensities. Considering the data in Table 1, according to the source types determined in Task 37, the countries with the highest share of electricity and heat generation from WWTPs are Switzerland with 43.50%, Sweden with 35%, Austria with 28%, and Finland with 23%. It is seen that the DH potential to be integrated into WWTPs is high in countries with high energy production shares due to biogas obtained in these systems (see Fig. 3). The major contribution to the significant increase in total biogas production in the EU (from 357 PJ to 654 PJ) between 2010 and 2015 came from biogas produced by anaerobic digestion from wastewater sludge [43]. Denmark is one of the leading countries in spreading district heating applications among EU countries. The country had six large central DH areas with a total heating supply of 67 PJ in 2014 and it was about 56% of the national DH supply. There were also around 400 small and medium-sized DH areas with an annual heating supply of approximately 53 PJ. In 2014, the total DH supply in Denmark amounted to 122 PJ, and 68.9% of all DH was produced in cogeneration with electricity. Using waste heat and exhaust gas of the cogeneration for DH applications and simultaneous power production saves a significant amount of fuel compared to the separate heating and power generations [44] (see Fig. 5) (see Fig. 4).

In this study, first, the current data on wastewater treatment in all geographical regions of Turkey, the number of WWTPs, the total amount of stabilized sewage sludge, annual biogas and electricity productions, or electricity generation potential, are revealed. Then, two different DH scenarios are developed based on the operating and economic data of an existing municipal WWTP located in Gaziantep city. These scenarios are basically designed as projections for establishing an efficient DH system connected to a WWTP. The biogas produced through the anaerobic digestion system and waste heat of the cogeneration will provide heat and power to public housing already located close to the WWTP. The DH systems, designed to be integrated into the existing WWTP, increase the total system efficiency. The data obtained from the scenarios developed to obtain district heating based on this existing WWTP in Gaziantep are used to reveal the potential of each sample city selected from all geographical regions of the country for similar studies. Thus, this work will guide the design of a hybrid system with different renewable energy sources and establish an energy hub. This study has the quality of being the very first paper that presents the current inventory of Turkey's sewage sludge-based energy recovery potential in detail, to the best of the authors' knowledge. Besides, the methodology used in the evaluation of the case study is based on the well-established 4e's method: Energy and exergy analyses, exergetic cost-based economic analysis, and environmental assessment. Thus, these two reasons create the main motivation behind this study. When we consider the recent related studies published in the scientific literature, this study is very original in scope within its methodology and scenarios developed based on an existing wastewater treatment plant.

2. An overview of sewage sludge-based bioheat and biopower productions obtained from WWTPs in Turkey

The total number of municipal WWTPs in Turkey reached 991 by the end of 2018 with an approximate capacity of 6,367 Mm^3/year and the annual amount of wastewater treated in these plants was reported approximately as 4,237 Mm^3 [45]. As of 2018, a total of 991 WWTPs with the following breakdown of physical (55), biological

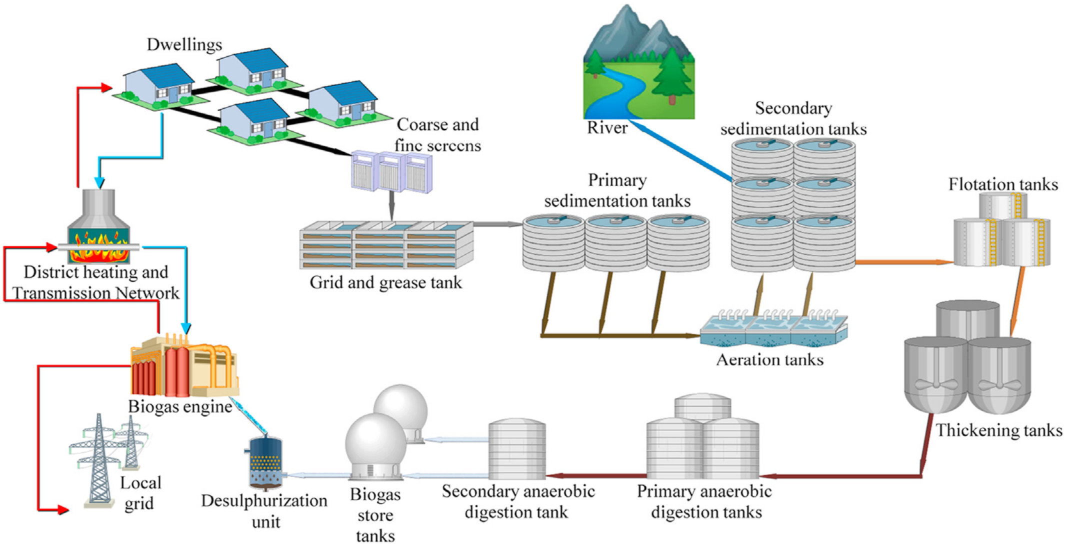


Fig. 3. A schematic of high-grade heat recovery for DH based on BEDC in WWTPs.

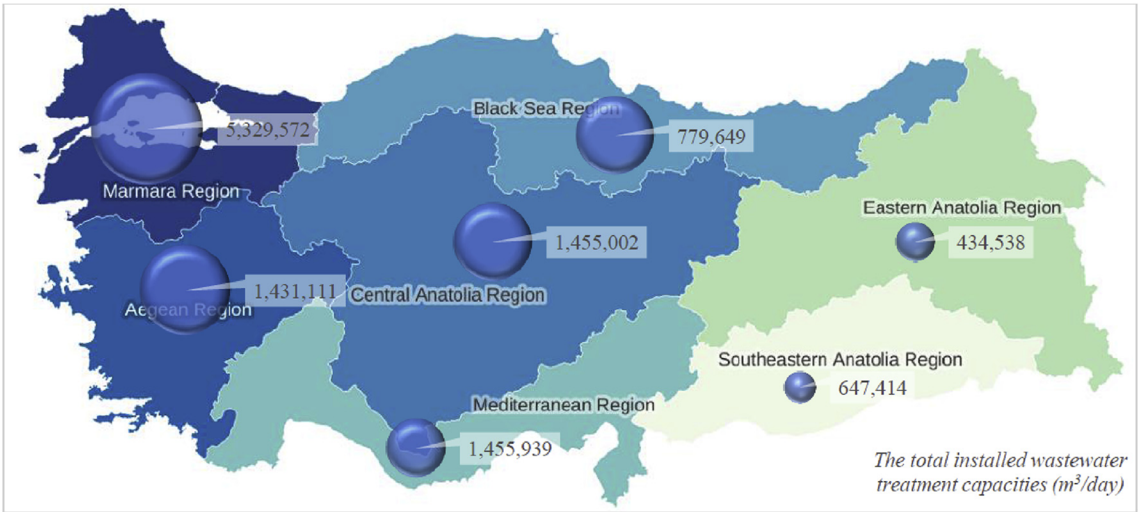


Fig. 4. The total installed capacities of WWTPs in each geographical region of Turkey.

(527), advanced (203) and natural (206) treatment were in operation serving 644 municipalities. Of the total amount of wastewater that was processed in Turkey, 45.3% was processed via advanced treatment, 25.4% via biological treatment, 25.4% via physical treatment and 0.41% via natural treatment (see Tables 2 and 3). The ratio of the Turkey population that was serviced by sewage network managed by a municipality was 91% in 2019 and this corresponds to 90% of the total municipality population. The ratio of the Turkey population that would be serviced by a municipality that has a WWTP is 79% and this corresponds to 83% of the total population that would be registered within a municipality. The average wastewater discharged into the receiving environment per person in the municipalities via the sewage network was determined as 183 L per day in 2019. The distribution of wastewater discharge per person for each geographical region in Turkey is given in Table 3.

The total daily amount of sewage sludge generation in each geographical region of Turkey is extracted from the data of the Turkish Statistical Institute (TUIK) [45]. Herein, it is calculated that 4.73 kg of sewage-sludge is obtained from every 1 m^3 of wastewater in the facility. Thus, the sewage-sludge production can be evaluated depending on the amount of wastewater. Accordingly, the lowest amount of sewage sludge is formed in the Eastern Anatolia Region, where the WWTP capacity is the lowest (2,053 ton-dm/day). In contrast, the highest amount of sludge occurs in the Marmara Region (25,177 ton-dm/day). The total daily amount of sewage sludge obtained in WWTPs of each geographic region of Turkey is given in Table 4. According to the data received from Ref. [45], the total daily amount of sewage sludge produced in the country is calculated as 54,484 ton-dm.

Biogas powered cogeneration systems have been increasingly preferred energy production method in WWTPs of Turkey. On the other hand, it cannot be claimed that all the biogas produced in WWTPs of the country is used for energy conversion. There are only seven WWTPs that currently produce power from the biogas in Turkey. According to the data taken from Ref. [45], as of 2019, Turkey's total installed power capacities of the cogeneration facilities within WWTPs were 10.12 MW. In most of the remaining WWTPs, biogas is not produced since there is no anaerobic sludge

Table 2
The numbers of WWTPs, the facilities' total installed capacities and the annual amounts of treated wastewater in each geographical region (extended sub-regions) of Turkey.

Geographical region	The numbers of WWTPs				The capacities of WWTPs ($\times 10^3$ m^3/year)	The amount of treated wastewater in WWTPs ($\times 10^3$ m^3/year)
	Biological	Natural	Physical	Advanced		
Western Marmara	61	4	1	17	230,567	121,305
Eastern Marmara	41	83	5	37	810,901	486,208
Western Black Sea	44	38	8	9	243,614	139,030
Eastern Black Sea	27	0	26	4	210,921	113,022
Western Anatolia	32	13	0	20	450,607	343,347
Aegean	123	25	0	61	765,869	525,678
Northeastern Anatolia	10	5	0	3	50,023	43,913
Eastern Anatolia	9	0	0	12	143,480	118,314
Southeastern Anatolia	16	3	1	5	343,620	237,809
Middle Anatolia	37	29	4	5	211,384	139,627
Mediterranean	60	5	2	20	783,122	534,799
Istanbul	67	1	8	10	2,122,540	1,433,366
Total	**527**	**206**	**55**	**203**	**6,366,650**	**4,236,419**

Table 3
The total capacities of the WWTPs according to treatment methods and average wastewater discharge per person for each geographical region in Turkey.

Geographical region	The total capacities of WWTPs (x10^3 m^3/year)				Amount of wastewater discharged per person (L/day)
	Biological	Natural	Physical	Advanced	
Western Marmara	120,686	555	13,697	95,630	144
Eastern Marmara	74,109	3,621	34,073	699,098	196
Western Black Sea	88,200	6,522	31,553	117,340	163
Eastern Black Sea	21,723	0,0	168,885	20,313	212
Western Anatolia	321,136	2,638	0,0	126,833	131
Aegean	193,608	5,423	0,0	566,839	168
Northeastern Anatolia	15,584	1,007	0,0	33,432	143
Eastern Anatolia	76,727	0,0	0,0	66,753	182
Southeastern Anatolia	218,069	343	22,265	102,944	141
Middle Anatolia	70,418	4,982	1,465	134,519	154
Mediterranean	499,688	861	541	282,032	207
Istanbul	18,090	46	1,465,387	639,016	262
Total	**1,614,439**	**25,998**	**1,737,866**	**2,884,749**	–

Table 4
The total daily amount of sewage sludge for each geographical region of Turkey.

Geographical region	Abbreviations	Amount of sewage sludge (ton-dm/day)
Marmara Region	MAR	25,177
Aegean Region	AR	6,761
Black Sea Region	BSR	3,683
Central Anatolia Region	CAR	6,874
Eastern Anatolia Region	EAR	2,053
Southeastern Anatolia Region	SAR	3,058
Mediterranean Region	MER	6,878
Total		**54,484**

digestion process in the facilities. However, in the near future, biogas-based power production within WWTPs is among the future targets and projects of the municipalities.

The potential amounts of treated wastewater, anaerobically digested sewage sludge, and biogas production of WWTPs for each geographical region of Turkey are shown in Figures from 4 to 6. Also, electricity production potentials of these WWTPs via biogas engine powered cogeneration are shown in Fig. 7 (see Fig. 9) (see Fig. 10) (see Fig. 11) (see Fig. 12) (see Fig. 13) (see Fig. 14) (see Fig. 8).

The amounts of treated wastewater and stabilized sewage sludge in addition to biogas and electricity production potentials of each of the sample cities chosen from each geographical region of Turkey for this study, which are Istanbul, Denizli, Samsun, Kayseri, Erzurum, Gaziantep, and Adana are shown in Figures from 8 to 14.

The total electricity generation from renewable energy sources of Turkey, while 12,346 GWh in 2014, increased to 38,710 GWh in 2018. This clearly shows that there is a dramatic increase in the utilization of renewable energy sources in Turkey. According to the source types, the distribution of total electricity generation between 2014 and 2018 in Turkey is shown in Fig. 15.

According to the TUIK, as of 2019, only seven WWTPs in Turkey utilized biogas obtained from anaerobic digestion to generate electricity. The total annual installed power output of these plants was 88.476 GW. In 2018, the total annual electricity production of the country was 304,802 GW, and 38,710 GW of it was generated from renewable energy sources. While the total electricity produced from WWTP based biogas was only about 0.029% of the total electricity produced in the country, this ratio was about 0.228% of the electricity generated from all renewable energy sources. Considering the total biogas potential that could be produced from sewage sludge in the WWTPs given in Fig. 6, the total annual electricity production potential of all these facilities in the country would be about 748 GW. This output would correspond to nearly 2% of the total electricity produced from all renewable sources and to

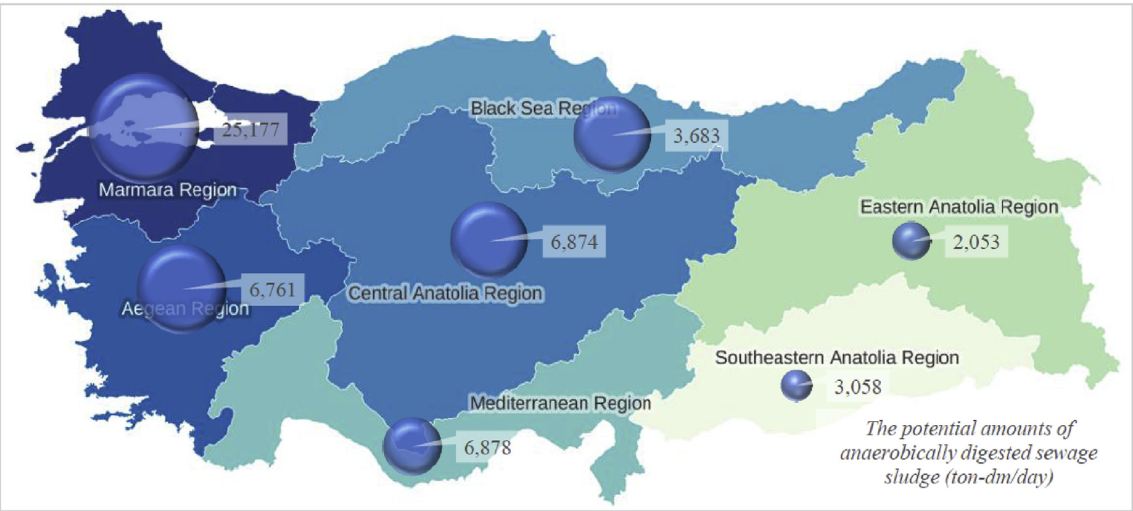


Fig. 5. The potential amounts of anaerobically digested sewage sludge of WWTPs in Turkey.

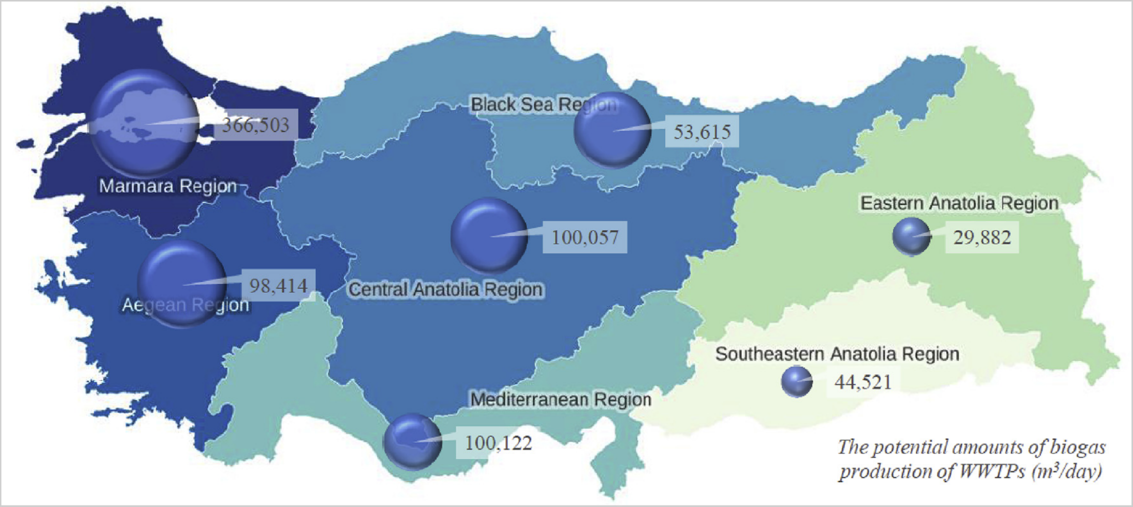


Fig. 6. The potential amounts of biogas production of WWTPs in Turkey.

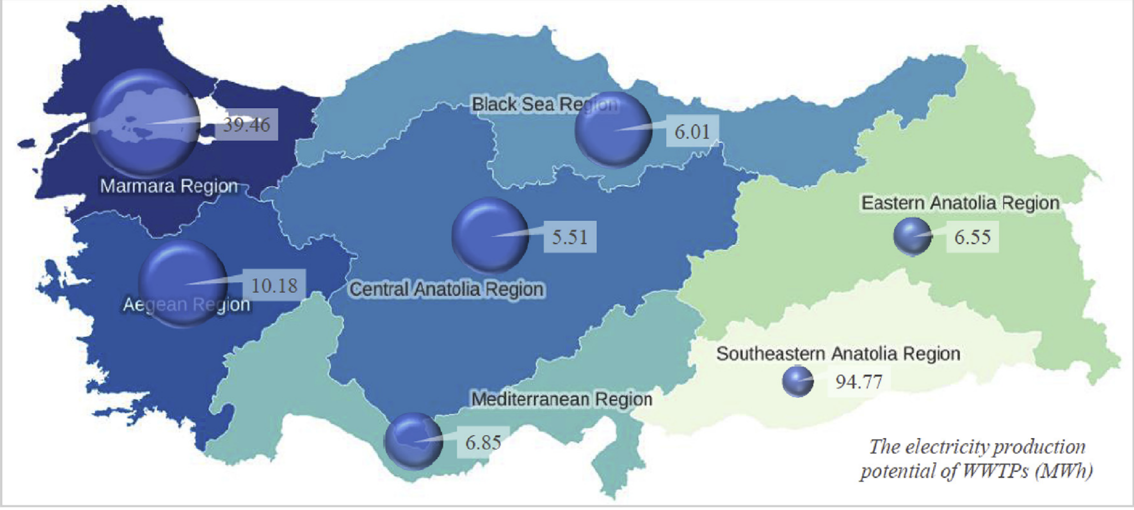
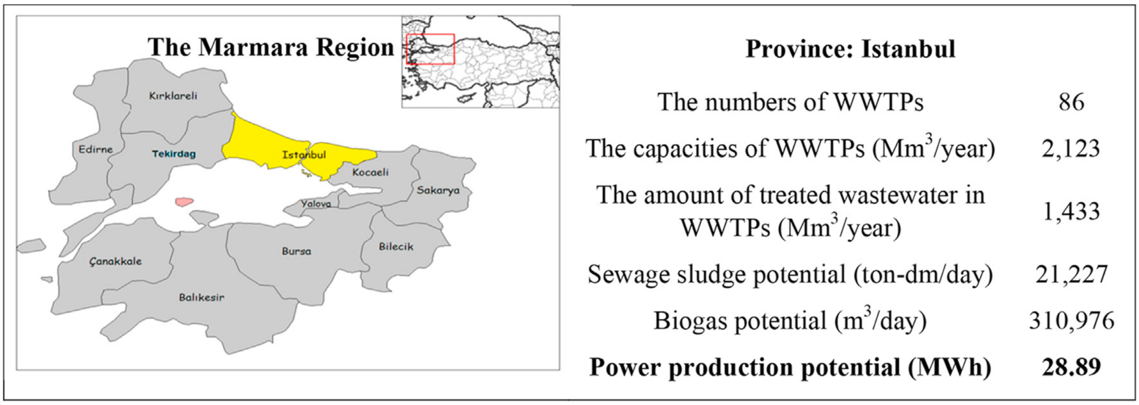


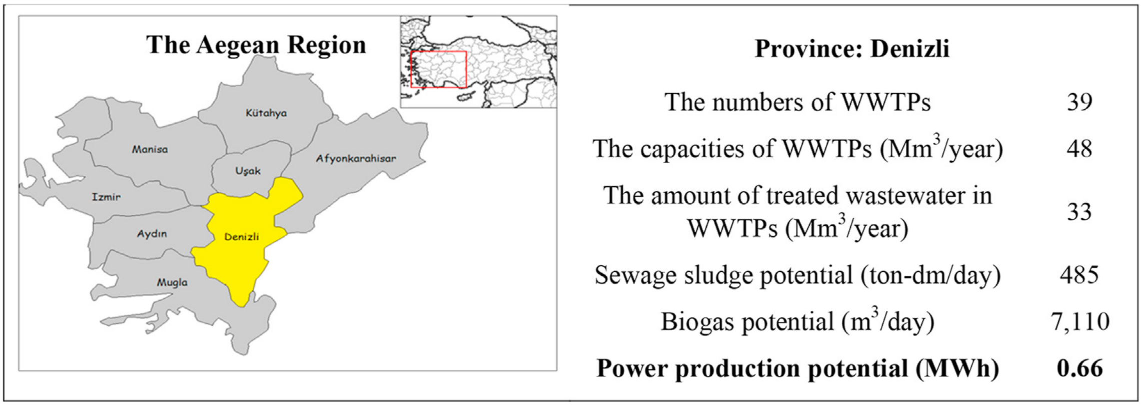
Fig. 7. The biogas-based electricity production potential of WWTPs in Turkey.



Province: Istanbul

The numbers of WWTPs	86
The capacities of WWTPs (Mm^3/year)	2,123
The amount of treated wastewater in WWTPs (Mm^3/year)	1,433
Sewage sludge potential (ton-dm/day)	21,227
Biogas potential (m^3/day)	310,976
Power production potential (MWh)	**28.89**

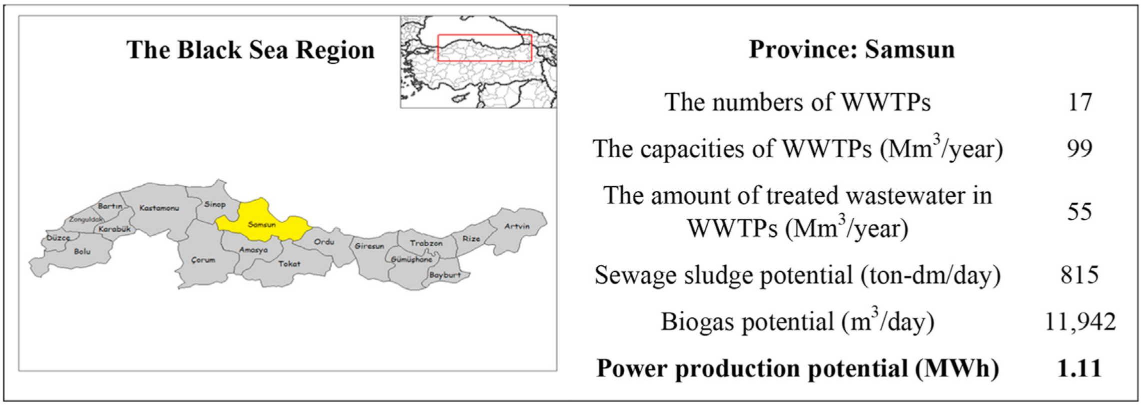
Fig. 8. The current portrait of the energy potential of WWTPs for Istanbul province.



Province: Denizli

The numbers of WWTPs	39
The capacities of WWTPs (Mm^3/year)	48
The amount of treated wastewater in WWTPs (Mm^3/year)	33
Sewage sludge potential (ton-dm/day)	485
Biogas potential (m^3/day)	7,110
Power production potential (MWh)	**0.66**

Fig. 9. The current portrait of the energy potential of WWTPs for Denizli province.



Province: Samsun

The numbers of WWTPs	17
The capacities of WWTPs (Mm^3/year)	99
The amount of treated wastewater in WWTPs (Mm^3/year)	55
Sewage sludge potential (ton-dm/day)	815
Biogas potential (m^3/day)	11,942
Power production potential (MWh)	**1.11**

Fig. 10. The current portrait of the energy potential of WWTPs for Samsun province.

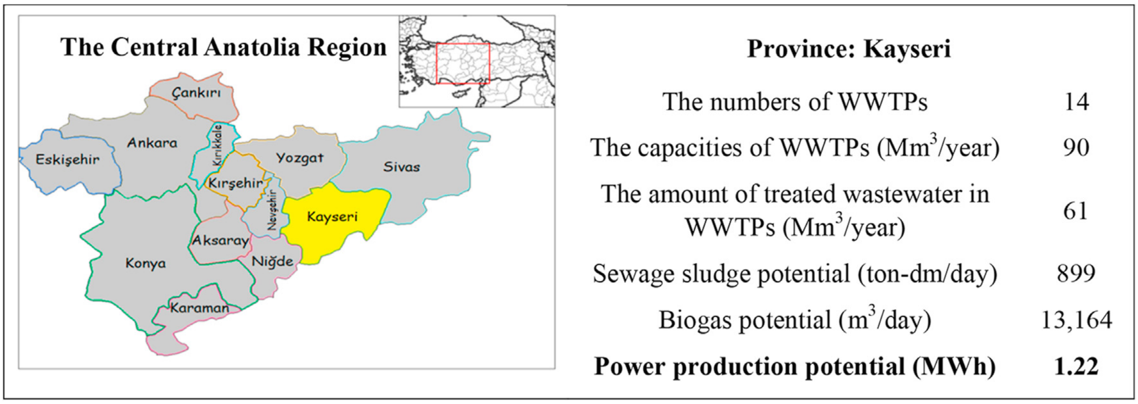
0.245% of the total electricity produced from all sources, including fossil fuels. The bioenergy production potential based on sewage sludge here is significant.

3. The description of a DH system integrated with an existing municipal WWTP in Gaziantep

Gaziantep is one of the oldest cities that connect Anatolia, the Mediterranean, and Mesopotamia, host dozens of civilizations thanks to its geopolitical location, and has a strong historical background blended with the cultures of the civilizations. The city is located between 36° 28′ and 38° 01′ east longitudes and 36° 38′ and 37° 32′ north latitudes. It includes about 1% of 6,222 square kilometers of the land area of Turkey (see Fig. 16).

3.1. *GASKI wastewater treatment plant and biogas engine driven cogeneration (BEDC) system*

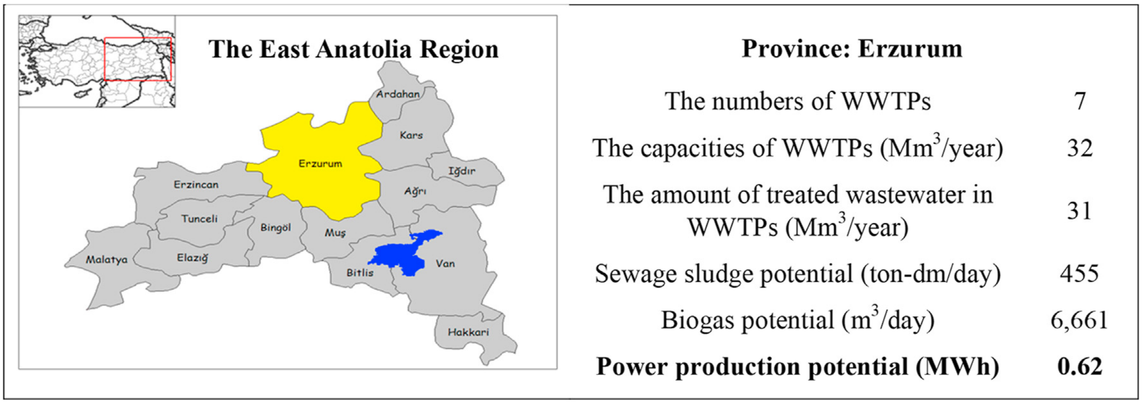
The project contract of the GASKI Wastewater Treatment Plant (WWTP) was signed by the consortium of Gaziantep Municipality Water and Wastewater Works, Gunal Construction Incorporated Company, and Degremont Company (France), in Gaziantep city, in



Province: Kayseri

The numbers of WWTPs	14
The capacities of WWTPs (Mm^3/year)	90
The amount of treated wastewater in WWTPs (Mm^3/year)	61
Sewage sludge potential (ton-dm/day)	899
Biogas potential (m^3/day)	13,164
Power production potential (MWh)	**1.22**

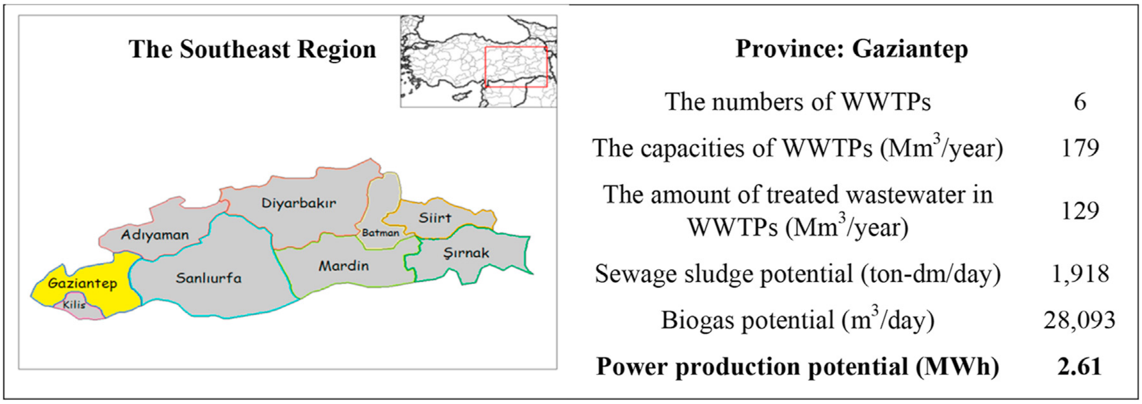
Fig. 11. The current portrait of the energy potential of WWTPs for Kayseri province.



Province: Erzurum

The numbers of WWTPs	7
The capacities of WWTPs (Mm^3/year)	32
The amount of treated wastewater in WWTPs (Mm^3/year)	31
Sewage sludge potential (ton-dm/day)	455
Biogas potential (m^3/day)	6,661
Power production potential (MWh)	**0.62**

Fig. 12. The current portrait of the energy potential of WWTPs for Erzurum province.



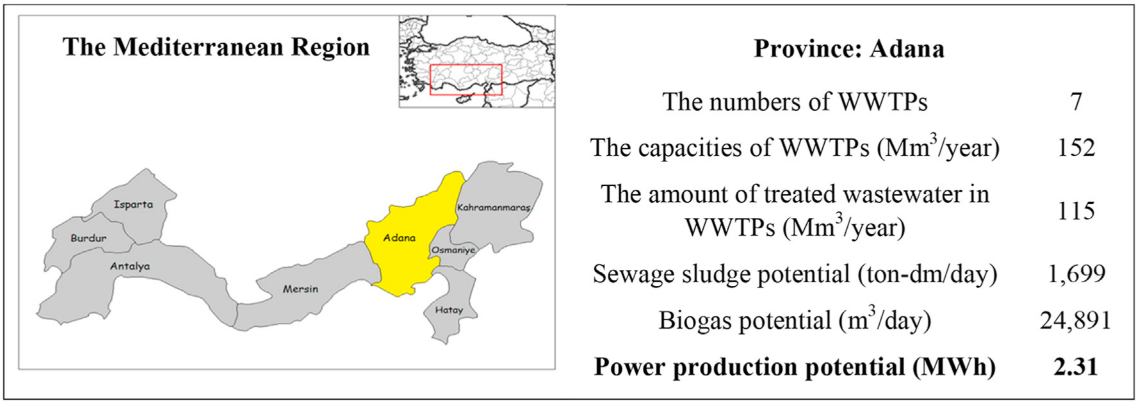
Province: Gaziantep

The numbers of WWTPs	6
The capacities of WWTPs (Mm^3/year)	179
The amount of treated wastewater in WWTPs (Mm^3/year)	129
Sewage sludge potential (ton-dm/day)	1,918
Biogas potential (m^3/day)	28,093
Power production potential (MWh)	**2.61**

Fig. 13. The current portrait of the energy potential of WWTPs for Gaziantep province.

1990. GASKI WWTP was financed by European Social Development Bank with the credit of 56 million US Dollars. Wastewater treatment in the plant was started in 1999. The plant has been serving 1,000,000 equal inhabitants in the city, and the total daily capacity of treated wastewater of the plant is 222,000 m^3 (see Fig. 17). Treated wastewater is discharged to a local river for water irrigation of 80 million m^2 of agricultural land located in the region.

GASKI WWTP - BEDC system was started to operate in 2006. The total capital investment of the system was 1.237 million US dollars. The total installed capacity of power and hot water productions of the BEDC system are 1660 kWh and about 135 tons/h, respectively. The total annual electricity production is 8760 GWh, and the annual biogas consumption is nearly 5.57 Mm^3 at its intended operating conditions. The working principle of the cogeneration system can be viewed elsewhere [46,47]. The system consists of a four-stroke, spark-ignition, 12-cylinder, V-configuration Deutz TCG 2020 brand engine, and other auxiliary equipment (see Fig. 18). The content of the biogas produced in the facility is given in Table 5.



Province: Adana	
The numbers of WWTPs	7
The capacities of WWTPs (Mm^3/year)	152
The amount of treated wastewater in WWTPs (Mm^3/year)	115
Sewage sludge potential (ton-dm/day)	1,699
Biogas potential (m^3/day)	24,891
Power production potential (MWh)	**2.31**

Fig. 14. The current portrait of the energy potential of WWTPs for Adana province.

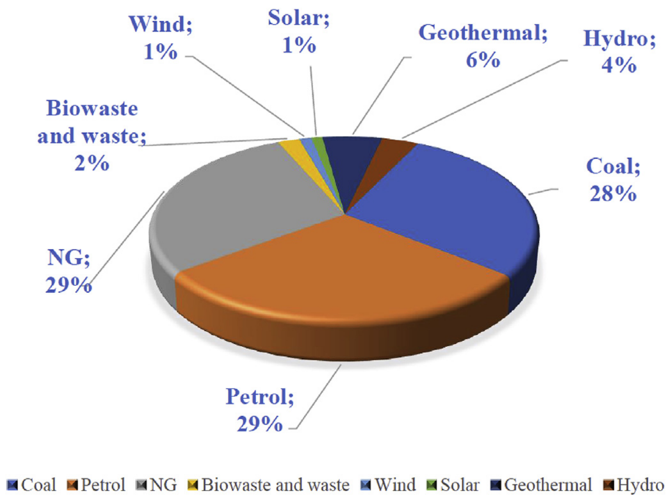


Fig. 15. The distribution of the total electricity production of Turkey by energy sources as of 2018.

3.2. Thermodynamic and thermoeconomic evaluation methodology of the BEDC system

In this study, thermodynamic and thermoeconomic analyses of the district heating scenarios based on WWTP were carried out by using the actual operational data of the facility. The governing thermodynamic and thermoeconomic relations, including economic assumptions used in the analyses, are presented in Table 6. The following assumptions are made for thermodynamic analysis:

- All subsystems in the district heating scenarios operate in the steady-state conditions.
- The values for the reference environment (dead state) temperature and pressure are taken as 20 °C and 1.0 bar, respectively.
- The kinetic and potential energy changes are negligible.
- The pressure losses taking place in the flows of working fluids through the pipes and heat exchangers are negligible.
- The exhaust gas is assumed as air. The exhaust gas and the air are assumed to be handled with sufficient accuracy by the ideal gas model at all states considered in the analysis.

3.3. DH system scenarios developed for the use of the WWTP-based biogas, electricity, and heat productions

In this study, two different district heating scenarios are developed using electricity and heat produced by the BEDC system. The process flows and working principles of these scenarios are presented in the following:

Scenario I: *DH system integration both to excess biogas storage of the WWTP and exhaust gas of the BEDC with the actual power output.*

In this scenario, the existing working conditions, and actual operational data of Gaziantep GASKI WWTP are considered. In the facility, approximately 61% of the biogas obtained is burned to generate electricity in the cogeneration system. The remaining biogas is stored in the facility. In the first district heating scenario, this stored biogas and the waste heat of the exhaust gas discharged from the biogas driven engine are used as energy sources. The schematic layout of the system is shown in Fig. 19.

The exhaust gas-water line: The exhaust gas leaving the engine first flow through the first heat exchanger unit to transfer its heat to the feed water, and then it is released into the atmosphere. The hot water leaving the first heat exchanger is then sent to the second heat exchanger unit near the dwellings to supply district heating depending upon the amount of heat demand of the buildings.

The stored biogas line: The stored biogas in the WWTP must first be putrefied from its carbon dioxide content in the biogas purification unit. For this, biogas leaving the storage tank is pressurized through the compressor unit, and it enters the absorption tower (tower 1) in which it is washed with pressurized water. The washed biogas leaving the absorption tower enters the desorption tower (tower 2) in which it is decomposed to methane and carbon dioxide. Lastly, the biogas with high methane content is sent to the local natural gas line to provide natural gas demand of the dwellings for domestic purposes.

A relatively small amount of carbon dioxide separated from the biogas purification unit is directly released into the atmosphere. As the amount of carbon dioxide emitted from the purification unit increases, it may be a reasonable solution to produce synthetic fuel by combining carbon dioxide with hydrogen. Considering the carbon dioxide emissions resulting from biogas purification, biogas produced from sewage sludge also can potentially provide alternative clean fuel production.

Scenario II: *DH system integration to exhaust gas of the BEDC with*

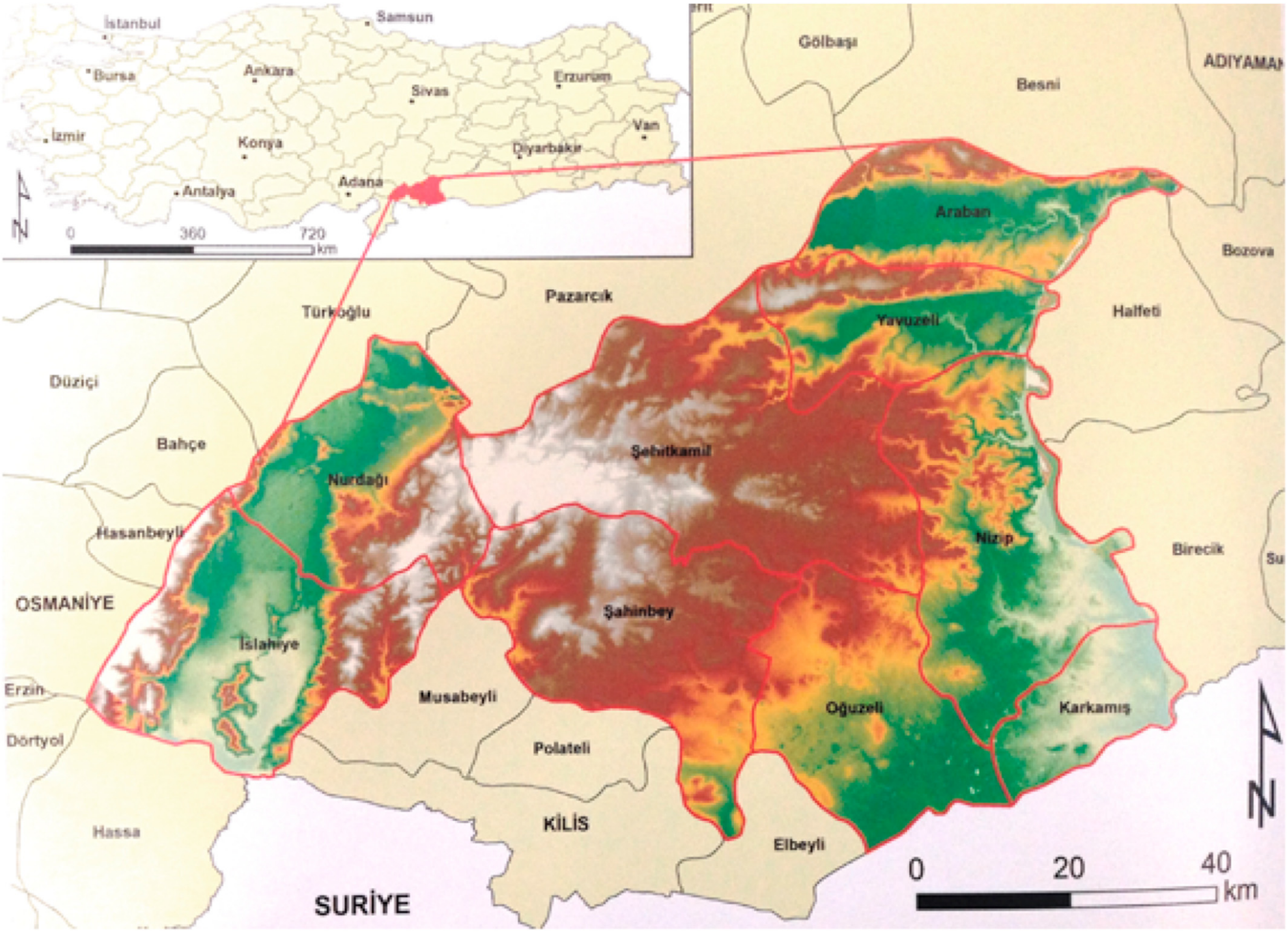


Fig. 16. Location of the Gaziantep city in Turkey.

Fig. 17. Satellite view of the GASKI WWTP (Accessed in October 2020).

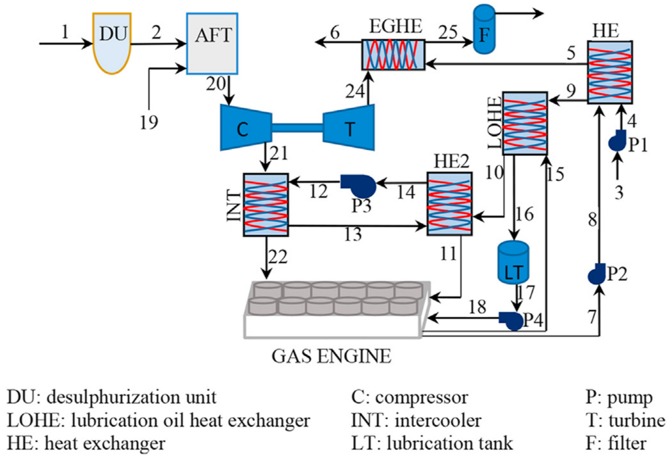


Fig. 18. Schematic of the BEDC system located in the WWTP facility area.

Table 5
The biogas content produced from sewage sludge at GASKI WWTP.[a]

Content	Volumetric value (%)
CH_4	60.00
CO_2	35.00
CO	2.70
N_2	1.50
H_2	0.30
O_2	0.50
H_2S (2500–3000 ppm)	2.50–3.00
LHV (kJ/kg)	17,892
HHV (kJ/kg)	21,250

[a] These values were taken directly from the official activity report prepared by GASKI WWTP management in 2019.

the increased power output using all the biogas produced.

In this scenario, it is assumed that all the biogas produced in the wastewater treatment plant are used in the cogeneration plant to generate electricity. The schematic layout of the second scenario is shown in Fig. 20. Burning all the biogas produced at the facility in the biogas driven engine increases the amount of exhaust gas discharged from the engine. The processes designed to provide district heating after the exhaust gas leaving the engine are the same as in the first scenario, but this time the district heating system developed would provide heat for much more domestic dwellings.

The following assumptions are made for the district heating models developed in both scenarios:

- The district heating network operates in a closed circuit.
- There is no heat loss, water, and natural gas leakages in the pipelines.
- The effectiveness of each heat exchanger in the system is considered as 0.88.

In Table 7, total key indicative emissions for the BEDC plant as well as limit values according to each scenario are given. Data presented in this table was measured by a licensed environmental consultancy and testing company. Determination of pollutant gas emissions such as CO, NO, NO_2, and particulate matter was measured by a portable stack gas analyzer, which is simply an electrochemical gas detector based on an electrolytic measurement cell having a solid organic electrolyte.

4. Results and discussion

4.1. Thermodynamic and thermoeconomic analysis and assessment of WWTP-based DH scenarios

Each DH scenario is divided into three subsystems, as shown

Table 6
The thermodynamic and thermoeconomic governing equations used in the analysis of the WWTP based-district heating scenarios.

Thermodynamic relations		Thermoeconomic relations	
$\Sigma\dot{m}_i = \Sigma\dot{m}_e$	$\dot{m}$; mass flow rate i; inlet e; exit	$\dot{Z} = (PEC*CRF*\varphi)/(3600*N)$	$\dot{Z}$; capital cost rate
$\dot{Q} - \dot{W} = \Sigma\dot{m}_e h_e - \Sigma\dot{m}_i h_i$	$\dot{Q}$; net heat transfer $\dot{W}$; net work transfer h; enthalpy	$CRF = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1}$ $\varphi = 1.06$ $n = 15$ $N = 8040$ $i = 15\%$	CRF; capital recovery factor φ; maintenance factor n; total life time N; annual operation time i_r; interest rate
$\dot{E}x_{Heat} - \dot{W} = \Sigma\dot{m}_e\psi_e - \Sigma\dot{m}_i\psi_i + \dot{E}x_D$	$\dot{E}x_{Heat}$; net exergy transfer ψ; specific flow exergy	$PEC_{HeatExc} = 2681(A_{HeatExc})^{0.59}$ $PEC_{Pump} = 1120(\dot{W}_{pump})^{0.8}$	PEC; Purchased equipment costs $HeatExc$; Heat exchanger
$\psi = (h - h_0) - T_0(s - s_0)$	s; entropy T; Temperature 0; dead state	$\dot{Q}_k = U_k A_k LMTD$	$\dot{Q}_k$; heat exchanger load A_k; heat transfer area k; component
$\dot{E}x = \dot{m}\psi$	$\dot{E}x$; Exergy rate	$U = 0.7$	U; heat transfer coefficient
$\dot{W}_{net} = \dot{m}_{wf}[(h_{t,i} - h_{t,e}) - (h_{p,e} - h_{p,i})]$	$\dot{W}_{net}$; net power	$LMTD = \frac{((T_{H,i} - T_{C,e}) - (T_{H,e} - T_{C,i}))}{\ln\frac{(T_{H,i} - T_{C,e})}{(T_{H,e} - T_{C,i})}}$	$LMTD$; logarithmic mean temperature difference H; hot C; cold
$\dot{Q}_{in} = \dot{m}_{wf}(h_i - h_e)$	$\dot{Q}_{in}$; heat transferred to the working	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k} \cdot \dot{E}x_{D,k}}$	f_k; exergoeconomic factor c_f; unit exergy cost of fuel
$\eta = \left(\frac{energy\ in\ products}{total\ energy\ input}\right) = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$	η; energy efficiency	$r_k = \frac{c_{p,k} - c_{f,k}}{c_{f,k}}$	r_k; relative cost difference c_p; unit exergy cost of product
$\varepsilon = \left(\frac{exergy\ in\ products}{total\ exergy\ input}\right) = \frac{\dot{W}_{net}}{\dot{m}_{wf}(\psi_i - \psi_e)}$	ε; exergy efficiency	$\dot{D}_{D,k} = c_{f,k}\dot{E}x_{D,k}$	$\dot{D}_{D,k}$; exergy destruction cost rate

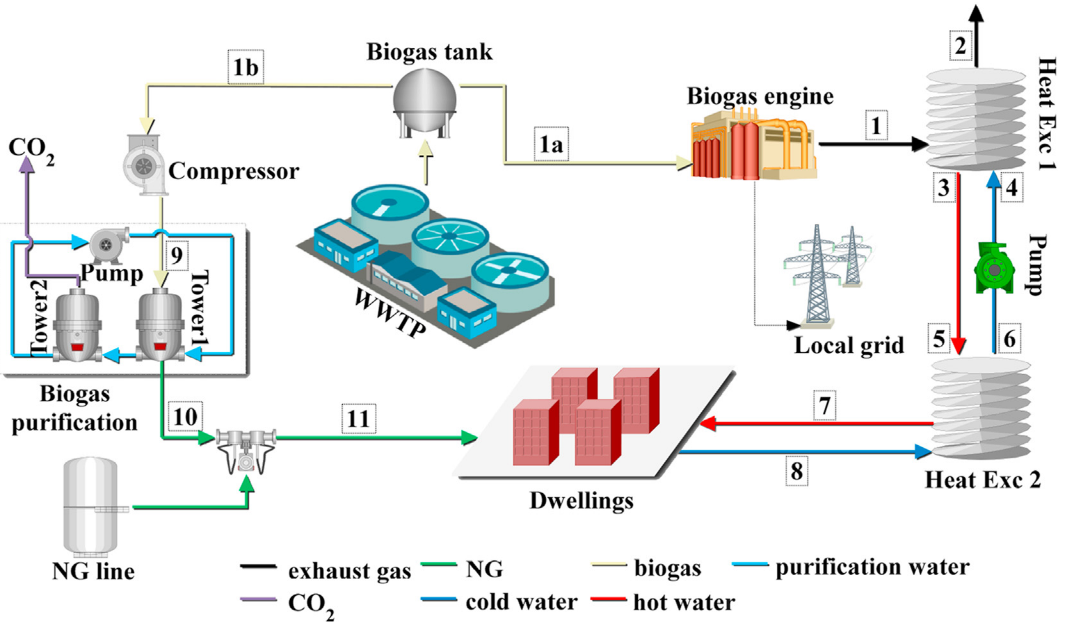


Fig. 19. The schematic layout of the DH Scenario I.

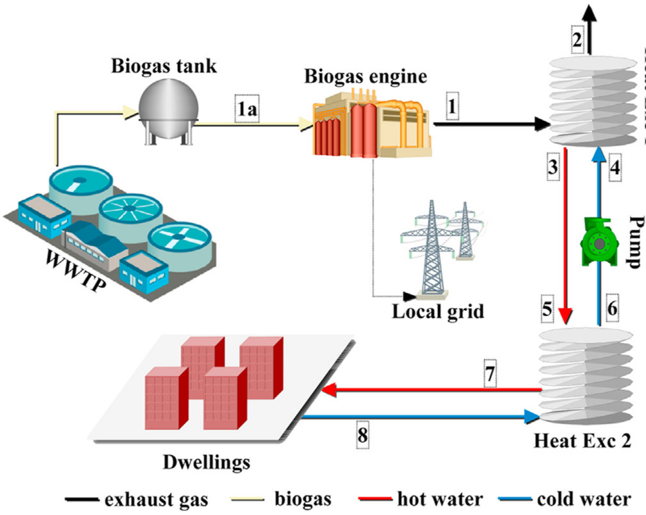


Fig. 20. The schematic layout of the DH Scenario II.

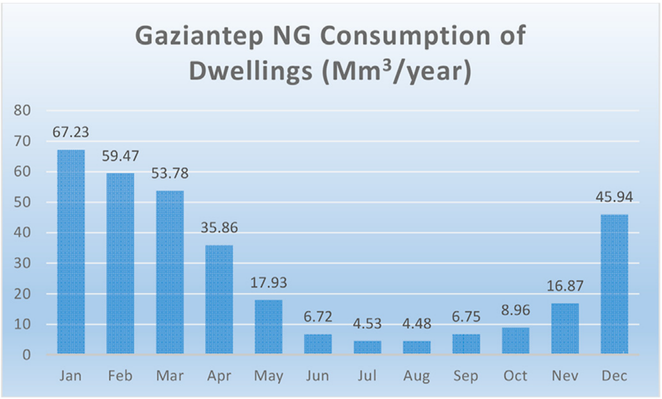


Fig. 21. Natural gas (NG) consumption of dwellings in Gaziantep province by month.

schematically in Figs. 20 and 21. The thermodynamic relations of these subsystems are formulated using the governing equations given in Table 6. The temperature, pressure, and mass flow rate data and specific exergy evaluations of each scenario, according to the nomenclatures shown in Figs. 20 and 21, are presented in Table 8

Table 7
The data of the cogeneration system and emission parameters of the biogas engine according to two separate DH scenarios.

Parameter	Total amounts of engine emissions[a] (kg/h)		Limit values** (kg/h)
	DH Scenario I	DH Scenario II	
NO	23.1042 ± 1.8256	No data	≤40 for total NO_x constituents
NO_2	11.1298 ± 3.5180		
CO	75.6066 ± 1.4898		1000
Particulate matter	10.8237 ± 3.6669		15
Biogas consumption	0.129 kg/s	0.212 kg/s	
Air-fuel ratio	10.75		
Power output	1000 kWh	1600 kWh	
Exhaust gas temperature	460 °C		
Exhaust gas flow rate	1.5 kg/s	2.49 kg/s	

[a] Exhaust emission values are obtained from the plant management, which were available in "Environment Assessment Report", a legal document prepared by a licensed company. **According to the "Air Quality Protection Regulation" [48].

Table 8
Thermodynamic properties of the DH Scenario I.

State	Fluid	*T* (°C)	*P* (kPa)	$\dot{m}$ (kg/s)	*h* (kJ/kg)	*s* (kJ/kgK)	$\dot{E}x$ (kW)
0	Air	20.0	100	–	293.5	4.360	–
0	Water	20.0	100	–	93.2	0.294	–
0	Biogas	20.0	100	–	−4650	11.620	–
0	NG	20.0	100	–	−4661	9.192	–
1a	Biogas	30.1	102	0.129	−4639	11.640	0.6626
1b	Biogas	30.1	102	0.083	−4639	11.640	0.4263
1	Exhaust	360.6	117	1.500	642.9	5.103	197.50
2	Exhaust	71.0	117	1.500	344.8	4.477	25.76
3	Water	130.0	600	1.599	587.9	1.582	175.90
4	Water	70.0	600	1.599	341.9	0.921	97.39
5	Water	130.0	600	1.599	587.9	1.582	175.90
6	Water	70.0	400	1.599	325.6	0.932	68.17
7	Water	68.0	400	4.997	317.4	0.908	66.40
8	Water	50.0	400	4.997	243.6	0.686	53.42
10	NG	20.0	100	0.0498	−4661	9.192	–

Table 9
Thermodynamic properties of the DH Scenario II.

State		*T* (°C)	*P* (kPa)	$\dot{m}$ (kg/s)	*h* (kJ/kg)	*s* (kJ/kgK)	$\dot{E}x$ (kW)
0	Air	20.0	100	–	293.5	4.360	–
0	Water	20.0	100	–	93.2	0.294	–
0	Biogas	20.0	100	–	−4650	11.620	–
1a	Biogas	30.1	102	0.212	−4639	11.640	1.089
1	Exhaust	360.6	117	2.470	642.9	5.103	325.20
2	Exhaust	71.0	117	2.470	344.8	4.477	42.43
3	Water	130.0	600	2.633	587.9	1.582	289.70
4	Water	70.0	600	2.633	341.9	0.9209	160.40
5	Water	130.0	600	2.633	587.9	1.582	289.70
6	Water	70.0	400	2.633	325.6	0.9319	112.30
7	Water	68.0	400	8.229	317.4	0.9079	109.30
8	Water	50.0	400	8.229	243.6	0.6855	87.96

Table 11
The exergy flow rates, cost flow rates and the unit exergy costs associated with each stream of the DH Scenario I. State numbers refer to Fig. 20.

State	$\dot{E}x$ (kW)	*c* ($/GJ)	$\dot{C}$ ($/h)
1	197.5	23.52	16.72
2	25.76	23.52	2.18
3	175.9	51.42	32.56
4	97.39	51.42	18.03
5	175.9	68.29	43.24
6	68.17	68.29	16.76
7	66.4	566.8	135.49
8	53.42	566.8	109.00

and Table 9, respectively. The energy and exergy calculations are done using commercial software with built-in thermodynamic property functions for a variety of substances [49]. Energy and exergy analysis results of DH scenarios are presented in Table 10.

Solving the linear system consisting of related thermoeconomic equations given in Table 6, the cost flow rates and unit exergetic costs associated with each DH scenario can be obtained. These results are given in Table 11 and Table 12.

The exergetic costs for each subcomponent of both DH scenarios are given in Table 13. Herein, the exergetic cost analysis of Scenario I includes the total cost of purifying the stored biogas in the WWTP before it is supplied to the local natural gas distribution line and the hot water heating system's total cost generated by utilizing the waste heat of the cogeneration system. In Scenario II, since district heating is provided using only the waste heat of the cogeneration system, the exergetic costs of the subcomponents of this system are considered. The economic data used for the biogas purification process in Scenario I is taken from Ref. [50].

Considering the WWTP-based DH scenarios developed in this study, the number of dwellings provided district heating for Gaziantep province can be determined. To be able to apply Scenario I and Scenario II to the residential houses in Gaziantep, the heating loads of the medium-sized (100–150 m^2) houses in this region must be calculated first. To determine the heating loads of the dwellings, we need to know their annual natural gas consumption. Fig. 21 shows the natural gas consumption of dwellings in Gaziantep province by month. The data in the table is taken from the 2019 Natural Gas Sector Report of the Natural Gas Distribution Companies Association of Turkey (GAZBIR) [51].

It is reported that the annual total natural gas consumption of an average dwelling in Gaziantep is about 1,177 m^3 [51], which corresponds to an annual heating load of about 0.9144 kW. Considering the annual heating load of 0.9144 kW per dwelling, in the district heating model developed by using the exhaust gas of the cogeneration plant in Scenario I, it is calculated that 458 dwellings can be heated. In the same scenario, by purifying the biogas stored in the WWTP and connecting it to the local natural gas distribution line, the natural gas consumption of 1112 dwellings with the same annual heating load can also be met. Thus, with the district heating system designed in this scenario, it would be possible to meet the annual heating need of 1571 dwellings in Gaziantep. In Scenario II, it is considered that electricity production could be increased to 1643 kWh by burning all the biogas produced in the cogeneration plant. With the increase in the mass flow rate of the exhaust gas, the number of dwellings to be applied district heating will increase

Table 12
The exergy flow rates, cost flow rates and the unit exergy costs associated with each stream of the DH Scenario II. State numbers refer to Fig. 21.

State	$\dot{E}x$ (kW)	*c* ($/GJ)	$\dot{C}$ ($/h)
1	325.2	23.52	27.54
2	42.43	23.52	3.59
3	289.7	51.42	53.63
4	160.4	51.42	29.69
5	289.7	68.29	71.22
6	112.3	68.29	27.61
7	109.3	566.8	223.02
8	87.96	566.8	179.48

Table 10
Energy and exergy analysis results of the DH Scenarios.

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	ε (%)
DH Scenario I						
Heat Exc 1	447.15	–	171.74	78.51	93.23	45.71
Pump	–	29.22	29.22	26.06	3.16	89.18
Heat Exc 2	419.41	–	107.73	12.98	94.75	12.04
DH Scenario II						
Heat Exc 1	736.30	–	283.07	129.3	153.77	45.67
Pump	–	48.10	48.10	42.91	5.19	89.22
Heat Exc 2	690.63	–	177.4	21.34	156.06	12.02

Table 13
The exergetic costs for each subcomponent of both DH scenarios.

System	Exergetic cost	Scenario I	Scenario II
District Heating Cost (US$)	Heat Exc 1	25,051	33,634
	Heat Exc 2	52,042	69,852
	Pump	57,051	85,047
	Electricity	10,180	16,763
	Pipeline	66,666	66,666
	Pipeline insulation	32,808	32,808
	Operation & Maintenance	44,732	62,818
	Total	288,530	367,588
Biogas Purification Cost (US$)	Installation	88,933	–
	Maintenance	30,667	–
	Operation	12,267	–
	Electricity	36,800	–
	Water	9,875	–
	Chemicals	1,533	–
	Pipeline	6,660	–
	Total	186,735	–
Total Scenario Cost		475,265	367,588

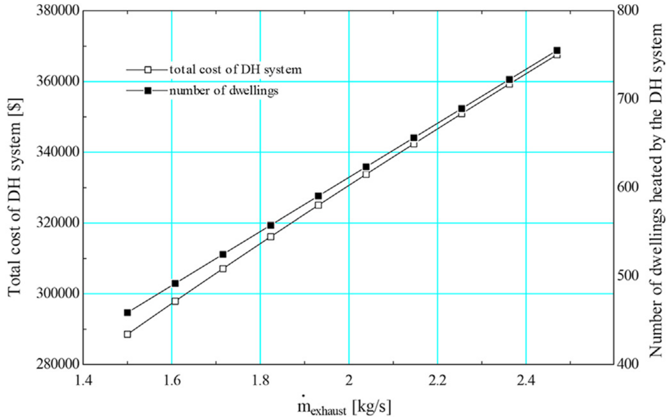


Fig. 22. The effect of exhaust gas on the total cost of the DH system and the number of dwellings heated by the DH.

(see Fig. 22). In this scenario, the annual heating load of 755 dwellings can be covered using the waste heat in the district heating system. The economic indicators for the scenarios developed for WWTP based DH systems are shown in Table 14. The biogas purification system designed in Scenario I increases the initial investment cost of the overall system and extends the payback period of the DH system investment. As a matter of fact, in Scenario II, using only the waste heat of the cogeneration system in the DH system will reduce both the total investment cost and the payback period accordingly. However, it should not be ignored that the number of dwellings that Scenario I met the heating load is almost twice that of Scenario II.

4.2. Application of the DH scenario II to the pilot provinces in each geographical region of Turkey

The DH Scenario II developed in the previous section is adapted to the pilot provinces selected from each geographical region of Turkey by considering the capacities of WWTPs of these provinces. The WWTP capacity of each province is first obtained from TUIK [45]. The amounts of sewage sludge produced during the stabilization processes and biogas obtained during the anaerobic digestion are then calculated. After determining the biogas production capacity, the electricity output of the cogeneration system installed in the WWTP can be calculated. The results calculated for each pilot province depending upon their wastewater capacities are presented in Table 15. The values for Gaziantep province are taken from the existing WWTP and its actual operational data. The values presented in Table 15 are calculated according to the daily wastewater capacities of the pilot provinces. Here, the purpose is to calculate the power produced in a cogeneration plant installed in the WWTP site. Only in this way will it be possible to provide district heating by using the cogeneration plant's waste heat in each WWTP. Thus, the heat capacity and amount of the exhaust gas released from the cogeneration plant is highly essential.

According to the calculated power production capacities given in Table 15, the exhaust gas flow rate for each province is determined considering the actual data of the GASKI WWTP. Using these values, the procedure developed in Scenario II is applied to the pilot cities. Thus, the number of dwellings to meet the heating load with the DH system is determined. The total cost of the proposed DH system for each province is also calculated. The average annual amount of natural gas consumption of the dwellings in each province is essential in determining the payback periods. Moreover, since the gas price paid by homeowners in Turkey varies by province, the payback period for each province is determined considering the natural gas price applied in that province. Table 16 shows the economic assessment as a result of the adaptation of the DH Scenario II to the provinces selected.

As seen in Table 16, as the capacities of urban WWTPs increase, the total investment costs of the DH system increase depending on the potential productions of sewage sludge and biogas and also power output (hence high exhaust gas mass flow rate). The record total investment cost in this table seems to belong to Istanbul, where the total current population is based on the limit of 16 million people. On the other hand, increasing heat source flow (exhaust gas flow) also increases the number of dwellings to be provided district heating. Therefore, when such a DH system investment was made in Istanbul, the payback period of the system would reduce to less than one year. Among the seven provinces in the table, it is seen that the city that uses natural gas at the lowest cost is Adana. The reason for this is that the city has more opportunities to benefit from solar energy due to its climate conditions, and thus, the amount of annual natural gas consumption is very low. However, due to its high population, Adana is one of the cities

Table 14
The economic indicators for the Scenario I and Scenario II.

	DH Scenario I	DH Scenario II
Number of dwellings heated by the DH system	458	755
Number of dwellings heated by the BP System	1112	–
Total number of dwellings heated by the DH & BP	**1571**	**755**
The total monetary gain from the DH system	110,594	182,111
The total monetary gain from the BP system	81,365	–
The total monetary gain from the DH & BP	191,959	182,111
Total Cost [US$]	475,265	367,588
Payback period (year)	**2.476**	**2.018**

Table 15
The amount of daily wastewater, the mass flow rates of treated sewage, sludge and biogas, and power production, for each pilot province.

Province	Amount of WW (m^3/day)	Mass flowrate of treated sewage (kg/s)	Mass flowrate of sludge (kg/s)	Mass flowrate of biogas (kg/s)	Power production (kWh)
İstanbul	3,902,194	44,824	212.02	3.727	28,893
Denizli	89,218	1,025	4.85	0.085	661
Samsun	149,854	1,721	8.14	0.143	1,110
Kayseri	165,184	1,897	8.97	0.158	1,223
Erzurum	83,586	960	4.54	0.080	619
Gaziantep	352,515	4,049	19.15	0.337	2,610
Adana	312,341	3,588	16.97	0.298	2,313

Table 16
The economic assessment as a result of the adaptation of the DH Scenario II to the provinces.

Province	Mass flow rate of exhaust gas of the BEDC [kg/s]	Annual average gas consumption [m^3/dwelling]	Natural gas price [US$/$m^3$]	Total number of dwellings heated by the DH system	Total cost of the DH system [US$]	Payback period of the DH system (year)
Istanbul	43.62	887	0.2049	13,339	2,274,000	0.9382
Denizli	1.00	955	0.2059	305	242,191	4.028
Samsun	1.67	954	0.2023	510	303,229	3.077
Kayseri	1.85	999	0.2036	565	318,343	2.767
Erzurum	0.93	1,307	0.2127	284	235,221	2.976
Gaziantep	3.94	1,177	0.2442	1,205	472,679	1.365
Adana	3.49	812	0.1914	1,067	441,844	2.663

with a high amount of wastewater, and a possible DH/DC system payback period would be relatively low. On the other hand, it is seen that the city that consumes natural gas with the highest price among the provinces in the table is Gaziantep. Again, Gaziantep would be the second province with the lowest payback period for a WWTP based DH system. Erzurum is one of the cities with the lowest amount of urban wastewater (see Table 15), depending on its population. So, the payback period of a WWTP based DH system investment in Erzurum would be longer than the rest of the provinces in the table. Denizli appears to be the city with the longest payback period for a WWP based DH system investment. This is because the amounts of wastewater and sewage sludge are low due to the relatively low population. Samsun and Kayseri have middle-sized WWTPs and hence, the payback period of a WWTP based DH system investment in one of these cities would be longer than the provinces like Gaziantep or Adana.

5. Conclusions

In this paper, two separate district heating scenarios are developed for direct and indirect use of biogas obtained from sewage sludge, which is the most important by-product of WWTPs. The proposed DH scenarios are first applied to an existing WWTP installed in Gaziantep, i.e., GASKI WWTP. In light of the results obtained from this actual case study and a comprehensive inventory including the current wastewater data of all Turkey provinces, the DH Scenario II is adapted to the pilot provinces selected from each geographical region of Turkey. In the following some concluding remarks are given:

- The total daily amount of sewage sludge produced in Turkey is calculated to be 54,484 ton-dm.
- As of 2019, Turkey's total installed power capacities of the cogeneration facilities within WWTPs were 10.12 MWh.
- Considering the total biogas potential that could be produced from sewage sludge in the WWTPs, the total annual electricity production potential of all these facilities in the country would be about 748,025 GWh. This output would correspond to nearly 2% of the total electricity produced from all renewable sources and to 0.245% of the total electricity produced from all sources, including fossil fuels.
- As a result of the adaptation of DH Scenario I based on an annual heating load of 0.9144 kW per each dwelling to Gaziantep province, it is calculated that 458 dwellings can be heated. In addition to this, the natural gas consumption of 1112 dwellings with the same annual heating load can also be met using the purified biogas.
- In DH Scenario II, it is considered that electricity production could be increased to 1643 kWh by burning all the biogas produced in the cogeneration plant. In this scenario, the annual heating load of 755 dwellings in Gaziantep province can be covered using the waste heat in the district heating system.
- The payback period for DH Scenario I is calculated as almost 2.5 years, while for DH Scenario II, it is 2 years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.119904.

Nomenclature

A_k	heat transfer area, m^2
$\dot{C}$	cost rate, $/h
c	cost per exergy unit, $/GJ
c_f	unit exergy cost of fuel, $/GJ
c_p	unit exergy cost of fuel, $/GJ

$\dot{D}_{D,k}$	cost rate of exergy destruction, \$/h
e	exit
$\dot{E}x$	exergy rate, kW
f	exergoeconomic factor
h	specific enthalpy, kJ/kg
i	inlet
i_r	interest rate, %
$\dot{m}$	mass flow rate, kg/s
n	total life time
N	annual operation time
P	pressure, bar
$\dot{Q}$	heat addition, kW
r	relative cost difference
s	specific entropy, kJ/kg-K
T	temperature, ^{0}C
U	heat transfer coefficient, kW/m^2-K
$\dot{W}$	power, kW
$\dot{Z}$	capital cost rate, \$/h

Subscripts and Abbreviations

0	dead state
BEDC	biogas engine driven cogeneration
BP	biogas purification
CEPCI	chemical engineering plant cost index
CHP	combined heat and power
CRF	capital recovery factor
D	destruction
DH	district heating
DHC	district heating and cooling
Heat Exc	heat exchanger
IEA	international energy agency
k	component
LMTD	logarithmic mean temperature difference
NG	natural gas
PEC	purchased equipment cost
TUIK	Turkish statistical institute
WWTP	wastewater treatment plant

Greek symbols

ε	exergy efficiency, %
η	energy efficiency, %
ϕ	maintenance factor
ψ	specific flow exergy, kJ/kg

Appendix. The inventory list based on the current wastewater treatment data for each city in Turkey as the end of 2019

Province	Geographical Region	The numbers of WWTPs	The amount of treated wastewater (m^3/day)	Sludge amount (kg/s)	Sludge amount (ton-dm/day)	Biogas potential (m^3/day)	Electricity production potential (kWh)
Adana	MER	7	312,341	17.08	1,476	21,479	2,313
Adıyaman	SAR	5	30,796	1.68	145	2,118	228
Afyonkarahisar	AR	14	54,192	2.96	256	3,727	401
Ağrı	EAR	–	–	–	–	–	–
Amasya	BSR	4	18,205	1.00	86	1,252	135
Ankara	CAR	29	671,741	36.73	3,173	46,194	4,974
Antalya	MER	33	580,625	31.75	2,743	39,928	4,299
Artvin	BSR	–	–	–	–	–	–
Aydın	AR	33	149,411	8.17	706	10,275	1,106
Balıkesir	MAR	22	143,952	7.87	680	9,899	1,066
Bilecik	MAR	5	1,976	0.11	9	136	15
Bingöl	EAR	2	17,418	0.95	82	1,198	129
Bitlis	EAR	4	14,845	0.81	70	1,021	110
Bolu	BSR	3	56,503	3.09	267	3,886	418
Burdur	MER	7	23,029	1.26	109	1,584	171
Bursa	MAR	114	463,303	25.33	2,189	31,860	3,430
Çanakkale	MAR	17	46,907	2.56	222	3,226	347
Çankırı	CAR	9	1,173	0.06	6	81	9
Çorum	BSR	12	65,452	3.58	309	4,501	485
Denizli	AR	39	89,218	4.88	421	6,135	661
Diyarbakır	SAR	2	96,618	5.28	456	6,644	715
Edirne	MAR	9	11,050	0.60	52	760	82
Elazığ	EAR	2	70,701	3.87	334	4,862	523
Erzincan	EAR	7	25,642	1.40	121	1,763	190
Erzurum	EAR	7	83,586	4.57	395	5,748	619
Eskişehir	CAR	8	138,981	7.60	657	9,557	1,029
Gaziantep	SAR	6	352,515	19.27	1,665	24,242	2,610
Giresun	BSR	10	15,444	0.84	73	1,062	114
Gümüşhane	BSR	3	8,194	0.45	39	564	61
Hakkari	EAR	–	–	–	–	–	–
Hatay	MER	12	140,530	7.68	664	9,664	1,040
Isparta	MER	9	50,903	2.78	240	3,501	377
Mersin	MER	11	265,069	14.49	1,252	18,228	1,963
İstanbul	MAR	86	3,902,194	213.36	18,434	268,345	28,892
İzmir	AR	67	743,193	40.64	3,511	51,108	5,503
Kars	EAR	1	2,788	0.15	13	192	21
Kastamonu	BSR	9	7,095	0.39	34	488	53
Kayseri	CAR	14	165,184	9.03	780	11,359	1,223
Kırklareli	MAR	14	35,293	1.93	167	2,427	261

(*continued*)

Province	Geographical Region	The numbers of WWTPs	The amount of treated wastewater (m^3/day)	Sludge amount (kg/s)	Sludge amount (ton-dm/day)	Biogas potential (m^3/day)	Electricity production potential (kWh)
Kırşehir	CAR	4	27,891	1.52	132	1,918	207
Kocaeli	MAR	22	422,821	23.12	1,997	29,076	3,131
Konya	CAR	29	246,570	13.48	1,165	16,956	1,826
Kütahya	AR	8	70,714	3.87	334	4,863	524
Malatya	EAR	7	127,400	6.97	602	8,761	943
Manisa	AR	17	108,738	5.95	514	7,478	805
Kahramanmaraş	MER	4	36,045	1.97	170	2,479	267
Mardin	SAR	4	58,627	3.21	277	4,032	434
Muğla	AR	29	187,816	10.27	887	12,916	1,391
Muş	EAR	–	–	–	–	–	–
Nevşehir	CAR	5	21,531	1.18	102	1,481	159
Niğde	CAR	5	38,742	2.12	183	2,664	287
Ordu	BSR	24	98,096	5.36	463	6,746	726
Rize	BSR	5	19,087	1.04	90	1,313	141
Sakarya	MAR	5	133,123	7.28	629	9,155	986
Samsun	BSR	17	149,854	8.19	708	10,305	1,110
Siirt	SAR	1	12,632	0.69	60	869	94
Sinop	BSR	1	–	–	–	–	–
Sivas	CAR	13	76,720	4.19	362	5,276	568
Tekirdağ	MAR	21	93,038	5.09	440	6,398	689
Tokat	BSR	26	36,978	2.02	175	2,543	274
Trabzon	BSR	15	166,867	9.12	788	11,475	1,235
Tunceli	EAR	1	6,727	0.37	32	463	50
Şanlıurfa	SAR	3	28,226	1.54	133	1,941	209
Uşak	AR	2	27,828	1.52	131	1,914	206
Van	EAR	5	85,007	4.65	402	5,846	629
Yozgat	CAR	25	18,548	1.01	88	1,275	137
Zonguldak	BSR	14	53,141	2.91	251	3,654	393
Aksaray	CAR	8	4,552	0.25	22	313	34
Bayburt	BSR	2	7,108	0.39	34	489	53
Karaman	CAR	7	16,416	0.90	78	1,129	122
Kırıkkale	CAR	1	26,952	1.47	127	1,853	200
Batman	SAR	1	56,492	3.09	267	3,885	418
Şırnak	SAR	1	–	–	–	–	–
Bartın	BSR	4	14,039	0.77	66	965	104
Ardahan	EAR	1	425	0.02	2	29	3
Iğdır	EAR	–	–	–	–	–	–
Yalova	MAR	6	75,914	4.15	359	5,220	562
Karabük	BSR	3	32,557	1.78	154	2,239	241
Kilis	SAR	2	11,508	0.63	54	791	85
Osmaniye	MER	4	47,397	2.59	224	3,259	351
Düzce	BSR	3	31,027	1.70	147	2,134	230
Total		**991**	**11,533,225**	**630.60**	**54,484**	**793,114**	**85,391**

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