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Important aspects for the planning of biogas energy plants: Malatya case study

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ABSTRACT

Conventional energy use causes various environmental impacts of global warming. Also, as a result, renewable energy sources are more beneficial because they generate virtually no emissions. Biogas is historically recognized as a by-product of the anaerobic (oxygen-free) decomposition of agricultural waste. One of the most critical issues for biogas plants in electricity production is the economically and environmentally safe disposal of vast volumes of digestate. In this study, an extensive pathway for the establishment of a large-scale biogas energy plant was presented. Under these lightings, a case plant built in Akçadağ-Malatya was investigated from the techno-economic point of view. The case plant was built to generate heat and power as well as solid and liquid fertilizer. The produced biogas and methane were respectively recorded as 229,49 m^3/h and 139,08 m^3/h. It was determined that electricity generation in an amount of 5,256,000 kWh per year from the digested feedstock was available with the maximum power capacity of 625 kWh. The annual and daily heat energy outputs were calculated as 6,482,400 kWh and 640 kWh, respectively. The solid and liquid fertilizers were respectively determined as 40,891.03 t/a and 5,152.74 t/a. According to the results, total investment costs per the produced electricity for the biogas energy plant were calculated as 1451.53 €/kWh. The payback period was calculated as 2.22 with a net present value of 944,714.44 €. CO_2 emissions have been reduced by 14,105 tons per year thanks to the co-generation system.

1. Introduction

Day by day, the number of countries that used renewable energy sources has increased because conventional sources have caused big environmental problems [1,2]. The usage of carbon-based fuels and sources should be limited to reduce the level of global warming [3–5]. One of their main goals is the efficient use of their local energy due to the rising population and limited conventional fuels [6–8]. Moreover, environmental problems such as global warming and air pollution are related to energy efficiency [9,10]. Thus, biogas being a renewable energy fuel provides the utilizing biodegradable municipal waste, and the energy diversity for the countries is growing [11,12].

Biogas is a final product of the anaerobic digestion (AD) of organic feedstock that contains the integrated process included feedstock supply and pre-treatment. Biogas consists methane (CH4) of 50–70%, carbon dioxide (CO_2) of 25–45%, water (H_2O) of 2–7% at 20–40 °C, nitrogen (N_2) of 2–5%, oxygen (O_2) of 0–2% and less than hydrogen (H_2) of 1%, ammonia (NH_3) of 0–1% and hydrogen

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sulphur (H_2S) of 0–6000 ppm [13]. Biogas systems that use liquid manure and crop residue mixtures for feedstock have developed from predominantly small on-farm plants. Besides, the cow dung and chicken waste are used in varying proportions in some studies; they got the maximum methane yield of 68% on the 30th day. The slurry had bio-manure containing nitrogen of 1.7%, phosphate of 0.8%, and potassium 0.4% [14]. On the other hand, the composition obtained from various waste can be treated with hydrothermal heating to increase methane production by 65.5% [15].

If sufficient crop output is available, manure may be used as a fertilizer with significant economic value [16]. The livestock industry is looking for more cost-effective and environmentally sustainable options to cope with manure residues. Several studies have shown that AD of organic waste can handle these problems in a cost-effective and environmentally sustainable way [12,13]. Some of these studies have related to the fuel-cycle emissions from various biogas systems [14], the choice of the optimum variety and genotype [15], and the developments in different fermentation processes [16]. Although some studies producing biogas are not industrial scale, they could be a significant source of biogas for the household because of the decreasing emissions [17–19].

Recently, people have become more and more interested in using AD to treat organic waste generated from farms, such as manure, crop residues, and organic residues in food and agro-industry, to generate renewable energy [20–22]. The manure is processed into biogas through AD to recover energy, thereby reducing the risk of pathogens caused by the spread of land because the thermophilic or mesophilic AD through the disinfection step can eliminate all or almost all pathogens [23,24]. In addition to biogas, AD also produces digestive juice, consisting of a mixture of liquid and solid parts. In terms of environmental issues, digestive juice on the land is the most attractive option because it can recycle nutrients and reduce the loss of organic matter suffered by the soil under agricultural development [25,26]. Biogas plants' economic and environmental feasibility depends on a reliable and commonly agreed method of disposing of the relatively large quantities of digestate produced [27,28]. The electricity selling prices, investment costs, and sustainability are taken into account to assess the biogas power plant as an economic point [29,30].

The biogas production systems ranging among small, medium, and large scales have various designs and applications. Most of the literature studies have generally deal with the small and medium scale of the biogas production systems [31,32]. The factors determining the stability and productivity are more critical to invest in the production facilities [33]. The faults of the components are identified in detail to investigate whether it works efficiently for the systems [34]. Especially family (medium) size biogas production system has several manure resources and produced different biogas volumes like 3,816.85m3/a from only cow manure, 152.05 m^3/a from only sheep dung, 1,279m3/a from sole energy maize in a case study [35].

On the other hand, although the produced electricity and the power plant's cost are very high in large-scale systems, the reduced emissions are high at the same time. For instance, the total produced electricity of 2,223,951 kWh and heat energy of 2,566,098 kWh per year were obtained from Çiçekdağı case study. Simultaneously, the co-generation system has reduced emissions by 7,506 tCO_2 per year [36].

Previous studies have proved that, due to the large amount of undigested organic matter retained in biogas, biogas residues may be generated during the liquid digestive storage. As suggested by these authors, giving up the digestive juices' residual potential may lead to two additional disadvantages, namely severe environmental pollution and loss of factory revenue. Pollution is caused by the critical components of biogas namely CH_4, and CO_2, which are also greenhouse gases (GHG) that influence the global atmosphere and climate. As a result, reducing gaseous waste during the digestate storage process would certainly make anaerobic digestion's environmental resilience much more appealing.

According to preceding studies in the literature, it is clear that the papers have mainly related to small and medium biogas production and power plants. Moreover, they have generally focused on one or two essential parameters dealing with mere production or economic aspects. In this study, unlike other studies, a large-scale biogas energy plant (BEP) was planned in detailed techno-economic perspectives. In this regard, the critical issues were argued to establish a large-scale BEP. The pipe and instrument (P&I) diagram of the system was prepared, and the necessary codes were specified on the diagram, and the system's automation was provided in this way. Hematite was used for the conditioning of obtained biogas, and the capacity study of the desulphurization system was given in deep detail. Under these details, the BEP was designed for cogenerative purposes including heat and power generation. The ruminant energy and gross energy concepts were argued proportional to the amount of obtained biogas through the necessary calculations. Besides, the fertilizer production and its use were also investigated. Finally, a detailed cost analysis was conducted for each piece of required equipment. The net present value (NPV) analysis concept was carried out by performing both the capacity and economics of the BEP.

2. Materials and methods

2.1. Considerations in Biogas Energy Plant Design (BEP)

The following issues are prerequisite for the design of a biogas plant and should be necessarily taken into account:

- The BEP should be designed and manufactured following worker health and safety standards.
- The BEP must be designed and manufactured following environmental legislation and standards.
- Attention should be paid to optimization in terms of energy consumption in the BEP, and minimum energy consumption should be targeted in process design.
- BEP must be designed and manufactured following the standards in terms of security elements, horizontal and vertical transportation issues, access to equipment and instruments.
- BEP should be designed so that the necessary transport-lifting spaces and roads are to be transported horizontally and vertically for the heaviest part and the most significant factor.

- The machinery required for the transportation of equipment inside and outside the facility should be designed to be access roads.
- Adequate flow paths should be considered in the project to prevent liquid accumulation on the ground and platforms.
- Process, workshop, management, and living areas in the BEP must have healthy ventilation and air conditioning systems.
- The BEP should be projected separately from the environment conditions at a maximum rate like dust, moisture, and steam. It should be designed and manufactured to have equipment and equipment to prevent such problems in case of failure.
- Maximum ergonomic attention should be paid to the facility, and different process areas should be created.
- Traffic flow should be considered in the project, and traffic safety should be taken into account.
- Entries and exits to the facility should be designed under security and hygiene controls.
- Full automation should be applied in the project, and the facility should be designed to work with a minimum of personnel.
- All kinds of inputs and outputs entering the process should be measured, recorded, and reported in the project. There should be no shortage of instruments and equipment to provide mass and energy balance.
- The facility should be designed to cover the main production cost as well as the operational costs of each component of the system.
- BEP automation; from the security entrance, electricity, water, hot water, waste (solid, liquid, gas), lighting, visual and audio communication systems, esp. auxiliary facilities, indoor-outdoor lighting, mechanization, and workshop units should be integrated into the primary control system with all their hardware and technological structures.
- Faults and problems in the project units should not affect other units and equipment and should not cause the facility's common stop.
- There should be ready backups for the malfunctions and problems in the project and should be designed considering the infrastructure that will provide sufficient time to fix the malfunctions.
- There must be a ready backup in the biogas energy plant project (transformers, busbars, pumps, etc.) to do maximum maintenance without stopping.
- An emergency combustion system should be established to ensure the safe combustion of biogas in emergencies.
- The fresh mixed manure collector and the digester heating system collector should be installed in the machine room. A pumping system that can circulate waste between the slurry, pre-digester and post-digester, buffer tank, separator, and lagoon should be installed.
- Monitoring and controlling the biogas energy plant from a single point should be ensured. A PLC and SCADA system that can activate security systems without operator intervention should be installed in line with the system's signals. This system will be directed from the control room via a PC. It should be designed so that it is possible to monitor all kinds of equipment from the screen to determine the malfunctions by starting/stopping and giving a warning with an alarm.
- Monitoring and control of waste input amount in the biogas power plant are based on the measurement and management of temperature and flow rate of produced biogas, measurement and controlling of produced biogas content (CH_4, CO_2, CO, H_2S, N_2, O_2, etc.). Temperature measurement and control in fermenter units, the enterprise's instant production and consumption values should be continuously monitored.
- The limits of all parameters should be defined in the system, and the system should be in a structure to give an alarm when the limit values are exceeded and to stop the system safely by activating fire extinguishing and all other necessary security systems. The machines' (such as motors, pumps, and mixers) operating times should be recorded daily, weekly, and monthly. Working hours, consumption values, and fault information should be included in the work reports, and the co-generation system should be able to fulfill the following functions through the control unit and automation system;
  - ✓ Automatic activation,
  - ✓ Synchronization - reverse synchronization,
  - ✓ Adjustable power flow and factor control,
  - ✓ Ensuring that the system works in islanding mode with distributed generation,
  - ✓ Automatic stop and load shedding control,
  - ✓ Load sharing system adjusted to alternative conditions in parallel operation for more than one unit,
- The amount of waste remained in the biogas for the sudden stops,
- The duration of the waste in the biogas facility, the restart time, and conditions at sudden stops (this period should not exceed 24 h).
- It should be determined how to control the biogas composition and quantity. A connection point should be left in the transformer to meet the electricity requirement of the biogas plant and co-generator. This connection point should be 50 kW for biogas plants with a co-generator up to 370 kW capacity and 80 kW for biogas plants with a co-generator capacity up to 1 MW.
- The BEP protection control and SCADA unit, digital control system and information about all devices in the BEP, relay values, network information, gas analyzer information, valve positions, information about control valves, information about the heating system, information about the co-generator, transformer and AC - DC voltage information should be collected and evaluated employing programmable smart controls. It should be designed so that the operator can monitor it on the screen via SCADA screen, touch screens, or both. In addition, gas engine start-stop operations must be equipped on the SCADA screen for protection, control, measurement, synchronization, alarm, etc. An advanced SCADA system should be provided for mains synchronization performed in the control room.
- Warning for all concrete tanks with fermentation substrate regularly during operation of the plant should be taken into consideration. There are wear elements in concrete tanks with fermentation substrate and/or mixing regularly. It is recommended that the fermentation tanks should be entirely covered with special protective paint o reduce these elements and extend their service life to reduce these elements and extend their service life. When the protective paint is applied, the concrete itself is not exposed to

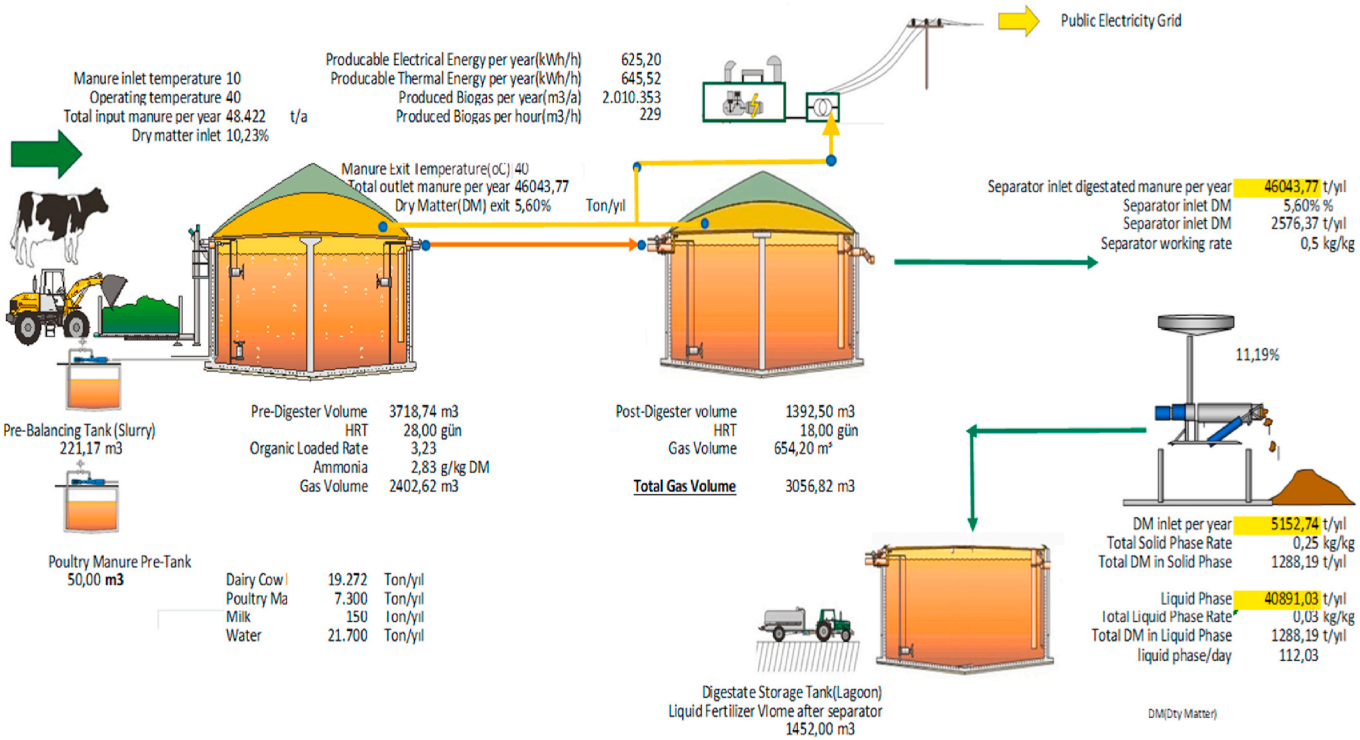

Fig. 1. Flow diagram of the Biogas Energy Plant.

corrosion, and the paint is corroded due to possible corrosive and acidic fermentation. The protective paint should be checked regularly and renewed to protect the concrete for approximately 5–8 years.

- Daily consumption of animal waste (approximately 132 tons/day, 10% dry matter, 80% organic dry matter), produced biogas (about 5,496 m^3/day), electricity generation in the co-generator unit as 625 kWh/h, and heat production as 640 kWh/h. In addition to meeting the facility operating criteria, some information must be reported, namely;
  - ✓ Percentage of methane in biogas,
  - ✓ Electricity consumed per ton of manure in the biogas energy plant,
  - ✓ The amount of water consumed and discharged for each volumetric manure quantity in the BEP,
  - ✓ Digested manure outlet temperature from the pre-digester unit and post-digester unit
  - ✓ Compliance of all emissions with environmental legislation (legislation provisions/EU norms),
  - ✓ Odor removal (legislation provisions/EU norms),
  - ✓ Noise Prevention (legislation provisions/EU norms),
  - ✓ Energy Production and Efficiencies (legislation provisions/EU norms),
- The foundation static grounding of all units in the biogas power plant should be produced with a galvanized strip. For the body (protection) grounding of steel columns and equipment, sprouts should be removed from the foundation ground, and grounding should be produced with braided copper. The static grounding system must be done according to the provisions of the regulation in high current installations.
- All pipelines should be laid underground as much as possible. If aboveground piping is required, the material of the pipelines should be stainless steel.
- Pipes should be connected by welding, flanged coupling, or both. PE should be used in the piping of the hot water lines obtained from the co-generator unit, where ST material should be used in the piping of aboveground hot water lines. HDPE should be used as pipe material in the feedstock line.

When the biogas power plant investment is decided, two fundamental questions should be asked. From an economic point of view, does the biogas power plant provide an opportunity for the investor? Is it on a suitable basis in terms of timing, training, and required skills? In case of asking the questions about the total investment mentioned above and reaching a positive consensus, the feedstock supply and dimensioning of the plant should be questioned when the biogas power plant will be built. Is it possible or not to achieve continuous access to substrates with a fee or free of charge? Are the analyzes on the characterization and quantity of substrates available? Is it possible to sell bio-fertilizer fractions with a guarantee? Is there enough land for the planned biogas energy plant? Is the distance of the power transmission lines to the BEP available? All these questions should be addressed before starting the establishment.

After the feasibility study is carried out, some situations need to be considered in financial terms. It is necessary to know how much of the electrical energy produced in the biogas power plant will go to domestic consumption and how long the available electricity will be sold at a reasonable and sustainable price. Is there a local market for the sale of heat energy produced in the co-generator? If so, what about the sales price and the piping costs for the transportation of the heat? Besides, it is necessary to know about the available grant or loan for the planned power plant, the loan interest rates, and the grant amount. The highest income depends on the sale of electricity and fertilizer. For both, the market values must be kept dynamic. In addition to all these evaluations, the expenses of the report of environmental impact assessment, all necessary legal licenses and approval costs, maintenance and repair costs should be taken into account.

2.2. Case study of a large-scale BEP

The case study was carried out in Akcadağ with a distance of 39 km from Malatya. Biogas energy plant was projected in 2018 and inaugurated in September 2020 by 19,272 tons dairy cow and 7,300 tons poultry manure with a total installed capacity of 26,572 tons of input annually. In addition to cow manure, the device also uses other co-digestible materials, such as poultry manure. While the daily incoming fresh manure amount was 132,66 tons and the daily output was 126,15 tons, approximately 6.51 tons of manure per day turned into biogas. The flow diagram of the biogas energy plant (BEP) is given in Fig. 1.

According to Fig. 1, the Biogas Energy Plants contain Slurry tank, Pre-Digester, Post-Digester, the units for recovering generated methane, separators, and solid digested tanks, and lagoons for digested liquid manure. The Turkish company of AK-SÜT farm & livestock was tasked with establishing the first animal manure-fueled biogas plant at Akcadağ, Malatya, with a capacity of 625 kWh_{el} and 640 kWh_{th}.

Biogas plant feedstock is transported to the biogas plant area or pumped. The feedstock is supplied to the digester in portions 8–12 times a day. Automatics controls feeding intervals. The hydraulic retention time in an anaerobic reactor makes 20–40 days at a 30–40 °C temperature. Digesters are gas and leak-proof tanks made of metal and concrete. The mixing system inside the digesters makes even substrate mixing. Digesters are equipped with a floor and walls heating system to obtain a constant operational temperature. The fermented substrate is discharged in automatic mode with the same periodicity as substrate loading. The programmed module makes plant operational control in a time-program mode based on control gauges limiting values. Produced biogas is distributed to the membrane. From membrane, biogas is constantly fed into gas treatment system and co-generation unit. Gas transportation is made by the pipeline that is equipped with a condensate discharge unit and pressure excess safeguard system. All the unit work is based on gauges limiting values. If the engines fail and the remaining biogas has to be burned, the plant is supplied with an emergency flare. After the biogas plant, the treated substrate is sent to the mechanical separation system to handle liquid and solid bio-fertilizer fractions. The processing and granulation applications of bio-fertilizer are necessary. The operation of the biogas plant is shown on a monitor in the central control room. The control room is equipped with a central control unit that enables local or remote switching of any biogas plant module into automatic or manual mode.

A scraper machine was used to extract fresh manure from 1500 dairy cow stables. Throughout the experiment, the dairy cows were a constant. Manure from dairy cows and poultry was extracted from digester units and then dripped into the slurry tank of the biogas plant. Twenty tons of poultry manure per day, which is 5 km away from the farm where the biogas plant was built, was transported to the biogas plant's fertilizer tank by the tractor. The input materials were mixed slurry unit pumped firstly to the primary fermenter and then to the post digester unit stays there for 28 days and 11 days, respectively.

The slurry tank was constructed as open cellar storage with a 5 m height, 8 m diameter, and 0.6 m in space. The pre-tank dimensions, also named slurry designed for poultry manure, were determined open cellar storage with a dimension of 4x5x3 m. The biogas yield of the digester will reduce if methane is produced in a slurry unit. Methane emissions from an exposed slurry unit known as a digested liquid storage tank are also harmful to animals' health. As a result, the manure can be transported as quickly as possible from the slurry device to the pre-digester. This transportation was performed regularly in the BEP using a substrate pump. The total slurry volume was about 221.17 m^3. The substrates are warmed in the digester, and the fermentation process takes place. Biogas and digested substrate are the two end products of this process. Three stirrings of the fresh substrate are needed to maintain an even temperature in the pre-digester and boost the bacteria's metabolism. The primary digester has a useable volume of 3,718.724 m^3 with a diameter of 27 m, a useable height of 6.5 m, and an unusable height of 0.7 m. It was built as a vertical digester with a double – membrane, an upright fermenter heated to 40 °C by stainless steel heating pipes (32x2 mm and pipe length 764 m) positioned as 11 turns on the chamber inner walls. The digester's walls and floor are insulated with extruded polystyrene with a thickness of around 80 mm to minimize heat loss. The digester's floor and walls were made of reinforced concrete. The digester was designed to be airtight. For integrated gas storage, the cover was made of a flexible, synthetic membrane roof. The post digester has a useable volume of 1392,5 m^3 with 17.5 m diameter, 5.8 m useable height, and 0.7 m unusable height. The substrate, which was fermented for 28 days in the primary digester unit, was fermented in the post digester unit for 11 days to increase the gas yield. Pre-digester, Post-digester, and technical mechanical room are illustrated in Fig. 2.

Concerning the minimum winter temperatures of the slurry and the outside air to the digester, it is necessary to provide heat to the slurry in the fermentation to maintain the manure at the design temperature (36–40 °C), so a heat exchanger tube bundle, made entirely of stainless steel and positioned within each digester, is a need. The heat exchanger is placed near the bottom of the digesters, and the recoverable hot water from the combustion cycle of the biogas is transported through pipes made of stainless steel in the co-generation module. P&I diagram of gas pipes, substrate pipes, and heat pipes is given in Fig. 3. Biogas contains about 0.05–0.3% hydrogen sulfide (H_2S). Many biogas reactors produce between 0.05 and 0.30% hydrogen sulfur by biogas volume. While it is 0.05% by volume for 500 ppm H_2S, this value is 0.30% for 3000 ppm H_2S. Since this has a corrosive effect on metals, it can damage the engine and piping.

As a result, it is crucial to get rid of the H_2S. In this study, hydrogen sulfide removal was performed both by mixing some air (0.375%) to the upper part of the digester near the biogas outlet of the biogas tank and by using a desulphurization system using hematite (Fe_2O_3) material. The desulphurization system is illustrated in Fig. 4.

As shown in Fig. 4, the desulphurization system consists of two cylindrical tanks into which hematite material is placed with a height of 2 m and a diameter of 1 m and a cyclone unit with a height of 1.6 m and a diameter of 1 m. Three stirring devices in the primary digester plant and two stirring devices for the post-digester plant of the case study are screw propellers. An electric motor with a load capacity of 11 kW and 15 kW is used in a screw propeller configuration for post and Pre-Digester, respectively. Within the

Fig. 2. The view of Pre-Digester, Post-Digester, and technical mechanical room.

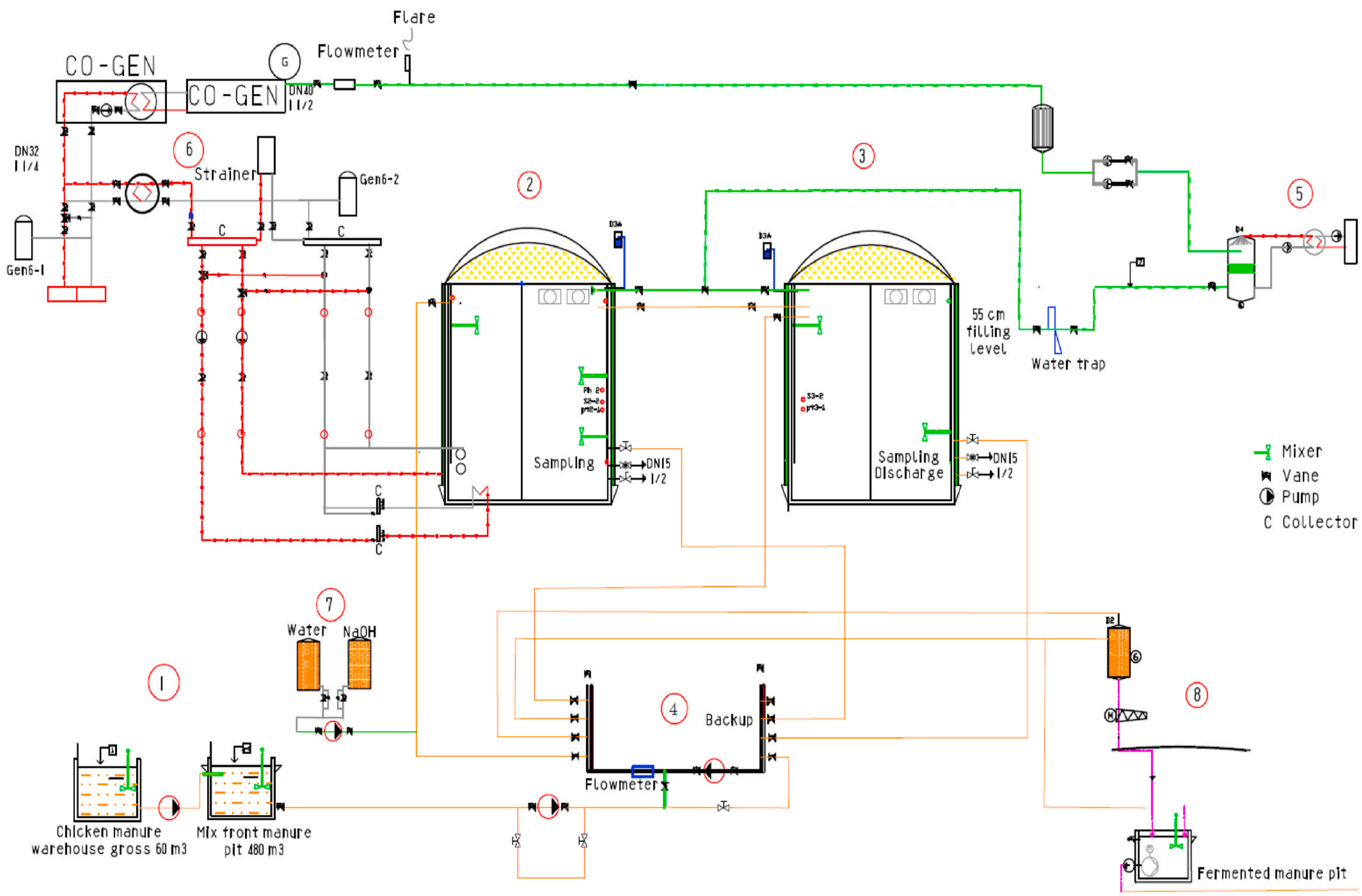

Fig. 3. P&I diagram of the Biogas Energy Plant.

Fig. 4. Desulphurization unit and CHP connection line.

fermenter, three stirring units have been operated for 8 min per hour. The plant was fed dairy cow manure and poultry manure by-products during the investigation time. Substrate pipe with a diameter between 160 and 200 mm was used to transport substrate using a manure pump. A diameter of at least 150 mm is expected for longer distances. In this study, the digestate from the farm-scale biogas plant is divided into solid and liquid fractions using a separator device. The main parameters of the pre-digester and post-digester units and digestate storage unit have been reported in Table 1.

According to Table 1, approximately 132.66 tons of fresh mixed manure (40% dairy cow manure, 15% poultry manure, and 55% water) were loaded daily into the slurry tank. The fresh feedstocks were first loaded into the pre-digester unit using the slurry tank's manure pumping unit, running 8.29 min per hour. The produced solid fertilizer and liquid fertilizer have been 5152.74 t/a and 40891.03 t/a, respectively.

The biogas from pre-digester and post digester, produced by digesting dairy cow and poultry manure, was used for combined heat and power (CHP) generation. All of the biogas generated were burning in the CHP unit to generate electricity and heat. The co-generation allows recovering from a single energy source (chemical), two secondary sources of energy (electrical and thermal). The engine fueled with biogas is coupled to a machine capable of producing electrical energy transferred to the network. At the same time, some part of the engine's heat is recovered to heat the anaerobic digester to keep the optimum process temperature, where the remained heat is transferred to the user. The recovery of thermal energy occurs through a plate heat exchanger part of the primary circuit cooling hydraulic. There is a need to recover the heat of the exhaust gases through heat exchanger fumes. The biogas plant was powered by 625 kWh electric energy. The electrical energy generated by a CHP unit is fed into the public grid at a market price of $ 0.133 kWh in Turkey.

Thermal energy from the combustion process is used to heat the pre-digester and post-digester plants To keep the regularity of the anaerobic process stable. Currently, there is no market for heat. The farm-scale biogas plant also produces digestate divided into solid and liquid fractions using a separator device. The digested solid and liquid fractions were first fed to the separator, and then the liquid fraction was fed to the lagoon, which has a total capacity of 1452 m^3 and is fitted with mixing and pumping systems. The digested solid

Table 1
The main parameters of the digesters and digestate storage unit.

Number of digesters	2		
	Pre-Digester	Post-Digester	Slurry
Diameter (m)	27.00	17.50	8.00
Useable height (m)	6.50	5.80	4.40
Useable volume (m3)	3,718.74	1,392.5	221.17
Hydraulic retention time (HRT) (day)	28	11	-
Biogas storage capacity in EPDM membrane (m3)	2,402.63	654.20	-
Needed liquid digestate storage capacity time (day)	12.96		
Needed solid digestate storage capacity time (day)	90.00		
Total solid fertilizer (t/a)	5,152.74		
Total liquid fertilizer (t/a)	40,891.03		
Needed solid digestate storage capacity (m3)	1,431.30		
Needed liquid digestate storage capacity (m3)	1,452.00		
Organic loaded rate (OLR)(kg ODM/m3 d)	3.23		

fraction was stored in a static heap next to the separator on an exposed concrete base.

2.3. Quantity and description of the substrates

The fermenter's primary feedstock was the untreated dairy cow and poultry manure, which had been blended in a 40/15 mixture in a slurry tank and pumped to the fermenter at a rate of 8.29 min per hour. The dairy and poultry manure is produced in the farm located at Akcadağ, Malatya, Turkey. The quantity and description of the substrates are shown in Table 2.

According to Table 2, this farm raises 1500 cows and 158,000 laying hen that produce daily wet manure of 52.8 tons from dairy cows and 20 tons from poultry. The fermenter was filled with a mixture of 52.8 tons of fresh dairy cow manure and 20 tons of poultry manure in a dry matter (DM) ratio of 15% and 28%. For feedstocks with DM contents, a wet digestion process was used to allow for pumping and stirring. The addition of 3 tons of water per 1 ton of poultry manure resulted in a DM content of 9.5%. Dairy cow manure had an initial organic dry matter content of 89.4%, while sheep dung had an initial organic dry matter content of 87%. For dairy cow manure, the dry organic matter (ODM) amount was 2584 t/a, and it was1778 t/a for poultry manure.

2.4. Methods

2.4.1. Size of the components

The digester, insulation, CHP unit, mixers, pumps, and piping are the main components. Estimating the installation costs should be built on the basis of the digester's key components and sizes. The following formula can be used to measure the digester's necessary size or volume as a rule of thumb.

$$V_D = (m_{manure} + m_{CS}) \times \frac{HRT}{365} \tag{1}$$

where VD, m_{manure}, and m_{cs} are the digester volume (m3), manure quantity (t/a), and co-substrate quantity (t/a), respectively. HRT is the hydraulic retention time that is the time for which the substrate is inside the digester. The amount of time needed for optimum biogas output is determined by the temperature. A retention period of 25–40 days is needed for the mesophilic temperature range.

For the biogas membrane, the size of the membrane required to cover the biogas digester is determined by the vertical biogas digester diameter. The amount of gas stored under the double-membrane is relatively less. This number increases when the digester is not fully finished since the extra room can be used for gas storage. As a result, the digester's diameter is equal to:

$$D^2 = \frac{4 \times V_D}{H \times \pi} \tag{2}$$

where D, VD, and H, respectively, defined the digester's diameter, digester volume, and height of the digester. In fact that choosing a larger digester to maximize biogas storage capacity can be beneficial.

In certain situations, storing the digestate is either practicable or necessary. Separating fresh manure from digestate is not possible in most manure cellars with semi-open floors. In this case, external digestate storage is needed where the established storage (such as a silo or a manure bag) or new storage may be used for this purpose. The size of post-digestion storage can be calculated as follows:

$$V_{pds} = (m_{manure} + m_{CS}) \times \left(\frac{t_s}{12}\right) - V_D \tag{3}$$

Here, V_{pds} (m3) and ts (months) defined the post-digestion storage volume and required storage time, respectively. Biogas is either contained in an external gas bag or in a filter that protects the digester. In reality, a CHP unit with a storage capacity of 20–50% of daily biogas output is adequate. This figure may be much lower if the CHP unit is still on.

Table 2
The quantity and description of the substrates.

Manure	Dairy Cow Manure	Poultry Manure
Total manure (t/a)	19,272	7,300
Input manure (t/d)	52.8	20
Dry Matter DM (%)	15	28
Organic Dry Matter ODM (%)	89.4	87
C content in DM (kg/d)	578.16 (7.30%)	1176 (21%)
N content in DM (kg/d)	22.97 (0.29%)	72.80 (1.30%)
Dry Matter (t/d)	2,891	2,044
Organic Dry Matter (t/a)	2,584	1,778
Carbohydrates (g/kg)	400	340
Fats (g/kg)	30	10
Proteins (g/kg)	150	220
Cellulose (g/kg)	220	180
Total N (g/kg DM)	48	50
Total NH4–N (kg/a)	76,752	53,455

$$V_{bs} = \frac{V_{biogas}}{365} \times 0.2 \tag{4}$$

where V_{bs} (m^3) and V_{biogas} (m^3/d) define the biogas storage volume and daily biogas production, respectively. The insulation for the digester's walls and the bottom is given by:

$$A_{insulation} = H \times D \times \pi \tag{5}$$

$$A_{bottom,insulation} = D^2 \times 0.785 \tag{6}$$

where $A_{insulation}$ and A_{bottom}, insulations are wall insulation area and the bottom insulation of the digester, respectively.

The volume of slurry and its dry matter quality, and the height at which the slurry must be drained determine the form and scale of the manure pump. The homogenization operation is performed, an agitator-type submerged variable direction, mounted on a flag, for eight adjustment operations. The consent of command can also be given manually, depending on the level of electronic switches placed in the tank. The agitator's type and size rely mainly on the digester's dry matter content and size. The capacity of the agitator ranges between 2 and 25 kW.

Once the perfect mixing of the product is obtained by emptying the tank load, which occurs within a day, it is automatically transferred to the digester. The transfer pumps, particularly suitable for dense liquids, are submerged to complete quick guide tubes in hot galvanized steel. Adjusting the flow rate of the load occurs through the electronic adjustment of the charging times. Both the agitator (mixer) that the lifting pumps have a safety locking operation for lack of slurry.

2.4.2. Biogas yield

The average yields obtained from the anaerobic digestion process of organic matter (OM) found in effluents, expressed as a percent of dry matter, can be used to assess biogas capacity. The average amount of biogas derived from the amount of manure is calculated. The biogas yield can be calculated by using the following formula:

$$V_{biogas} = m_{manure} \times DM_{manure} \times ODM_{manure} \times BY_{manure} \times m_{CS} \times DM_{cs} \times ODM_{cs} \times BY_{cs} \tag{7}$$

where V_{biogas} and, BY_{manure} respectively, define the biogas yield (m3/a) and conversion index of the given manure (m3biogas/t ODM). Here, DMmanure and ODMmanure define the dry matter and the organic dry matter content in % of the given manure. Here, DMcs, ODMcs, BYcs define the dry matter, organic dry matter, and conversion index of the co-substrate, respectively.

A different calculation was also carried out based on the total organic matter content in the manure. Besides, it was assumed that the biogas production remained unchanged. As previously mentioned, the obtained biogas can produce electricity, heat, or both using a CHP device at this point. In Germany, biogas-to-CHP is the most common use. The provided energy is fed into the public grid, while the heat is distributed into district heating networks under average transmission losses. A part of the produced heat is used to monitor the AD process and, if possible, sterilize the feedstock. In this study, efficiencies of CHP unit are 40% in electricity and 46.67% in heat.

As a reason, the equivalence principle can be used to determine conversion between two energy sources. Therefore, 1 m^3 of biogas produces 2.76 kWh/h of electricity and 3.3 kWh/h of heat, considering the total calorific energy value of biogas is 6.06 kWh/m^3. The total energy generation was determined as 15.37 and 25.68 kWh/tons for dairy cow manure and poultry manure, respectively. The amount of electricity generated by biogas produced from given manure is calculated as follows:

$$E_{el} = \frac{m_{manure} \times DM_{manure} \times ODM_{manure} \times BY_{manure} \times 6.06 \times \mu_{el}}{t} \tag{8}$$

$$E_{lh} = \frac{m_{manure} \times DM_{manure} \times ODM_{manure} \times BY_{manure} \times 6.06 \times \mu_{th}}{t} \tag{9}$$

$$Q_{r,h} = E_{th} - Q_D \tag{10}$$

where Qr,h (kW), and QD (kW) are the amount of residual heat demand and the total heat losses through the digester.

2.4.3. Energy balance of the biogas reactor

The following is the simple time-dependent energy balance equation for the manure in the biogas reactor. It can be written as: Assuming that the manure in the biogas reactor is still well combined and therefore at a constant temperature that changes only over time, the energy balance for the manure in the reactor can be written as:

$$\rho_m \times V_m \times C_{p_m} \times \frac{dT_m}{dt} = \dot{Q}_{th} - \dot{Q}_m - \dot{Q}_D \tag{11}$$

The digester temperature is kept at a constant temperature thanks to a large portion of the heat provided. As a result, heat is needed to warm up the new substrate and compensate for energy losses caused by transmission. The above is determined by the digester's isolation and the temperature outside the digester. The digester's heat demand can be estimated as follows:

Table 3
The investment cost calculations of the case study.

	Size	Unit	Cost (€)	Percentage
Digester's systems			195,200	21.52
Pre-Digester concrete construction cost	4119.53	m^3	83,000	9.15
Post-Digester concrete construction cost	1562.64	m^3	31,300	3.45
Slurry unit	221.17	m^3	13,400	1.48
Co-generation module building construction	280 (5x8x7)	m^3	11,300	1.25
Grounding strip and mechanical equipment grounding	1	set	1,770	0.20
Lightning rod system	1	set	5,100	0.56
5 cm Insulation for Pre-Digester	610.73	m^2	3,200	0.35
5 cm Insulation for Post-Digester	357.36	m^2	1,759	0.19
Geotextile water retaining seal for Pre-Digester	572.56	m^2	190	0.02
Geotextile water retaining seal for Post-Digester	240.53	m^2	85	0.01
Pre-Digester epoxy coating (2 m height)	169.65	m^2	432	0.05
Post-Digester epoxy coating (2 m height)	109.96	m^2	240	0.03
Aluminum sandwich panel cladding for Pre-Digester	610.73	m^2	19,569	2.16
Aluminum sandwich panel cladding for Post-Digester	357.36	m^2	11,167	1.23
EPDM membrane for Pre-Digester	774	m^2	5,354	0.59
The profile made of stainless steel material and membrane fixing hose for Pre-Digester	87	m^2	1,350	0.15
Pre-Digester under-membrane stretching knitted mesh	774	m^2	1,196	0.13
EPDM membrane for Post-Digester	324	m^2	2,236	0.25
The profile made of stainless steel material and membrane fixing hose for Post-Digester	57	m^2	856	0.09
Post-Digester under-membrane stretching knitted mesh	324	m^2	639	0.07
Compressed air distributor for hose system	1	set	1,057	0.12
Agitator system			**14,510**	**1.60**
Blade agitator for Pre-Digester	3	pieces	6,140	0.68
Blade agitator for Post-Digester	2	pieces	3,630	0.40
Blade agitator for Slurry	1	pieces	2,070	0.23
Submersible agitator for lagoon	1	pieces	2,670	0.29
Substrate pumping, piping, and distribution system			**31,250**	**3.44**
Substrate pump (30 m^3/h, 2 bar, 4 kW,224 rpm)	1	pieces	8,100	0.89
Substrate pneumatic valve	8	pieces	1,295	0.14
Substrate ball valves	15	pieces	1,356	0.15
Substrate collector and 160 m HDPE piping	1	pieces	20,499	2.26
Digesters heating and heat distribution system			**27,658**	**3.05**
Floor heating system for Pre-Digester (D = 16 mm, Pe-RT Pipe)	1550	m	3,200	0.35
Wall heating chromium pipe for Pre-Digester (D = 32 mm)	803	m	5,500	0.61
Wall heating chromium pipe for Post-Digester (D = 32 mm)	257	m	1,860	0.21
Plate heat exchanger	1	pieces	5,000	0.55
Expansion tank	1	pieces	500	0.06
Ball valve for heating system	33	pieces	4,600	0.51
3-way solenoid valve (DN 50)	4	pieces	1,510	0.17
Circulation valve (Lowara ecocirc XL 25–60)	4	pieces	2,088	0.23
Single serpentine 800-L water boiler (WENTA)	2	pieces	1,620	0.18
Thermometer	10	pieces	125	0.01
Manometer	2	pieces	30	0.00
Brass heat distribution collector (1″-16x2 PN 10-9 edged)	4	pieces	125	0.01
Labor costs			1,500	0.17
Compressed air system			**3,575**	**0.39**
Compressor and oil retainer hose	500	liters	2,500	0.28
Island valve group for mounting on PLC panel	1	pieces	500	0.06
Connecting hose and air control sensor	1	pieces	575	0.06
Gas system			**25,750**	**2.84**
Flare (140 m^3/h)	1	set	14,500	1.60
Biogas analyzer (SWG 100, CH4, CO2, H2S, O2)	1	set	11,250	1.24
System control automation			**60,182**	**6.63**
Main system control automation and PLC panel	1	set	22,000	2.42
22″ screen PC Hardware for SCADA	1	set	2,700	0.30
230 V AC, 4 KVA for control	1	set	450	0.05
Hydrostatic level sensor for Pre-Digester	1	piece	675	0.07
Hydrostatic level sensor for Post-Digester	1	piece	675	0.07
Flowmeter for slurry	1	piece	1,500	0.17
Flowmeter for a buffer tank	1	piece	1,500	0.17
Level control sensor for slurry	1	piece	100	0.01
Level control sensor for a buffer tank	1	piece	120	0.01
Maximum level control sensor for Pre-Digester	1	piece	110	0.01
Pre-Digester heat control sensor (Pt-100, 50 cm)	1	piece	90	0.01
Temperature sensor for heating circuit	1	piece	110	0.01
pH control sensor for Pre-Digester and Post-Digester	1	piece	291	0.03

(*continued on next page*)

Table 3 (*continued*)

	Size	Unit	Cost (€)	Percentage
Dosing pump for NaOH	1	piece	491	0.05
Reflow prevention	2	piece	150	0.02
instant requirement panel, fire detection, and alarm system	1	set	10,025	1.10
Lightning rod system for transformer protection	1	set	4,285	0.47
Ambient lighting	1	set	2,400	0.26
Cable in the galvanized pipe for lighting	1	set	6,200	0.68
A detector, alarm, and telephone	1	set	6,310	0.70
Separator unit			**34,100**	**3.76**
Screw manure separator (EYS SP600, up to %26 DM)	5.5	kW	28,800	3.17
Separator concrete base and protection platform	1	set	5,300	0.58
Biogas conditioning and desulphurization system			**40,082**	**4.42**
Biogas blower	230	m^3/h	3,067	0.34
Chiller (MIT-SG-S 161 Air cooled,R410A)	13760	kcal/h	1,550	0.17
After cooler (Shell tube double pipe heat exchanger, 230 m^3/h, 500 mbar)	45–10	^oC	2,710	0.30
Turbine meter and quantometer (from 8 m^3/h to 6500 m^3/h, steel body, PN 16)	1	piece	1,440	0.16
Biogas filter	1	piece	215	0.02
Desulphurization tank for H2S removal with Fe2O3 (2 unit AISI 304 stainless steel cylindrical tank)	0.78	m^3	3,900	0.43
Cyclone tank for moisture removal (AISI 304 tank)	2	units	2,500	0.28
Fe2O3	4	tons	200	0.02
Biogas flare unit	140	m^3/h	24,500	2.70
Combined Heat and Power System			**342,400**	**37.74**
CHP module (JMS 312 GS-BL)	625	kWh/h	301,400	33.22
Other mechanic instruments for CHP (gas flow meter, manometer, thermometer, oil tank, control panel, activated carbon filter, cable and oil channels, etc.)	1	set	41,000	4.52
Grid connection system and MV cells			**125,050**	**13.78**
Breaker ınput-output unit	3	units	16,000	1.76
Voltage transformer cell	1		3,200	0.35
Transformer protection with load breaker	1		3,150	0.35
Measuring cell with load separator	2		7,200	0.79
LV panels (3 units)	1600	kVA	42,000	4.63
LV output compensation (3 units)	1600	KVA	31,500	3.47
Transformer (4 units)	500	kVA	22,000	2.42
Additional costs			**7,500**	**0.83**
Customs, insurance, security			7,500	0.83
Total costs			**907,257**	**100.00**

$$\dot{Q}_D = \frac{2\times\pi\times H\times k_{insulation}\times(T_D - T_{m,a})}{\ln\left[\left(D/2\right)+\left(\frac{L_D+L_{insulation}}{D/2+L_D}\right)\right]} + k_{insulation}\times\left(\frac{T_D - T_{m,a}}{L_{insulation}}\right) \tag{12}$$

where T_D, L_D, $L_{insulation}$, and $T_{m,a}$, respectively, define the digester temperature (^oC), digester wall thickness (m), insulation material thickness (m), and minimum ambient temperature (^oC).

$$\dot{Q}_m = m_{manure}\times C_{p_m}\times(T_D - T_m) \tag{13}$$

The following formula can be used to quantify the volume of heat per meter of heating pipe:

$$Q_p = \frac{T_{w,a} - T_D}{2\times\pi\times\left(\frac{D_p - 2\times L_{p,w}}{2}\right)\times 10^{-2}\times h_i + \left[\frac{D_p/2}{\frac{D_p - 2\times L_{p,w}}{\pi\times k_p}}\right] + \frac{2}{2\times\pi\times\frac{D_p}{2}\times 10^{-2}\times h_o}} \tag{14}$$

where, Q_p is the heat capacity of heating pipe installed digester per meter, Tw,a denotes the average temperature of the water, D_p is the pipe's diameter, $L_{p,w}$ defines wall thickness of the pipe. Also, kp, hi, and ho denotes the heat transfer coefficient of heating pipe material, coefficient of convective internal heat flow of the heating pipe, and the coefficient of external convective heat flow of the heating pipe, respectively.

The total length of the heat pipe used to heat the digester for anaerobic fermentation is written as:

$$L_p = \frac{(Q_D + Q_m)}{Q_p} \tag{15}$$

where L_p (m) is the total length of the heating.

2.4.4. Capacity of the desulphurization unit

Fe_2O_3 in the amount of 870.15 mg has approximately 1 gr H_2S removal capacity. The density of biogas is 1.2 kg/m3, there is 0.05–0.3% H_2S in 1 m^3 of biogas. The hydrogen sulfide ppm value (parts per million) in the Biogas Energy Plant was taken as 2000 ppm (2000/1.000.000 = 0.002). The density of Fe_2O_3 is taken as 5300 kg/m3. 229 m^3/h of biogas was produced in the AK-SÜT Biogas Energy Plant. According to these data, the volume of the desulphurization tanks was made as follows:

$$V_{ds} = \frac{V_{biogas} * 720\ h * 1.2 \frac{kg}{m^3} * 0.002 * \frac{870.15}{1000} \frac{mg}{mg}}{5300 \frac{kg}{m^3}} \tag{16}$$

Fe_2O_3 (hematite) can be used for more than 30 days (720 h) to adsorb H_2S. Where V_{ds} is the volume of the desulphurization tank, Vbiogas is the biogas yield. When all values are written in equation (16), the desulphurization tank's annual volume is found as 0.78m^3. Approximately 4.134 kg of hematite per year is sufficient.

2.4.5. Economic analysis

The economic viability of this investment, like any other, is a vital consideration in making a final decision to proceed or not. In this part, the cost and benefits of a biogas energy plant including investment costs such as construction of the digesters systems, agitators, substrate pumping, piping and distribution systems, digester heating system, gas treatment system, automation system and software, separator unit, CHP module, grid connection, and MV cells are discussed. The total expense of the device covers investment expenses, operating and repair costs, premiums, and taxation, as well as the system's intake and end-use. The cost of an anaerobic digester depends on the installation's particular criteria. As a result, determining investment costs in advance is challenging. It is important to note that an anaerobic digester's overall investment costs range from €1250 to €3500 per kWh/h electricity generation to understand better what has been said so far. The investment cost calculations of the case study were given in Table 3.

According to Table 3, the highest investment cost of this study was calculated as 342,400 € for the combined heat and power system, where the lowest one was obtained as 3,575 € for the compressed air system. On the other hand, the investment cost of the digester system by 198,949 € is an essential part of the investment costs. Also, Table 3 shows the investment cost calculations of this study for the digestion of 19,272 t/a of dairy cow manure plus 7,300 t/a poultry manure.

An anaerobic digester's numerous components will fail, and they will always need to be repaired. As a consequence, maintenance is required regularly. The CHP unit needs service for 2,000 to 20,000 operational hours and needs an overhaul for every 40,000

Table 4
Comparison and periodic maintenance data of CHP for the biogas yield of 229 m^3/h (LHV:5.5 kWh/h).

Parameter	Unit	Perkins 2x4006 TRS1	Perkins 1x4008 TRS2	Camda 2xKDGH300-G	Ge Jeanbacher 1xJMS312 GS-BL	MWM TCG 2016 V12C
Engine Electric Power	kWh/h	2x311	509	2x300	637	600
CHP electrical efficiency	%	37.93	39.27	33.6	40.1	42.46
The average load of the engine	%	67.56	87.28	50	85	90
The average efficiency of the engine	%	36.70	38.80	31.30	39.5	41.5
The electrical power that the existing gas can generate	kWh/h	420	444	358	452	475
The available heat at full load	kWh/h	866	602	856	703	608
Oil consumption for 1 kW	g/h	0.17	0.14	1	0.2	0.12
Oil consumption in 8000 h	kg	796.16	570	4800	1019	576
Oil maintenance cost in 8000 h	3.65 €/kg oil	2905	2080	17520	3720	2102
Oil maintenance cost in 40000 h	3.65 €/kg oil	10603	10403	87600	18600	10512
Main maintenance time	h	64,000	64,000	25,000	60,000	48,000
Warranty period	year	2	2	1	2	2
Periodic and Main maintenance total cost	€	259,618	245,973	-	461,641	350,400
Average hourly cost	€	3.29	3.29	-	7.69	7.30
Price	€	277,704	219,363	-	301,400	300,000
Maintenance cost according to 40000 h	€	131,600	131,753	120,000	307,760	292,000
Total cost	€	447,667	397,696	306,714	627,361	602,512
Cost of electricity generated per hour (0.11 €)	€	46	49	39	50	52
Cost of electricity generated annually	€	369.8	391	315.4	398	418.2
The cost of electricity generated 40000 h	€	1,848,946	1,954,744	1,576,834	1,990,010	2,090,770
Total cost of CHP investment	€	447,667	397,696	306,714	627,361	602,512
Total income of the investment over 40000 h	€	1,342,469	1,713,046	1,384,336	144,892	1,835,461
Ratio of investment income to expenses	year	3.00	3.57	3.73	2.30	2.52

operational hours. In each 3–5 years, the pumps must be overhauled. The other installation components are unlikely to wear out by the end of the mechanical lifespan (10–20 years) under standard conditions, although certain repairs might be needed. Before choosing the CHP module, a comparison was made with other co-generators for the same power output. While making these comparisons, oil consumption, efficiency, initial investment cost, and maintenance costs were considered. For this reason, CHP comparison and consumption values were given in Table 4.

According to Table 4, the JMS312 GS-BL CHP module was preferred due to its 2.30-year depreciation period and ease of maintenance and repair. Moreover, the oil consumption of the CHP unit was taken as €3,720 per 8,000 operational hours, €18,600 per 40,000 operational hours; the periodic maintenance cost was taken as €30,7760 per 40,000 operational hours. The total cost, including investment cost, annual oil consumption, and recurring maintenance costs, was taken as €627,361 per 40,000 operational hours.

The definitions of net present value (NPV) and intrinsic return rate are used as assessment metrics to assess the system's viability. NPV is the sum of expected net cash flow measured in today's currency and is given by Refs. [37,38]:

$$NPV = -I + \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{17}$$

$$CF_t = p_t O_t - v_t X_t - FC \tag{18}$$

where CF, r, and I denote the expected cash flow at time t, the discount factor, and the initial capital investment cost. CF is a function of income pt from I outputs (O) where output relates to electricity, heat, and digestate; variable costs (X_t) includes feedstock prices, operating and maintenance costs, and disposal costs of digestate and water; and FC is all fixed costs such as labor cost and interest expense. The total investment cost is € 907257, which accounts for Pre-Digester, Post-Digester, Slurry, lagoon, CHP unit, separator, biogas treatment desulphurization unit, automation, pipe and instruments, grid connection and transformers, substrate and heat collector and gas system and analysis devices. The plant's total lifespan was predicted to be 20 years. The economic analysis is focused on a ten-year subsidy of €0.11 per kWh. The discount rate was assumed to be 14%. Full labor costs, poultry manure transport costs, operational and taxes were respectively taken as €49,411, €17,756, €24,197 per year. Periodic maintenance and overhaul costs were taken as €18,600 per operating year. However, it was taken as €41,200 for each fourth year and €326,360 at the end of each fifth year. Maintenance of the digester, CHP machine, pumps and agitators, and separator are all included in the operating and maintenance costs.

The cost of greenhouse gas pollution was estimated to compare the case study's environmental results. All the CO_2 generated by anaerobic digestion and the related combustion is biogenic. It is caused by living beings absorbing CO_2 from the environment. As a result, it is not a greenhouse gas, and biogas can supplement conventional greenhouse gas-producing energy sources such as electricity and natural gas. The combustion of 1 m^3 biogas generates 2.76 kWh/h of energy, equal to 1.96 kg CO_2. The cost of GHG emissions must be applied to the plant cost to account for global warming; hence, the cost of CO_2 for biogas combustion in a CHP generation unit is roughly €6.84/t CO_2.

For the development of an anaerobic digestion treatment facility, the energetic investment is embodied energy. The capital cost of an energetic investment may be related. A plant with a capacity of 625 kWh/h electricity generation needs an energetic expenditure of €907,257, according to the cost of Biogas energy plant.

3. Results and discussion

3.1. Results of technical analysis

The amount of produced biogas is determined by the feedstock's organic content, metabolic energy, gross energy of the ruminant animals, and biodegradability. Organic Dry Matters were 89.4% and 87% for dairy manure and poultry manure, respectively. Carbohydrate, fat, protein, cellulose, and total nitrogen values are given in Table 2. The amount of biogas obtained per 1 kg of ODM in the hydrolysis stage is shown in Table 5.

As can be seen from Table 5, the most biogas production per dry organic matter is obtained from fats with 1000–1250 L/ODM value. On the other hand, carbohydrates and cellulose produce a nearly identical range of biogas while the biogas obtaining protein is least among all dry organic matters. Besides, Table 6 presents metabolic energy (ME) and gross energy (GE) for ruminant animals.

According to Table 6, the moisture (M) and raw ash (RA) values were obtained as 9.7% and 15.42%, while DM and ODM were calculated as 90.3% and 74.88%, respectively. Simultaneously, ME and GE values for ruminant animals were calculated as 2611.93 kcal/kg DM and 2964.35 kcal/kg ODM, respectively. In contrast, the core material non-nitrogen (CMNN) was calculated as 606.53 g/

Table 5
The amount of biogas obtained per 1 kg of ODM in the hydrolysis stage.

Hydrolysis stage	Organic Dry Matter (ODM)	Theoretical Gas Value (lt/kg ODM)	Practical Gas Value (lt/kg ODM)	CH_4 content (%)	CO_2 content (%)
1	Carbohydrates	830–960	700–790	50	50
2	Fats	1,400	1,000–1,250	68	32
3	Protein	900	600–700	71	29
4	Cellulose	830	700–785	50	50

Table 6
Metabolic energy calculation in ruminant animals.

	Unit	Value	Formula
RP (Raw Protein)	g/kg DM	10	Sample Analysis
RF (Raw Fat)	g/kg DM	1.87	
RS (Raw cellulose)	g/kg DM	8.24	
RA (Raw ash)	%	15.42	
M (Moisture)	%	9.7	
ODM (Organic dry matter)	%	74.88	ODM = DM-RA
DM (Dry matter)	%	90.3	DM = 100-M%
RE (Ruminant energy)	kcal/kg DM	2,676.81	GE*DM/1000
ME (Metabolic energy)	kcal/kg DM	2,611.93	ME = 2.871*RP+7.416*RF+1.196*RS+3.349*CMNN
RP1	g/kg ODM	133.54	1000*RP/ODM
RF1	g/kg ODM	24.97	1000*RF/ODM
RS1	g/kg ODM	110.04	1000*RS/ODM
GE	kcal/kg ODM	2,964.35	3260+(0.455*RP1)+(3.51*RF1)-(4.037*RS1)
CMNN (core material non-nitrogen)	g/kg DM	606.53	1000-(RP-RF-RS-RA)

kg DM.

The methane produced in the biogas energy plant was approximately 13.6% of the gross energy (GE) and 5.3% of the metabolic energy (ME). Considering the motors' consumption values in the biogas power plant, the hourly electricity consumption value was calculated as 32,755 kWh/h. While calculating this value, the hourly working time of all machines has been taken into consideration. The internal electrical power consumption of BEP is summarized in Table 7.

According to Table 7, the highest power consumption was calculated as 15 kW for the pre-digester mixer and lagoon submersible agitator. In comparison, the lowest of that was founded as 0.1 kW for the circulation pump. The post-digester mixer's power consumption was calculated as the second-highest value with 11 kW for the internal consumption. On the other hand, approximately 5.24% of the biogas energy plant's electricity was calculated as internal consumption and 1.73% as losses. Table 8 summarizes the case study's technical findings, including biogas and power capacity per ton of input manure, as well as biogas characteristics.

Table 8 displays hourly, monthly, and annual biogas and methane production rates throughout the experiment period. In addition, the methane content in the biogas generated in the experiments recorded as 55% and 52% for the dairy cow and poultry manure, respectively. The reactor began receiving 52.8 t/d dairy cow manure and 20 t/d poultry manure in May, with an HRT of 33 days and an average OLR (organic load rate) of 3.23 kg ODM/m^{3}d for dairy cow manure and 0.44 kg ODM/m^{3}d for poultry manure, respectively. The average biogas yield per hour was 229.49 Nm^3, corresponding to 470 m^3/t ODM for dairy cow manure and 439 m^3/t ODM for poultry manure. The co-digestion of cow manure and poultry manure resulted in 909 m^3 biogas combined ton ODM waste. The producible electricity and heat energy, in-biogas energy plant consumption value, and losses are given in Table 9.

Table 9 shows the generation and consumption of electricity and heat energy amounts for the feedstock received by the biogas energy plant. The CHP framework covers minimal load. This load enables an annual running time of more than 5,000 h. In Akcadağ, Malatya, a case study was performed, and a JMS 312 GS-BL GE-Jeanbacher CHP unit, with 8,000 running hours a year, was installed to produce electricity and heat. This generating unit's power class is usually about 625 kWhe per hour. Biogas is used to generate electricity using a CHP generator, which derives mechanical energy from thermal energy. The maximum energy produced from 260.06 m^3/h biogas is 1576 kWh/h. The maximum available energy produced in the biogas energy plant from 229.49 m^3/h biogas, using 72.8 tons of dairy cows and poultry manure per day, is 1265 kWh/h. According to these results, the CHP module works with 80.26% efficiency. The highest possible conversion efficiency for electricity in this case study was about 40%. The rest of the electricity, with an

Table 7
The internal electrical power consumption of BEP.

Output unit	Connection	Voltage (V)	Power (kW)	Cable cross-section (mm2)	Quantity	Operation time per hour
Slurry Submersible agitator	direct	380	5.5	4x2.5	1	10 min
Poultry manure balancing unit mixer	direct	380	5.5	4x2.5	1	4 min
Manure Pump	direct	380	7.5	4x2.5	1	8,29 min
Pre-digester mixer	wye-delta connection	380	15	4x6	3	8 min
Post-digester mixer	wye-delta connection	380	11	4x6	2	8 min
Lagoon Submersible agitator	direct	380	15	4x2.5	1	8 min
Separator	direct	380	5.5	4x2.5	1	60 min
Separator pump	direct	380	5.5	4x2.5	1	60 min
Desulphurization Blower	direct	380	5	4x2.5	1	60 min
Membrane electrical panel	direct	220	3	4	1	60 min
Dosing pump	direct	330	1.5	2.5	1	5 min
Air compressor	direct	220	1.5	3x1.5	1	5 min
Circulation pump	direct	220	0.1	3x1.5	4	60 min

Table 8
The case study's technical findings, including biogas and power capacity per ton of input manure.

Output balance	Dairy cow manure	Poultry manure
Total gas yield per year (Nm^3/a)	1,222.02	788,750
Total gas yield per day (Nm^3/d)	3,348	2,160.96
Total gas yield per hour (Nm^3/h)	139.45	90.04
Total gas yield per ton DM (Nm^3/tDM)	420	382
Biogas yield per ton ODM ($Nm^3/tODM$)	470	439
Methane concentration (%)	55	52
Calorific Value of biogas (kWh/m^3)	6.1	6
Biogas density (kg/m^3)	1.2	1.2
Total energy for input manure per hour (kWh/h)	845.46	535.08
Energy efficiency per input manure (%)	60.79	38.47
Electricity energy per ton of input manure (kWh/t)	15.37	25.68

Table 9
The biogas energy plant's outcome of the generation and usage of electricity and heat energy.

Parameter	Unit	Value
Average annual operating hours	h	8,000
Biogas production	m^3/h	229.49
Methane production	m^3/h	139.08
Maximum input energy of CHP	kWh/h	1,576
Producible Energy of CHP	kWh/h	1,265
Total efficiency of CHP	%	80.26
Electrical efficiency	%	40.1
Producible electrical energy per year	kWh/a	4,915,002
Producible electrical energy per hour	kWh/h	625
Internal electrical energy consumption per hour	kWh/h	32,755
Internal electrical energy losses	kWh/h	10.82
Useable electrical energy per hour	kWh/h	581.42
Thermal efficiency	%	44.67
Producible heat energy per year	kWh/a	5,164,152
Maximum Producible heat energy per hour	kWh/h	640
Intercooler (Tin = 70 °C, Tout = 73 °C)	kWh/h	97
Lubricating oil heat (kWh/h) (Tin = 73 °C, Tout = 75.3 °C)	kWh/h	71
Engine jacket cooling heat (Tin = 75.3 °C, Tout = 81.1 °C)	kWh/h	186
Chimney waste heat exchanger (Tin = 81.1 °C, Tout = 90 °C)	kWh/h	286
Internal heat energy consumption of digesters	kWh/a	2,534,400
Useable heat energy per year	kWh/a	2,629,752
Useable heat energy per hour	kWh/h	328.72
Digester temperature	°C	40
The temperature of input material for pre-digester	°C	8
Temperature of input material for post-digester	°C	31
Minimum outside temperature	°C	-20
Annual average temperature	°C	7.5
Maximum heat energy consumption of pre-digester	kWh/h	246.48
Maximum heat energy consumption of post-digester	kWh/h	70.31
Maximum total heat energy consumption	kWh/h	316.79
Average heat energy consumption per hour for digesters	kWh/h	265.6

efficiency of 44.67%, has been held as heat. The case study produced 4,915,002 kWh of electricity per year from the digested feedstock. The maximum amount of electricity that could be generated was 625 kWh per hour. The producible heat energy has been 5,164,152 kWh per year and 640 kWh per hour, respectively. Heat requirements of the input material with the temperature of 8 °C and maximum heat energy consumption of the input material with the temperature of -20 °C for pre-digester and post-digester have been 316.79 kWh per hour. The maximum heat demand of the pre-digester and post-digester calculated by Eqs. (12) and (13) have been 246.48 kWh/h and 70.31 kWh/h, respectively, according to the minimum outside temperature of -20 °C. The average heat energy consumption of the digesters has been 265.6 kWh per hour. The useable electricity and heat energy rates for this period were respectively 581.43 kWh and 328.72 kWh per hour.

A significant percentage of pathogens and seeds have been destroyed due to the substrate being heated in the digester. The degree of this reduction increases by the increase of process temperature. The separator separates the solid and liquid fractions. These fractions are stored in the lagoon unit and the pond.

3.2. Results of economic analysis

The economic outlines for the BEP using dairy cow and poultry manure as substrates were investigated throughout the NPV analysis method since it considers the time value of the money. In the analysis, the average lifespan of the plant was taken into account as 20 years. The discount rate was included as 15.75%. The NPV analysis results are given in Table 10.

According to Table 10, the total initial investment cost was omitted as 954,315,82 € including the commissioning cost. Total labor cost was taken as 49,411.76 € per annum for the five qualified personnel, and taxes were taken as 24,194.67 €. The cost of short-distance transportation within the farm boundary with the total amount of 7,300 t/a poultry manure was taken as 17,756.00 €. Although the dairy cost manure forms the primary source of the biogas plant, it was not included in the analysis since any payment was not made due to the self-production. In terms of taxes, the emission taxes of CO_2 were taken into consideration. In this regard, the CO_2 production sourced by the combustion of biogas (1.96 kg CO_2/m^3 biogas) was calculated as 3,537.23 tons per annum. Therefore, a tax of 24,194.67 € per annum was included in the tariffs.

The operating and maintenance cost was taken as 18,600.00 € for every single year. Since the pumps and agitators need an overhaul every four years, an additional overhaul cost of 22,610.00 € was added to operating and maintenance costs. Taking the standard overhaul of the CHP unit, an additional cost of 307,760.00 € was also added to operating and maintenance costs for every five years. The economic analysis was based on a subsidy level of 0.11 €/kWh and 0.031 €/kWh for the first ten years and the remained years, respectively, considering the governmental regulations into consideration. After the internal usage, the electricity benefit was recorded as 502,951.76 € for the first ten years. It was recorded as 143,247.12 € for the last ten years. The benefits from the heat energy were mounted on the energy cost of the natural gas equivalent. It was determined as 36,404.79 € for every single year. The obtained solid and liquid fermented organic fertilizer was used for irrigation and fertilizer purposes on 4,290 decares of land. Therefore, the obtained solid and liquid organic fertilizer gains were not specified in the NPV analysis. The excellent price for this period leads to a payback time on the entire system investment of 2.22 years. The NPV of the system was determined as 944,714.44 €. So, the system was found appropriate for the investment.

3.3. Comparative evaluation

The case study of the biogas energy plant process is carried out in Malatya. In this regard, the feedstock, electricity and thermal energy, environmental effect, and economic analysis are obtained for the BEP. Tables 1 and 2 show the main parameters of the digesters (pre-digester, post-digester) along with the quantity and description of the substrates of the analyzed BEP. In the present study, the biogas energy plant was projected by 19,272 tons dairy cow and 7,300 tons poultry manure with a total installed capacity of 26,572 tons of input annually. The daily incoming fresh dairy cow and poultry manure are 52.8 tons and 20 tons, respectively. Bacanetti et al. [39] used as substrate 55 tWB/day silage maize and 45 tWB/day pig slurry in Vercelli BEP (produced 11,438 Nm3/d biogas), 33 tWB/day silage maize in Pavia biogas energy plant (produced 6,590 Nm^3 biogas), and 210 tWB/day pig slurry in Lodi biogas energy plant (produced 2,811 Nm^3 biogas). Although the substrates used in the present BEP differ from Ref. [39], the received biogas with a value of 5,508.96 m^3/d, obtained from the daily 72.8 tons of fertilizer mixture, is agreeable.

The producible energy was recorded as 1265 kWh/h comprising 625 kWh/h electrical energy and 645 kWh/h thermal energy. The electrical, thermal, and total efficiencies of the process are 40.1%, 44.67%, and 80.26%, respectively. These values are agreeable with the data in the literature [39]. The BEP of Malatya reduces 14,105 t/a of CO_2 emissions. From the obtained results, it is evident that the BEP system presents lower carbon dioxide emissions than reports by Bacanetti et al. [39], Manesh et al. [40], and Leonzia [41].

An economic analysis is conducted deeply for the biogas energy plant following the NPV method in the present study. The estimation of each equipment costs is analyzed according to their size and capacities. The results, exposed in Table 10, show a total investment of 907,257.00 €. Economic analysis shows that the plant is economically feasible with an NPV of 944,714.44 € and a payback period (PBP) of 2.22 years. The conducted BEP is more appropriate for the investment than Leonzia [41] and agreeable compared to

Table 10
Economic results of this study based on NPV model.

	Present	1	2	5	10	15	20
Investment							
Initial investment cost	-907,257.00	-	-	-	-	-	-
Commissioning cost	-47,058.82	-	-	-	-	-	-
Cash flow							
Expenses							
Taxes (CO_2)	-	-24,194.67	-24,194.67	-24,194.67	-24,194.67	-24,194.67	-24,194.67
Periodic maintenance and overhaul cost	-	-18,600.00	-18,600.00	-326,360.00	-326,360.00	-326,360.00	-18,600.00
Transport cost for poultry manure	-	-17,756.00	-17,756.00	-17,756.00	-17,756.00	-17,756.00	-17,756.00
Cost of dairy cow manure	-	0.00	0.00	0.00	0.00	0.00	0.00
Labor cost	-	-49,411.76	-49,411.76	-49,411.76	-49,411.76	-49,411.76	-49,411.76
Incomes							
Electricity benefit	-	502,951.76	502,951.76	502,951.76	502,951.76	143,247.12	143,247.12
Heat benefit	-	36,404.79	36,404.79	36,404.79	36,404.79	36,404.79	36,404.79
Salvage	-	-	-	-	-	-	90,725.70
Total cash flow		429,394.12	429,394.12	121,634.12	121,634.12	-238,070.52	160,415.18
Cumulative cash flow	-954,315.82	-524,921.70	-95,527.57	862,284.80	2,678,885.42	2,696,962.82	3,113,525.92
Discount rate (15.75%)	1.000	0.864	0.746	0.481	0.232	0.111	0.054
Present value	-954,315.82	370,966.85	320,489.72	58,539.69	28,173.80	-26,539.37	8,606.48
NPV	**944,714.44**						

Manesh et al. [40]. The unit investment reported as 1451 €/kW (1683 $/kW) is much more attractive than the literature values ranging between 2000 and 4000 $/kW [42]. Since most of the manure used in the BEP is self-obtained, the unit biogas production cost (0.32–0.61 $/m^{3}CH$_4$) is lovely in comparison to literature (0.5–0.8 $/m^{3}CH$_4$) [43].

4. Practical and policy implications

A BEP project development can be regarded as the process required to realize an operational anaerobic digester. The various steps of this process are shown in Fig. 5.

A BEP project development starts with an idea outlined at a basic level to provide a general impression of the feasibility (project creation). This level is then worked out to provide a detailed overview of the project's technical, economic, and feasibility study. If the feasibility looks promising, architectural, static, mechanical, and electrical projects are prepared, and all necessary actions are undertaken to start the actual implementation of the installation. At this point, as a project realization, BEP can be constructed. After this phase, the anaerobic digester is ready for commissioning and start-up. This section deals with all aspects of the development of an anaerobic digester up to project preparation.

Biogas Energy Plant projects are complex, and their economic success depends on various aspects that influence the technical and economic feasibility. Therefore, it is crucial to consider the relevant technical, organizational, economic, and financing issues at an early stage when developing biogas energy plant projects. In this first phase, project creation, some relevant questions have to be answered positively:

- What kind of technique will be used? Is the existing infrastructure of the desired location (a farm, for example) used optimally?
- What types of facilities are required? For example, is it technically possible to feed in the electricity using the current grid connection? Can the net heat energy be used ın places such as greenhouse, residential heating and process heat?
- Is it possible to supply co-substrates such as energy crops, poultry manure, and sheep dung at close range?
- How can the digested or co-digested manure be disposed of?
- Is the biogas energy plant project economically feasible?

The type of manure (from cattle, dairy cow, poultry, sheep, etc.) determines the biogas yield, but the dry matter and organic dry matter content in the manure are also essential. Economic feasibility is the basis of every commercial project. In the creation phase, a cost analysis at a basic level is sufficient. In section 2.6.5, a calculation method is presented for estimating the economic feasibility of a BEP. If this and the other questions have a positive outcome, the project development can continue with the next phase. The economic feasibility of BEP project depends on various factors. The feed-in tariff for electricity from biogas and possible subsidy schemes are determined mainly by the government. The electricity generated can be used by the farm in the field or fed into the electrical grid connection. This assessment will depend not only on the tariffs of both but also on the sustainability goals of the biogas energy plant owner. The heat produced with the biogas energy plant can satisfy a local heat demand. However, the transport of heat is relatively expensive. So the final heat demand should be within a small radius of the heat production (a maximum of 200 m as a rule of thumb, but preferably less) [44].

Is it possible to obtain necessary licenses such as environmental impact assessment, soil, geological structure, and protection of cultural assets? In general, building permits and environmental permits are necessary for BEP project installations. It is advisable to check whether permission is needed to use the digestate as a fertilizer. It should also be checked whether there is a zoning plan for the desired location of the digester. When planning to establish a BEP project where electricity is produced and fed, it is essential to apply the authority designated network access. Usually, this authority is either a government agency or a network operating company. However, certain conditions regarding grid access can affect costs. For example, the capacity of local power lines or converter substations may be smaller than required; therefore, additional line capacity may need to be created. Commonly BEP systems and related buildings have to be granted building permits for the erection of the system. In general, various technical skills in the assembly process of technical systems and only authorized personnel should work. Especially when working systems in the grid connection, only the company operating a particular network can do this under common rules and standards. Especially in gas lines, gas conditioning units, security systems, and pressure lines, all safety must be provided. Compliance with emission regulations is one of the most critical elements in biogas power plants and must be proven during the approval process. Emission regulations in Turkey, the type of fuel used, the power capacity, and the combustion process the technology used are essential. Emission limits set in relevant regulations often require specific flue gases, cleaning technologies, measurement equipment, and control devices. It is evident that it affects the investment costs; so do the feasibility of the project. For every 100 km increase in transportation distance, global warming potential benefits decrease by about 10% Therefore collection and transportation of organic waste within local range is environmentaly efficient, but extended transportation should be avoided [40].

As a result, various documents must be submitted to the different approval authorities, together with the official license application documents. Application forms include:

✓ Description of the project
✓ Architecture, static, mechanical, and electrical project drawings
✓ Description of the BEP
✓ Process flow diagram and P&I Diagram
✓ Operating times of system components

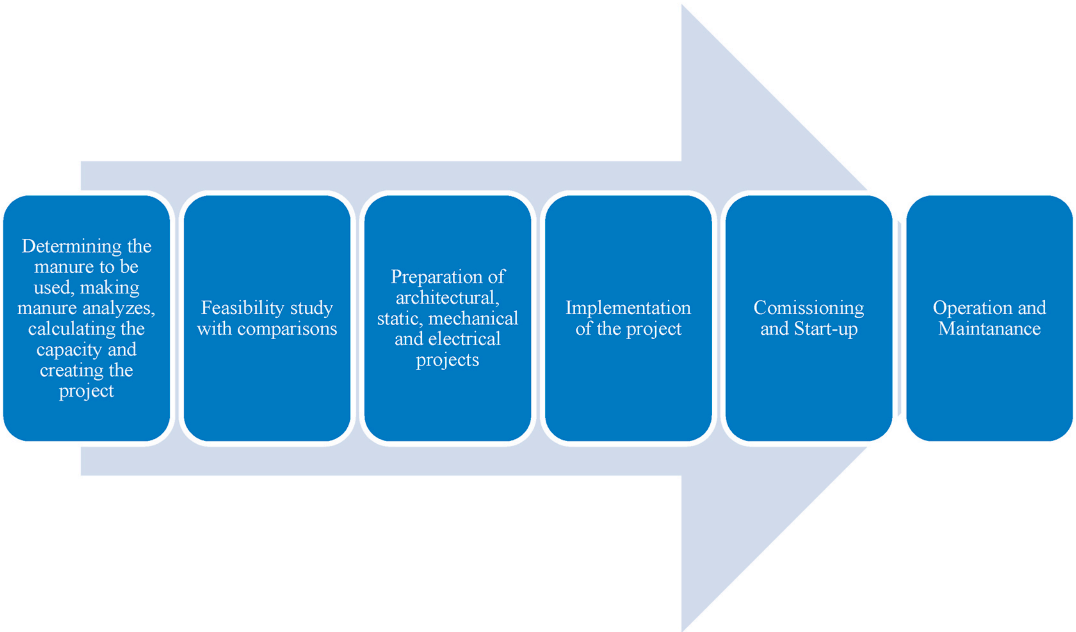

Fig. 5. Application steps of a BEP.

✓ Technical data on system and components
✓ Emissions reduction measures
✓ Safety measures
✓ Residue and waste removal

Turkey ranked 5th in Europe and 12th in the world in terms of installed capacity in renewable energy. As of the beginning of 2021, 52% of the installed power in Turkey consists of renewable resources. (Renewable Energy Law, REL) was enacted in 2005. Progress in the field of renewable energy following its introduction has begun to be recorded. However, secondary legislation and relatively low fixed price guarantee levels renewable energy between 2005 and 2010 due to investment in its resources remained limited. With this together, in the Renewable Energy Law in December 2010 higher for some resources with the change fixed price guarantee and various monetary and non-monetary incentives have been introduced. Hence, since 2010 Renewable compared to 2005–2010 period, it can be said that the energy sector has revived significantly. In particular, the revision of fixed-price guarantees renewable energy investments domestically and has attracted international investors' attention. The support mechanism was put into operation before December 31, 2015. It was foreseen for the purchased facilities. More Decision of the Council of Ministers issued as of December 2013 was extended to December 31, 2020. The support mechanism was put into operation before December 31, 2015. It was foreseen for the purchased facilities. More Decision of the Council of Ministers issued as of December 2013, and the pricing for biogas energy plants is set at 0.133 $/kWh. Purchase guaranteed electricity tariff price is determined as 0.54 TL/kWh (0.065 $/kWh) for Biogas energy plants that will be commissioned after June 30, 2021.

5. Conclusion

In this study, the essential aspects of the planning process of a biogas energy plant and its correct management were conducted. In this regard, a large-scale biogas energy plant with an installed capacity of 26,572 tons of input manner annually was designed and investigated from the techno-economical point of view. The quantity and classification of the substrates, gas yield, component size, ruminant energy, the generation and consumption of the electricity and heat energy in the biogas plant are all used in the technical investigations. The BEP was planned for the co-generative purpose including heat and power generation. The fertilizer production and environmental aspects of the BEP were also performed. The conducted system was investigated economically using the NPV analysis concept.

The produced biogas and methane were respectively recorded as 229,49 m^3/h and 139,08 m^3/h. from the feedstock including 72.8 tons of dairy cows and poultry manure per day. The methane produced in the biogas energy plant was approximately 13.6% of the gross energy. It was determined that electricity generation in an amount of 5,256,000 kWh per year from the digested feedstock was available with an installed capacity of 625 kWh. The annual and daily heat energy outputs were calculated as 6,482,400 kWh and 640 kWh, respectively. The solid and liquid fertilizers were respectively determined as 40,891.03 t/a and 5,152.74 t/a. According to these results, the CHP module has an efficiency of 80.26%. The highest possible conversion efficiency for electricity in this case study was about 40%. The rest of the energy, with an efficiency of 44.67%, was held as heat.

Total investment costs per the produced electricity for the biogas energy plant were calculated as 1451.53 €/kWh. The main part of the plant cost was recorded as CHP unit with 37.74% of the total followed by the digester system with 21.52%. Biogas energy plant with dairy cows and poultry manure has an excellent economic situation with 2.22 years of payback time. The NPV value of €944,714.44 was showed that the plant was investable. CO_2 emission was reduced by 14,105 tons per year.

Author statement

Assoc. Prof. Dr. Abdullah Akbulut: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision.

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Dr. Oguzhan Erbas: Conceptualization, Methodology, Validation, Data Curation, Writing - Review & Editing.

Dr. Halit Arat: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection (Investigation), Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data (Formal Analysis).

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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Nomenclature

A	Area (m^2)
a	annual
BY	Biogas yield (m^3/a)
Cpm	specific heat of the manure (kJ/kg ^oC)
BEP	Biogas Energy Plant
CHP	Combined Heat and Power
D	Diameter (m)
DM	Dry matter (%)
E	Energy (kW)
FC	All fixed costs (€)
GE	Gross energy
h_o	Coefficient of external convective heat flow of heating pipe (W/m^2K)
H	Height (m)
HRT	Hydraulic retention time
I	Initial capital investment cost (€)
K	Heat transfer coefficient (W/m^2K)
L	Length (m)
LHV	Low heating value (kWh/h)
ME	Metabolic energy
Q	Heat (kW)
ODM	Organic dry matter (%)

Greek Symbols

μ_{el}	electrical efficiency of the co-generator
μ_{th}	thermal efficiency of the co-generator

Subscripts

bs	biogas storage
cs	co-substrate
D	digester
el	electricity
m	manure
m,a	minimum ambient temperature

p pipe
pds post-digestion storage
p,w wall thickness of pipe
r,h residual heat
s storage
w,a average temperature of water

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