Signal Processing and Renewable Energy
June 2023, (pp. 91-113)
ISSN: 2588-7327
eISSN: 2588-7335

Benefits of Biogas CHP System with PEM Fuel Cell: a Case Study

Shayesteh Ebrahimizaker[1], Mostafa Khalatbari[2], Ashkan Abdalisousan[2,3*]

[1] Department of Mechanic and Energy, Shahid Beheshti University, Tehran, Iran.
[2] Department of Energy Engineering and Economics, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[3] Department of Technology and Engineering, Astara Branch, Islamic Azad University, Astara, Iran.

Received: 04-Jan-2023, Revised: 30-Jan-2023, Accepted: 01-Mar-2023.

Abstract
In recent years, in developed countries, the extraction of electricity and heat in municipal sewerage refineries has become very common. This technology generates significant amounts of energy in the form of electricity and heat. In this article, we will get acquainted with a CHP system with an average capacity of 1 MW of electrical energy and 1.2 MW of thermal energy which is used in South Tehran sewerage refinery. Due to the significant sensitivity of the economic results to the parameter of revenue from the sale of electricity to the grid and a significant effect on reducing greenhouse gas emissions, a slight increase in the purchase rate of electricity generated from biogas digesters can make this investment more attractive to many domestic and foreign investors. Also, due to the environmental importance of the anaerobic digestion of sludge in municipal sewerage refineries, such projects can also be considered from an environmental point of view. If biogas is used as fuel for this CHP power plant, the efficiency will be 44.9%, and the reduction in heating and electricity costs also will be 8299.25$/year and 66895.38$/year, respectively. In the CHP cycle of this treatment plant, we hypothetically added a PEMFC and studied this cycle, Due to the addition of this system in the cycle, the electrical efficiency of the cycle increased and also, the emission of polluting gases from the CHP system is reduced due to the consumption of the biomass source.

Keywords: Refinery, Costs, Electricity, Heat, Fuel.

1. INTRODUCTION

In recent years, the growth of energy the world. Increasing consumption of energy from fossil fuels with the release of pollutants from them, increasing carbon dioxide in the atmosphere and its consequences, and the

***Corresponding Authors Email: a.abdali@srbiau.ac.ir**

rapid economic growth of various societies, the world with threatening changes has encountered. On the other hand, the limitation of fossil resources and the non-renewability of these resources have caused energy policymakers and planners to conduct structural studies, replace energy carriers, and move towards clean fuels at the top of their plans. One of these options is the utilization of energy carriers from biomass sources such as biogas. Biogas can be used to generate electricity or heat. Since in the process of generating electricity, heat is usually generated in parallel, so heat recovery is possible in such a process. Such power plants are called CHP units for the simultaneous production of electricity and heat. Today, many countries in the world realize the importance of this issue and work on this field. [1]

It is necessary to mention that all system components are considered in steady state steady flow condition and the environment is at a temperature of 25 degrees Celsius and a pressure of 1 atmosphere.

Novelty of the paper: The combination of a PEM fuel cell with a CHP system and an anaerobic digestion tank is generally a new and rare cycle. Among the innovations used in the proposed plan, we can mention the high utilization of the cycle outputs, such as suitable uses for CO and CO_2, as well as the output heat of the CHP system. Usually, CHP systems are used only to provide electricity and heat, but in this cycle, an effective effort has been made to get benefit from the exhaust gases, including CO_2 and H_2O gas.

Also, in the proposed plan, electricity production is provided from two sources, and these two sources are both clean fuels, hydrogen and biomass, and this article also prevents the release of harmful pollution in the cycle.

Literature review: In recent years, many articles and research have been done in the field of electricity and heat production from biomass sources. In some research, some kind of fuel cells are embedded in the CHP cycle to increase the overall efficiency of the cycle. In this section, some of these researches are discussed.

In 2015 The Chartered Institution of Building Services Engineers (CIBSE) installed a solid oxide fuel cell (SOFC) micro-CHP system at its London headquarters – a converted, and recently renovated, Victorian townhouse – for testing and demonstration. Alem Tesfai reports that the fuel cell micro-CHPs have the potential to make a huge contribution towards the UK’s energy reduction targets. Initial results show the maximum heat recovered is about 1,000W at the return temperature of 15°C, and 300W at 45°C, which corresponds to an average combined efficiency of about 85%. The SOFC based micro-CHP initially started generating electricity at 62% efficiency, and after the first 3,506 hours of operation its efficiency dropped to 57%. Other results obtained in this research including the power production efficiency loss due to stack performance degradation are maintained at 1.5kW by increasing fuel flow from 2.5kW to 2.8kW. [2]

Research conducted by Huy Quoc Nguyen and Bahman Shabani under the title "Proton exchange membrane fuel cells heat recovery opportunities for combined heating/cooling and power applications" concluded that a significant amount of heat is generated by these fuel cells while operating that is equivalent to 45 to 60% of the total energy content of hydrogen entering the cells. The generated heat must be removed effectively from the stack by using a properly designed cooling system in order to prolong its lifetime and maintain its performance and the heat generated by proton exchange membrane fuel cells can be captured and used for a range of combined heating/cooling and power applications. [3]

In a research titled "Methane gas production from a mixture of cow manure, chicken manure, cabbage waste, and liquid tofu waste using the anaerobic digestion method" conducted by F Arifan et al. it is attempted to investigate methane gas production from a combination of several biomass sources. In this research, they used sources such as cow manure, chicken manure, cabbage waste, and liquid tofu waste. From the biogas produced, the maximum data obtained is in variable B4 (55% cow dung, 15% chicken manure, 15% cabbage waste, 15% liquid tofu waste) with a total amount of gas of 7140 ml. This shows that tofu liquid waste can increase the potential amount of biogas produced. [4]

According to a report from the U.S. Department of Energy and based on data from the CHP Installation Database, there are 126 fuel cell installations in the United States that are configured for CHP operation. These fuel cell CHP installations have an average capacity of 532 kW and a combined capacity of 67 MW. The majority of these fuel cells are used in commercial and institutional buildings where there is a relatively high coincident demand for electricity and thermal energy. Thermal energy recovered from fuel cells is most often used to satisfy hot water or space heating demands, although in some cases fuel cells have been integrated with absorption chillers to provide space cooling. The following table provides an overview of fuel cell operation in CHP applications: [5].

According to the investigations carried out in this report, using a fuel cell for a CHP cycle increases efficiency and is practical. Over the past years, fuel cell capital costs have decreased, and fuel cell use in multiple applications has increased. [5]

Table 1. ***Fuel Cell Attributes for CHP Applications [5].***

Size range	Fuel cells for CHP are available with capacities from 5 to 2,800 kW
Thermal output	Heat from fuel cells configured for CHP can be recovered to produce hot water, low pressure (<30 psig) steam, and chilled water (with an absorption chiller).
Part-load operation	Fuel cells have good part-load performance. At 50% of full load, the efficiency of a fuel cell will typically decline less than 2% compared to the full load value.
Fuel	Most fuel cells for CHP applications use natural gas or biogas. The gas is reformed into hydrogen, and the hydrogen is then reacted to generate electricity.
Reliability	Fuel cells use an electrochemical process with few moving parts and offer high reliability. While mechanical wear is not an issue, fuel cells do require periodic replacement or refurbishment of catalysts and fuel cell stacks.
Other	Fuel cells are quiet, have low emissions, and produce high-quality power

In 2020, research was conducted under the title "Prospects of Fuel Cell Combined Heat and Power Systems". This research that was done by Olabi and colleagues showed that proton exchange membrane fuel cell (PEMFC) operated at a lower temperature-oriented cogeneration has good efficiency, and is very reliable. The critical issue pertaining to these systems has to do with the complication associated with water treatment. This implies that the balance of the plant would be significantly affected; likewise, the purity of the gas is crucial in the performance of the system. An alternative to these systems is the PEM fuel cell systems operated at higher temperatures. [6]

The findings of the study conducted by Hossein Ali Dadi and his colleagues in the summer of 2017 under the title "Investigation of Biogas Production Process by the Mixture of Landfill Leachate and Animal Waste" revealed the possibility of producing biogas out of the mixture of waste leachate and animal wastes. Biogas reduces the risk of waste leachate disposal to the environment and facilitates the production of fertilizers containing nutrients (e.g., Na, K, N, and P). [7]

Jakub Kupecki and Krzysztof Badyda in a research titled "Mathematical model of a plate fin heat exchanger operating under solid oxide fuel cell working conditions" concluded that Micro-combined heat and power (micro-CHP) units with solid oxide fuel cells can exhibit high electrical and overall efficiencies, exceeding 85%. These values can be achieved only when high thermal integration of a system is assured. Selection and sizing of heat exchangers play a crucial role and should be done with caution. Moreover, the performance of heat exchangers under variable operating conditions can strongly influence the efficiency of the complete system. [8]

In the research conducted by Mohammad Sharifi et al. titled "Economic feasibility of energy production from animal waste using Dranco's anaerobic digestion process", from the economic point of view, the necessary calculations for a biogas power plant for the simultaneous production of electricity and heat have been carried out as a case study. The results of the study show that during the life of the project (20 years), the internal rate of return of the plan is equal to 19% of the net present value equal to 180,587,908 Tomans and also the benefit-to-cost ratio is equal to 1.032; therefore, the financial evaluation of the energy production plan in this system indicates that it is economical to implement. [9]

In an article, Alireza Soltani and his colleagues achieved the result that biological treatment is known as the most effective method for removing organic materials in urban solid waste. Biological purification includes aerobic composting and anaerobic digestion (producing biogas). In this research, the production of methane from urban waste materials was done on a laboratory scale, and at first, the effluent of a milk factory, which has a high BOD, was used, and the production of methane at medium (about 35 degrees Celsius) and high temperatures (about 65 degrees Celsius) was tested. The results show that methane production is more evident at low temperatures and about 0.21 to 0.65 cubic meters of gas methane are produced per kilogram of waste. [10]

Jabar Mohammadi Majd and Mohsen Khodabakhshipour conducted research under the title "Investigation and evaluation of methane gas production from the combination of buffalo manure and corn stubble in Khuzestan province" in 2018 to investigate the process of producing methane gas from the combination of corn stubble and buffalo waste in Khuzestan province. At the end of the research, which was a period of 28 days, the results showed that the maximum amount of methane produced in a mixture with a ratio of (20:80) was 30.83 liters and the lowest methane produced in the combination with the ratio (90:10) amounting to 13.04 liters. [11]

In a study conducted by Jalal Shaygan and Elahe Bazdar in 2018, they investigated how to collect biogas from the digester and biogas purification methods including physical, chemical, and biological purification for direct consumption in providing thermal and electrical energy and also as a Suitable option for utilization in internal combustion generators, microturbines and fuel cells to generate electricity. In this article, the process of biogas production from the source to the final consumer has been investigated. [12]

Venkatesh et el. presented a method of economic and environmental analysis for energy recovery and production from biogas produced in sewage sludge digesters in wastewater treatment plants (Oslo treatment plant in Norway). In this treatment plant, heat, electricity, and fuel can be produced from the biogas, which can be used in the treatment plant or sold. In their article, they defined seven cost scenarios for electricity, gas, wood pellets, biomethane, and gas, for each of them costs and environmental effects were determined for the years 2012 to 2021. [13]

Davodinejad et al. calculated the amount of sludge produced from sewage, biogas and the maximum electricity generation capacity in the country, and the results showed that equipping all treatment plants with an active sludge treatment system in the country has the potential to generate about 44 MW of electricity with anaerobic digesters and their exploitation and installation of the required power plant equipment. Also, considering the purification plants with anaerobic digesters, the electricity generation capacity is about 22 MW. [14]

In 2015, Hosseini et al. investigated the potential of biogas production and electricity produced from it in the treatment plants of the country, and these values are 111.6 mm^3/yr and 32.9 MW, respectively. According to the nominal capacity of the activated sludge treatment plants and based on the nominal treatment capacity, Houses with anaerobic digesters have 56.3 mm^3/yr of biogas and 16.6 MW of electricity produced. Also, in this article, effective factors and methods to increase biogas production have been investigated. The factors affecting biogas production include the type of anaerobic digester, the method of mixing in the digester, temperature, PH, C/N ratio, and retention time, and the effective methods for increasing production include ultrasonic pre-processing, oxidation pre-processing with Ozone and pre-treatment mentioned. [15]

In 2015, Sadeghi et al. investigated the production of energy from the sewage of

Kerman city from an economic and environmental point of view. In their article, they introduced the scenario of energy recovery from wastewater, which includes two scenarios of selling electricity and the scenario of consuming electricity produced in the treatment plant. They collected the required data from the energy balance sheet and the international energy website and evaluated the economic parameters of energy recovery from urban wastewater with engineering economy criteria factors such as annual life cycle cost, net present value, and internal rate of return. The results showed that the scenario of simultaneous production of electricity, heat, and sale of electricity to the grid was economically more economical. [16]

Salmani et al. investigated the CHP engine in 2015. They used the information of biogas produced in Kashan urban sewage treatment plant as an example and after explaining the components required for the installation and operation of CHP, they designed it in such a way that it is possible to produce 446 kilowatts of electricity and 556 kilowatts of heat. According to the investigations, the installation and investment costs in the mentioned year for the construction of two units of simultaneous production of heat and electricity with biogas were estimated at 270,000 dollars, which according to the income from this power plant, it was possible to return the investment within 4 years. [17]

In their article in 2017, MosayebNezhad et al. presented a proposal regarding the integration of micro gas turbines and solid oxide fuel cells (SOFC), where the fuel of both technologies is supplied through the biogas produced in the treatment plant. They presented two scenarios; the first scenario was the integration of CHP with SOFC (SOFC-WWTP) and the second scenario was the integration of microturbines with SOFC (SOFC-MGT-WWTP). The investment cost for SOFC-MGT-WWTP was estimated to be about 12% lower than SOFC-WWTP, and the investment return time for this system was estimated to be 4 years. [18]

In 2019, Talebi et al. investigated the utilization of CHP to generate electricity in the Tabriz treatment plant. In their article, they also investigated the utilization of microbial fuel cell (MFC) as an alternative, which has lower infrastructure costs, lower performance and produces less pollution than traditional treatment methods and systems, and does not require the collection and transportation of wastewater. It does not have a hard battery and it can perform the treatment locally in the process of producing wastewater. This treatment plant has two modules and has the potential to produce more than 2.5 megawatts of electricity, which provides most of the energy needed by the treatment plant itself. [19]

In 2020, Saberi Mehr et al. investigated the feasibility of creating a power plant for the simultaneous production of electricity and heat from biogas using a SOFC and a solar system. In their simulation, they used a fuel cell capable of producing 180 kilowatts of electricity and 125 kilowatts of heat. The results of this article show that a part of the heat needed by the digester is provided through solar power, which has saved the consumption of natural gas in this power plant. [20]

In 2021, Borelli et al. investigated the possibility of exploiting the sludge produced by a sewage treatment plant in the city of Genoa (Italy) to produce biogas. After receiving the treatment plant data and matching the data with the measured values, they calculated the amount of biogas available to feed the CHP. In the next step, they examined two scenarios for generating heat and electricity from CHP and finding operational conditions. The results showed that the generator can produce 3837 MWh/y of thermal power during 7000 hours of operation throughout the year, most of it, is used for preheating the pressure reduction station and the excess is used for heating the digesters and reduces the consumption of natural gas and has economic benefits. [21]

2. CHP FUNCTION

CHP is a system that simultaneously produces electricity and heat, but unlike many power generation systems, the energy produced can be used for processes such as heating, cooling, and generating electricity for other industrial purposes or on the same site. Also, it does not need special fuel to produce electricity and heat, but many types of fuel can be used to produce them. It is possible to use these technologies in various places such as municipalities, treatment plants, hospitals, etc. which advantages include reducing energy costs, increasing power reliability, and reducing carbon emissions. [22, 23]

2.1. The Proposed Cycle of South Tehran Refinery with PEMFC Configuration

In the designed cycle, municipal wastewater output from the treatment plant south of Tehran (flow 1) enters the anaerobic digestion system and the output of this system is biogas produced (flow 2). Biogas enters the CHP system embedded in the cycle

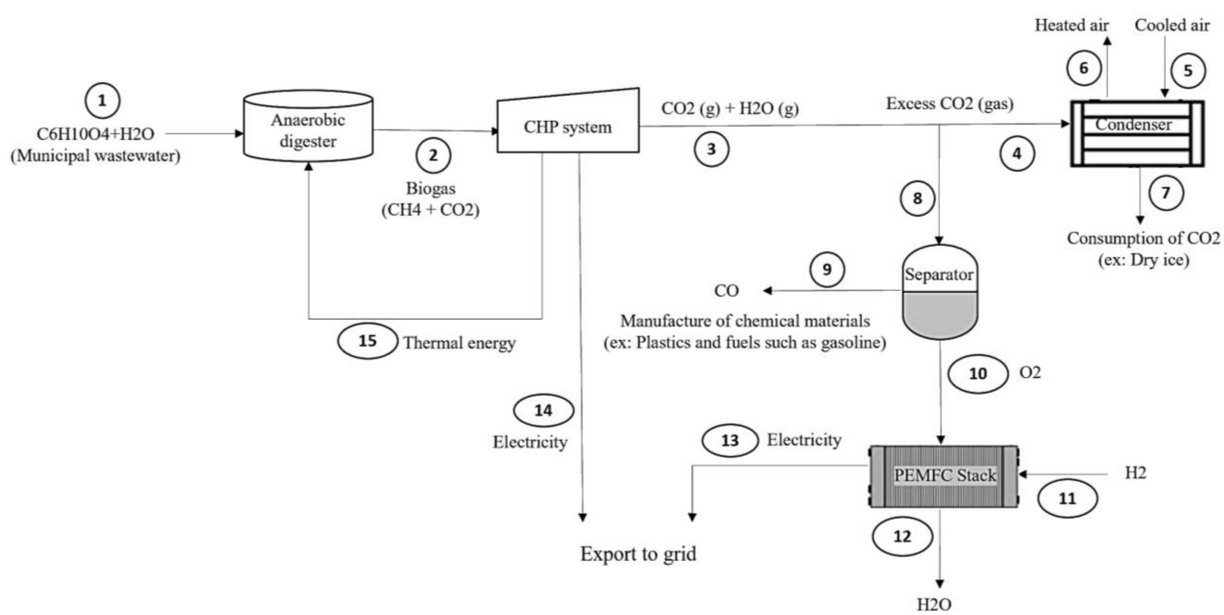

Fig. 1. General diagram of electricity and heat extraction in sewerage refineries with anaerobic process- organic waste enters anaerobic digesters and after that, the produced biogas enters CHP.

Table 2. ***Specifications range of engines used in refineries [26].***

Performance Characteristics Learn	Burn Engine	Advanced Generation
Size (kW)	110 – 2700	400 – 3370
Electrical Efficiency (%)	35 – 43	37 – 42
Thermal Efficiency (%)	41 – 49	35 – 43
Equipment Cost ($/kW)	465 – 1600	465 – 1200
Maintenance Cost ($/kWh)	0.01 - 0.025	0.01 - 0.025
Availability (%)	90 – 96	90 – 96
Overhaul Frequency (hours)	28000 – 90000	30000 – 90000
NO_X Emissions (lb/million Btu)	0.015 - 0.87	0.017 - 0.44
CO Emissions (lb/million Btu)	0.163 - 2.16	0.34 - 0.92

1. Performance at full continuous duty rated load
2. Performance characteristics provided by Caterpillar, Jenbacher, MAN, MWM, and Waukesha

and generates electricity and heat, which is used to accelerate the process of anaerobic digestion, and the generated electricity is transferred to the grid. Excess output carbon dioxide from the CHP system is also used for other purposes (flows 4 and 8). Some of the excess carbon dioxide enters the condenser (flow 4) and provides the dry ice product, and the other part, after separation (flow 8), decomposes into oxygen gas and carbon monoxide. Carbon monoxide gas can be used for industrial applications such as plastics (flow 9) and oxygen gas is used to feed the cathode in the PEM fuel cell (flow 10). The product of the electrochemical process of PEM fuel cell is water (flow 12) and electricity (flow 13) which is consumed by the grid. In this cycle, the energy loss is minimized and in fact, the exergy efficiency is maximized.

In the sewerage refinery of south of Tehran, the sludge is separated from the sewerage in two parts, then it is fed to the digestion tanks and after the stabilization process in the digestion and production of methane gas, dewatering is collected at the sludge depot. The sludge produced in each section is processed as follows:

1- Ordinary sludge processing: It is the use of sludge that is normally physically deposited by reducing the speed of sewage in primary sedimentation tanks and after collection by a pump is transferred to the next section. From there, after concentrating, it enters the digester for anaerobic digestion.

2- Secondary sludge processing: A major part of the biological process of sludge is called secondary sedimentation, which in this stage, part of the sludge is re-entered into the system and another part is entered as additional sludge to feed mechanical devices, and then its high-concentration parts enter anaerobic digesters.

Some parameters are effective on biogas production, the most important of them are the temperature of the digester, PH, and the concentration of the active substance in the slurry, although other factors such as C/N, the mixing of the digestate, and the particle size of the digestate also affect the amount of output biogas. [24] Sludge is placed in anaerobic digesters at a temperature between 38.5 and 39.5 degrees Celsius, and after a long period of 17 to 21 days, it stabilizes anaerobically (turns into organic matter) and methane gas accumulates at the top of the digester. Then the desulfurization process is formed to maintain the purity of the inlets of the gas storage tank, and then the gas is directed to produce electricity and heat. [25] The table below shows the approximate specifications of engines used in refineries:

The South Tehran refinery uses the engine in its CHP system which works according to the Otto cycle. In an ideal Otto cycle, the system executing the cycle undergoes a series of four internally reversible processes: two isentropic (reversible adiabatic) processes alternated with two constant volume processes.

In the Otto cycle, in the isotropic compression process, the pistons work on the gas and in the isotropic expansion process, the opposite of the previous process occurs, and the gas works on the piston. The difference between these processes is the amount of network produced by the cycle. [27]

2.2. Total Efficiency of the CHP Plant

Today, engineers are trying to increase the production of CHP power plants by maintaining high efficiency in addition to profitability. By using some thermochemical processes, CHP power plants can not only increase their operating time, but also increase their efficiency. [28]

Depending on the fuel used in the CHP plant, the type of plant as well as the characteristics of the heat requirement, the overall efficiency of the plant can range from 70 to 90%. [29]

Various indicators are defined in relation to energy consumption. Some of these indicators are electrical efficiency (η_e), heating (η_h) and CHP (η_{chp}) efficiencies of the plant. These are defined according to the following equations: [30]

$$\eta_e = \frac{p_{e,net}}{\dot{m}_f LHV_{f,ar}} \quad (1)$$

$$\eta_h = \frac{\dot{Q}_h}{\dot{m}_f LHV_{f,ar}} \quad (2)$$

$$\eta_{chp} = \frac{p_{e,net}+\dot{Q}_h}{\dot{m}_f LHV_{f,ar}} \quad (3)$$

In the above equations, $P_{e,net}$ is the net electric power output of the plant while $\dot{m}_f$ and $LHV_{f,ar}$ are the mass flow rate and low heating value (in as received basis) of biomass and The total output heating is ($\dot{Q}_h$). [30]

3. MATERIALS AND METHODS

3.1. Biomass & Biogas Fuel

Biomass combustion is a carbon-free process because the output CO_2 is consumed in the cycle. At present, biomass co-firing in modern coal power plants with efficiencies up to 45% is the most cost-effective biomass utilization for power generation. In cogeneration mode, the total efficiency may reach 85% - 90%. The International Energy

Agency projections suggest that the biomass share in electricity production may increase from the current 1.3% to some 3%-5% by 2050 depending on assumptions (IEA ETP, 2006). [31]

Biogas can be obtained by fermenting five types of biomasses; Livestock waste, agricultural waste, municipal sewerage, industrial sewerage, and municipal waste, which in this article the type of municipal sewerage is investigated. [26]

The utilization of organic waste in anaerobic digestion technology reduces the production of methane, carbon dioxide, and nitrous oxide in the environment. The greenhouse effect of methane and nitrogen oxides is more than CO_2, for example, the greenhouse effect of methane is about 21 times CO_2. [1]

According to global economic estimates, the price of crude oil should reach $ 140 per barrel in order for biofuels to be economically quite suitable for consumption without any subsidies. [28]

3.2. Biogas Production from the Sewerage

Production of biogas from sewage sludge is one of the suitable solutions for energy production because biogas is environmentally friendly, renewable, and efficient. Also, anaerobic biogas production can be done in simple reactors with low-cost methods. [24] From a physical point of view, the biogas produced in the wastewater treatment plant south of Tehran is mainly composed of methane and carbon dioxide, the composition and amounts of gases in the produced biogas are shown in Table 3. [32]

In the primary purification, some of the suspended solids in the sewerage are deposited in the primary settling tanks and separated from the sewerage. The sludge collected in these tanks is directed to anaerobic digesters after passing through a gravity concentrator. In the secondary purification, which is done biologically, the microorganisms in the system convert some of the organic matter in the sewerage into new microorganisms. Excess sludge is removed from the secondary settling tanks to maintain the sludge concentration in the secondary purification. This excess sludge enters the anaerobic digesters after passing through a mechanical concentrator and mixing with the initial sludge leaving the gravity concentrator. [33]

According to the design, the characteristics of the outlet sludge from the sludge concentrators and the inlet and outlet sludge of anaerobic digesters are according to Table 4. To digest this amount of sludge, three digesters with the specifications of Table 5 are considered. [33]

Table 3. ***The average composition of biogas [32].***

Component	Concentration	Component	Concentration
methane (CH_4)	50–75%	carbon monoxide (CO)	0–2.1 %
carbon dioxide (CO_2)	25–45%	nitrogen (N_2)	< 2%
hydrogen sulfide (H_2S)	20–20 000 ppm	oxygen (O_2)	< 2%
hydrogen (H_2)	< 1 %	Others	traces

Table. 4. ***Specifications of sludges [33].***

Description	Amounts of dry solids (kg)	Density (kg per cubic meter)	Concentration (percentage)	Volume (cubic meters per day)
Gravity concentrator output sludge	26,775	1,020	4	650
Mechanical condenser outlet sludge	38,853	1,020	7	539
Sludge entering the digester	65,628	1,020	5	1189
Sludge output from the digester	44,135	1,010	3/5	1189
Sludge out of mechanical dewatering	41,928	890	25	188/4

Table 5. ***Digestive characteristics [33].***

Title	Unit	Amount
The volume of each digester	cubic meter	8,900
Height	Meter	29
Diameter	Meter	22
Time remained	Day	20
Type of mixing	-	Mechanical

3.3. Biogas Production Reactions

Anaerobic digestion reactions involve a series of chemical and biological processes, in the absence of oxygen and the presence of anaerobic organisms, perishable organic matter is decomposed to produce a gas, most of that is a mixture of dioxide carbon (biogas) and methane gas. In addition to biogas, anaerobic digestion leaves residues that include inorganic matter, biodegradable organic matter, non-biodegradable matter, and microbial mass.

Anaerobic digestion materials may contain substances in varying concentrations (from slurry to solid material). After leaving the reactor, the material can be dehydrated in compaction equipment and the filtered liquid returned to the digester to prepare a slurry feed. The whole process can be divided into four stages:

- Hydrolysis in which complex molecules are broken down into simpler molecules.
- Acidogenesis or acid-producing phase in which organic acids are produced.
- Estrogenic or acetogenesis, which is the phase of acetate production.
- Methanogenic or methane-producing phase in which acetate and hydrogen are converted to methane in this phase.

3.3.1. Hydrolysis

In the first stage of the anaerobic digestion process, organic matter with a complex structure is broken down into a simpler structure through a process called hydrolysis. Proteins are converted to amino acids, fats to fatty acids, glycerol and triglycerides, and complex carbohydrates such as polysaccharides, cellulose, lignin, starch to simple sugars such as glucose.

The chemical formula $C_6H_{10}O_4$ is an estimate for organic waste. Equation (4) shows the conversion of organic waste to sugar, in this case glucose.

$$C_6H_{10}O_4+2H_2O \rightarrow C_6H_{12}O_6+H_2 \quad (4)$$

3.3.2. Acidogenesis

Immediately after the hydrolysis step, the acidification step begins. In this process, acid-producing bacteria hydrolyze phase products into simple organic compounds, often short-chain volatile acids (such as lactic acid, propionic acid, acetic acid, and butyric acid), ketones (such as ethanol, methanol, glycerol, acetone) and Alcohol. Equations 5 and 6 show the general reaction of the acidification step. In Equation (5) glucose is converted to ethanol and in Equation (6) glucose is converted to propionate.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH+2CO_2 \quad (5)$$

$$C_6H_{12}O_6+2H_2 \leftrightarrow 2CH_3CH_2COOH+2H_2O \quad (6)$$

3.3.3. Acetogenesis

The next stage is the acetogenesis, which is often considered part of the acidogenesis. At this stage, biochemical oxygen demand and chemical oxygen demand are reduced. The acetogenesis occurs through the fermentation of carbohydrates and the main product of this phase is acetate. At the end of this stage, we will have a combination of acetate, hydrogen, and carbon dioxide.

The conversion of organic material to organic acids during the acid formation process causes a decrease in the PH. This is in favor of acid-producing and acetate-producing bacteria that grow better in relatively acidic conditions with a PH between 4.5 and 5.5. But this is a problem for methane-causing bacteria.

$$CH_3CH_2COO^-+3H_2O \leftrightarrow CH_3COO^-+H^++HCO_3^-+3H_2 \quad (7)$$

$$C_6H_{12}O_6+2H_2O \leftrightarrow 2CH_3COOH+2CO_2+4H_2 \quad (8)$$

$$CH_3CH_2OH+2H_2O \leftrightarrow CH_3COO^-+2H_2+H^+ \quad (9)$$

$$2HCO_3^-+4H_2+H^+ \leftrightarrow CH_3COO^-+4H_2O \quad (10)$$

3.3.4. Methanogens

In this phase, methane-producing bacteria convert solute into methane. Two-thirds of the methane product is converted to acetate or alcohol, such as methyl alcohol, and the other one-third is the result of the reduction of carbon dioxide to hydrogen. The methane-generating phase controls the whole digestive reaction because of the rate of methane. producing reactions is much slower than acid-producing bacteria. Figure 2 shows the different parts of anaerobic digestion reactions for biogas production. [26]

4. INTEGRATION OF CHP SYSTEM WITH FUEL CELL

A fuel cell is an electrochemical energy converter that consists of three main components: anode, cathode, and electrolyte. The basis of these cells is oxidation-reduction reactions, so they produce electricity without direct combustion and it is much more efficient than internal combustion engines. Generally, a fuel cell reacts hydrogen and oxygen electrochemically, and the main product of the reaction is water and electricity. All fuel cell components are fixed and have no moving parts. The absence of these parts makes the fuel cell run smoothly. Their durability and reliability are also higher and pollutants such as nitrogen oxides and sulfur oxides are not produced in the fuel cell. When electricity is generated on site, a significant amount of energy can be saved and also a significant part of the generated heat can be used. One of the advantages of using CHP along with fuel cell is increasing energy security and reducing line vulnerabilities. [34,35]

The performance of a fuel cell can be analyzed by the Gibbs function. The Gibbs free energy of a reaction determines the maximum work that can be achieved by combining two substances in a chemical reaction. Maximum work is the work of Gibbs free energy difference theory of reactants and products:

$$W_{\max} = G_{react} - G_{\text{product}}$$

In a fuel cell, the useful energy output is electrical and thermal energy, and the input energy is the enthalpy of hydrogen. Assuming that all of Gibbs' free energy is converted into electrical energy, the maximum efficiency of the cell theory is:

$$\eta_{\text{F.C}} = \Delta G/\Delta H$$

The overall efficiency of a fuel cell in the ideal state is generally between 82-94%, which decreases due to ohmic losses due to concentration polarization and activation polarization. [34]

Electrolytes play an important role in the fuel cell and allow ions to pass through the cell with the necessary selectivity. The polymer membrane fuel cell uses an ion conducting polymer as the electrolyte. This electrolyte works well at low temperatures and generally allows fast start-up at temperatures of about 80 to 100 degrees Celsius. In this fuel cell, hydrogen is used as fuel at the anode and oxygen is fed to the cathode. Hydrogen ions and electrons are produced from the fuel at the anode, and hydrogen ions transfer to the cathode. Electrons are also transported through an external circuit to produce products by joining hydrogen ions and oxygen atoms at the cathode. The operation of a polymer fuel cell requires the maintenance of a certain amount of water in the cell, and too much water will cause it to fail. [34, 35]

The advantages of using a polymer membrane fuel cell along with the CHP system include the following: [34, 35, 36]

- Solid membrane reduces corrosion problems and electrolyte management.
- Due to low operating temperature, less startup time is required.
- It has low heat pollution, noise pollution, volume, and weight.
- It has a simple operation and has environmental pollution close to zero.
- Low risk of leakage due to the use of solid polymers.
- They are modular, meaning that their production capacity can be easily increased.

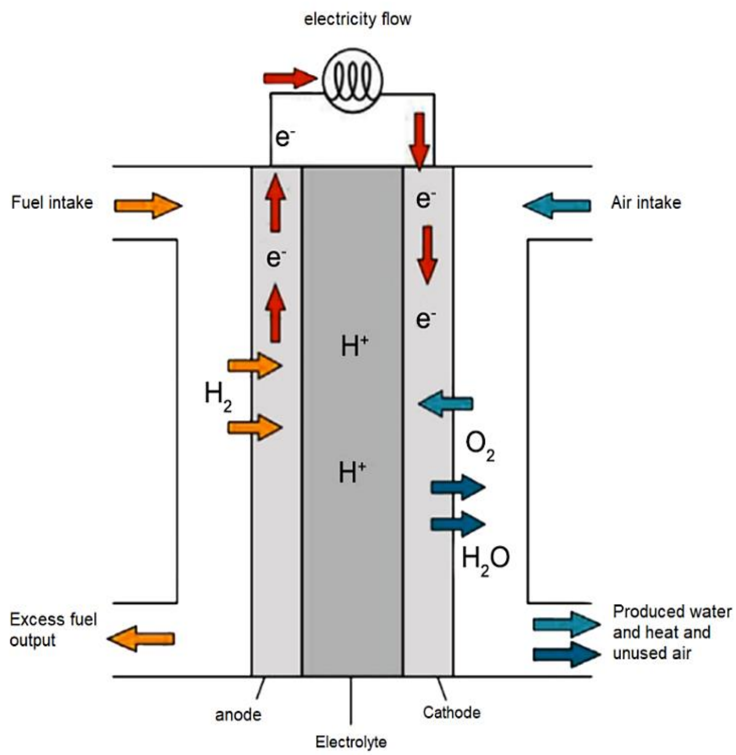

Fig. 2. The general structure of hydrogen fuel cells [35]- In these fuel cells, first the hydrogen molecule in the anode is decomposed into hydrogen atoms and the oxygen molecule is decomposed into its atoms in the cathode. Then oxygen and hydrogen ions combine in an exothermic reaction and water is formed.

- Density has a high force. Their efficiency is higher than other cells.
- Their operating time is much longer than conventional batteries. Only by doubling the fuel consumption can the operating time be doubled and there is no need to double the battery itself.

The most important disadvantages of PEM fuel cells are the following :[35]

- Sensitivity to carbon monoxide (lack of CO tolerance)
- Special storage conditions of the polymer (water and heat management)
- High costs (expensive catalyst)

5. DISCUSSION

5.1. Description of CHP System Products

5.1.1. Heat Consumption

The recyclable heat of the engine, which can be supplied from the smoke and the body of the engine, is provided to meet the heat needs of the digesters. Since the heat demand of digesters is generally about half of the recyclable heat of engines, the rest of the recyclable heat can be used to provide heating or cooling to surrounding buildings. [26]

- the kind, amount, and quality of the substrate

- the variant of the biogas production method
- the elements of biogas installation
- the technological scheme of the process
- the predicted biogas amount to be produced
- the predicted costs of the project
- the scheme of biogas plant
- the size of installation elements
- process parameters in the context of environmental conditions
- characteristics of the technological process of biogas production.

In traditional technologies, generators convert electrical energy in the rotating motor shaft into electricity. The boiler is an essential part of a traditional CHP power plant for heat recovery, as it recovers the heat consumed by the main engine and generator. Heat exchangers provide the simplest form of heat recovery by transferring heat from the exhaust gases to the boiler to increase steam production. Heat recovery systems are generally designed for specific exhaust conditions. [37]

5.1.2. Consumption of Generated Electricity

Generated electricity in generators can reach one of the following uses:

1- Sale of electricity to the network under the contract of guaranteed purchase of electricity from renewable energy sources (PPA) . In 2016 the purchase price of each kilowatt hour of electricity generated by digesters was $0.013.

2 - Electricity consumption by the refinery: Considering that refineries are generally the largest consumer of electricity in urban complexes, the consumption of electricity generated by the refinery, in addition to reducing the pressure on the electricity network in the city, also causes reducing the energy consumption costs of the refinery. [26]

5.1.3. The Implementation of The Biogas Plant on The Basis of The Design Algorithm

It is not easy to design a CHP with biogas because we need to consider a variety of factors before starting construction work. In the first step, we must examine the installation of biogas and determine the following:

With the above data, a concept project can be designed and information can be obtained in relation to the following:

In the next step, we focus on the cogeneration module. The size of the module depends on several factors, including the amount of biogas produced, the duration of the system operation per day, as well as the share of biogas in the total energy and heat required by the house.

In the first place, the choice is made based on the availability of substrates. The size of all aggregates and containers is determined by the amount of these substrates and the quality of the substrates (dry matter content, structure, origin, etc.), process technique, and its application. Preparation methods for pumping also depend on the composition and type of material. [32]

5.2. Economic Analysis of CHP System

The cost of producing CHP mainly depends on the cost of fuel. When electricity prices fall in global markets, the cost of producing CHP is often higher than the market price. Therefore, it is very important to extend the lifetime and create engineering plans for the investment, operation, and maintenance of CHP plants during their operational life. [38]

According to the latest inquiries, the investment costs are about 1,811,595 $\frac{\$}{kWh}$. The operating cost is 0.004 $\frac{\$}{kWh}$ of production. Considering that the generated electricity is purchased for 0.019 $\frac{\$}{kWh}$, the amount of income is also known. [26]

Due to the energy-intensive sewerage refining process, electricity and heat generated by this project will be consumed in the refinery. Therefore, this plant will reduce the procurement of electricity from the global grid and reduce fuel consumption in the refinery and will reduce energy costs. This reduction in energy costs can be considered as income of this project. [33]

5.2.1. Calculation of Power and Amount of Electricity and Heat Production

Having the approximate amount and composition of biogas produced and the electrical and thermal efficiency of the CHP system, it is possible to estimate the production of electricity and heat in this project and the amount of their daily and annual production. To perform these calculations, the assumptions of Table 7 have been used. In these calculations, for the reliability coefficient, it is assumed that the production of biogas in real conditions is equal to 80% of the design value, which will be equal to 16,800 cubic meters per day. [33]

Table 6. *The amount of biogas and electricity production in the south of Tehran refinery [26].*

Refinery	Nominal capacity (Km^3/year)	BOD input (Ton BOD/year)	Extractable methane (Ton CH_4/year)	Calorific value of methane produced (GJ/year)	electricity production (MWh/year)	Power generation capacity (MW)
south of Tehran	409968	71744/4	14348/88	719782/87	99969/84	11/41

Table 7. *Necessary assumptions for calculating electricity and heat production [33].*

Row	Title	Unit	Amount
1	Biogas production rate in real conditions	m^3/s	0.1944
2	Methane concentration in biogas	Volume percentage (%)	65
3	Thermal value of methane	kJ/kg	50010
4	Methane density	kg/m^3	0/716
5	CHP electrical efficiency	%	42/3
6	CHP thermal efficiency	%	47/5

a) Electricity

- **Power generation of electricity**:

$$P_{el} = 0.1944\frac{m^3}{s} \times 0.65 \times 0.716\frac{kg}{m^3} \times 50{,}010\frac{kJ}{kg} \times 0.423 = 1913.9kW \quad (11)$$

- **Electricity generation (kWh/day)**:

$$E_{el} = 1913.9kW \times 24\frac{hr}{day} = 45{,}933.6\frac{kWh}{day} \quad (12)$$

- **Electricity generation (MWh/year)**:

$$E_{el} = 45{,}933.6\frac{kWh}{day} \times 365\frac{day}{year} \times 0.001\frac{MWh}{kWh} = 16{,}765.76\frac{MWh}{year} \quad (13)$$

- **Reducing the electricity cost:**

Considering that the electricity tariff for sewerage refineries is about \$0.0038 (with 20% increase in summer), the reduction of the annual electricity cost of the refinery as a result of this project will be equal to: [33, 39]

$$16{,}765.76\frac{MWh}{year} \times 1{,}000\frac{KWh}{MWh} \times \left(\frac{9}{12} + \frac{3}{12} \times 1.2\right) \times 0.0038\frac{\$}{KWh} = 66895.38\frac{\$}{year} \quad (14)$$

b) Heat

- **Power generation of heat**:

$$P_{th} = 0.1944\frac{m^3}{s} \times 0.65 \times 0.716\frac{kg}{m^3} \times 60{,}010\frac{kJ}{kg} \times 0.476 = 2552.36kW \quad (15)$$

- **heat generation**:

$$E_{th} = 2149.67kW \times 24\frac{hr}{day} = 61{,}256.64\frac{kWh}{day} \quad (16)$$

$$E_{th} = 61{,}256.64\frac{kWh}{day} \times 365\frac{day}{year} \times 0.001\frac{MWh}{kWh} = 21{,}807.36MWh\frac{MWh}{year} \quad (17)$$

$$E_{th} = 21{,}807.36\frac{MWh}{year} \times 3.6\frac{GJ}{kWh} = 78{,}506.49\ GJ \quad (18)$$

- **Reducing the heating cost:**

Assuming that the thermal value of each cubic meter of gas (CH_4) is about 35,000 kJ, the amount of reduction in natural gas consumption due to the implementation of the project will be equal to:

$$78{,}506.49\frac{GJ}{year} \times 1{,}000{,}000\frac{kJ}{GJ} \div 35{,}000\frac{kJ}{m^3} = 2{,}243{,}042.57\frac{m^3}{year} \quad (19)$$

Considering that the natural gas tariff for sewerage refineries is equal to \$0.002, the reduction of the refinery gas cost due to the implementation of this project will be equal to: [33, 40]

$$2{,}243{,}042.57\frac{m^3}{year} \times 0.0037\frac{\$}{m^3} = 8299.25\frac{\$}{year} \quad (20)$$

6. CONCLUSION

6.1. Possible limitations

In every research, various limitations can affect the results. In engineering research, parameters such as volume, mass, and time usually affect the numerical results. In this research, a parameter such as creating a sudden time limit and a lack of time for the biomass content to remain in the anaerobic digestion tank can lead to a change in other parameters such as the input fuel of the CHP system, then a sudden decrease in the amount of electricity, heat production, and finally disrupting the urban electricity and heating network.

Another possible limitation that affects the result is the disturbance in the biomass transfer process to the anaerobic digestion tank, which has similar effects on the entire system, and another parameter such as the limitation of system pollution is also effective. The emissions of cycle outputs such as CO and CO_2 may exceed the permitted amount and lead to environmental pollution, in this case, the system should be temporarily shut down or process corrections should be made for the system.

On the other hand, if in the proposed cycle there is a problem in the process of transferring the incoming hydrogen to the fuel cell, the electricity produced in this part will also be lost and the consumer network may suffer from a lack of electricity. Establishing a spatial limitation is another possible limitation for this cycle. For example, a part of the power plant's site is occupied for another utilization and the space required to install all parts of the proposed cycle, such as anaerobic digestion tanks, CHP system, and fuel cell, is limited and causes problems in the whole process.

6.2. Final Results

Biogas is a source of renewable and clean energy. This gas is not considered as a pollutant, but also reduces greenhouse gas emissions because there is no combustion in the biogas production process. By using the fuel cell (which in this article used the PEMFC) it is possible to reduce the CHP emissions, which is relatively low, and by decomposing these pollutants and using them in the fuel cell it is possible to increase the efficiency of the power plant. This refinery generates income by receiving the difference between the cost of electricity, heat consumption, and electricity and heat produced by this power plant. Also, if the operating hours of a power plant increase, the power plant can generate heat and electricity by using less load. It also reduces spinning and restarting costs, which in addition to generating heat and electricity, also reduces power plant costs.

In addition to the utilization of the fuel cell in the cogeneration system, the recycled heat increases due to the increase of the inlet air temperature, and as a result, the energy efficiency of the system increases with the increase of the inlet air temperature. An increase in the inlet air temperature also leads to an increase in the exergy efficiency of the system in both simple and simultaneous production modes. [41]

Total costs will be reduced by about 3% by 2015, and this amount will reach 7% by 2030, which is due to reduced investment in non-CHP energy production capacity. [37]

When a power plant can produce heat and power with a minimum load (less than 40% P_{max}), the power plant's operating hours

Fig. 3. Types of possible limitations.

increase and so the amounts of products (heat and power) available for sale. At the same time, spinning costs are reduced because less fuel is needed to keep the plant in production. However, for start-up hours, the effect of start time is more significant. Shorter start-up times increase the number of start-ups, which naturally increases start-up costs while reducing the plant's operating hours. These factors indicate the high importance of working hours and the amount of heat generated in the overall profitability of the plant. [38]

The results also show that CHP power plants with biofuel consumption can be used to balance the gaps in the electricity market and can be profitable in future energy systems. However, this requires that fuel costs remain close to the current level or that the cost of excess heat generated be offset by financial measures, or that excess thermal energy waste be avoided. The most important technical parameter to increase the flexibility of the power plant and at the same time its economic feasibility, is the minimum load of the power plant. Increasing the minimum load of the CHP plant and reducing the start-up time required to generate electricity can improve the plant's ROI by up to one percent. This means that given the current selling price of electricity and heating and the cost of fuel, improving operational parameters should not increase the investment cost for the plant by more than 6%. [38]

The typical size of CHP power plants is ten times smaller (from 1 to 100 MW) than coal power plants because the local materials needed to fuel these power plants are less available and transportation costs are high. Based on life cycle assessments, the net carbon emissions of CHP units are less than 10% of the emissions from fossil fuel energy. using MSW, corrosion problems limit the steam temperature and reduce the electrical efficiency. If a good balance is struck between heat production and demand, it is predicted that in the new designs of CHP systems using MSW, the electrical efficiency will reach 28-30% and the overall efficiency will reach more than 85 to 90%. Municipal solid waste also offers a net reduction of CO_2 emissions. MSW can generate 600 kWh of electricity per ton and emit a net 220-440 kg CO_2 from the combustion of the fossil-derived materials (20-40% of MSW). Methane emissions from MSW in modern landfills would be between 50-100 kg/t (equivalent to 1150-2300 kg CO_2), 50% is collected and 50% is released in the atmosphere. Thus, electricity production from MSW offers a net emission saving between 725 and 1520 kg CO_2/t and this Saving is even higher for CHP. [31]

The CHP systems generate more efficient electricity and reduce the world's primary energy consumption. The overall efficiency of electricity generation in these systems (thermal and non-thermal) increased from 40.5% to 42.8% at an average annual rate of 1.1%. [42]

According to the results extracted from this article, researchers in their future research and studies can take action from different angles to optimize this cycle. One of the most important parameters in this research is increasing the engine efficiency of the CHP system. The thermal efficiency of the engine used in this system is about 45% and its electrical efficiency is about 39%, and these values can be improved. In CHP production systems, the closer the heat production rate is to the electricity production rate, the overall efficiency of the system increases.

Among other parameters that can be improved in the proposed plan, it is possible to benefit from the output products that have not been used. For example, the exhaust gases (H_2O and CO_2) in the proposed cycle can be used for different purposes to avoid energy loss in the system. On the other hand, if the hydrogen flow entering the desired fuel cell is the output of another cycle, it is also possible to somehow prevent energy loss in two different cycles. Another suggestion for future research, considering the advancement of technology in the field of fuel cells in the coming years, is to choose a fuel cell with the highest possible efficiency and suitable for this cycle.

REFERENCES

[1] Abdali M, Aminsalehi F. (2009) The need to develop power plants for the simultaneous production of electricity and biogas heat in the country. Iranian Journal of Energy. 30: 13-24

[2] Tesfai A. (November 2015) Small and mighty – the performance of a fuel cell micro-CHP. website of CIBSE Journal.

[3] Shabani B, Nguyen H. (November 2019) Proton exchange membrane fuel cells heat recovery opportunities for combined heating/cooling and power applications. Energy Conversion and Management.

[4] Arifan F, Abdullah, Sumardiyono S. (2021) Methane gas production from a mixture of cow manure, chicken manure, cabbage waste, and liquid tofu waste using the anaerobic digestion method. IOP Conf. Series: Earth and Environmental Science 623. doi:10.1088/1755-1315/623/1/012036.

[5] (July 2016) Fuel cells, Combined Heat and Power Technology Fact Sheet Series. Department of Energy Efficiency and Renewable Energy, U.S. Department of energy.

[6] Olabi A.G, Wilberforce T, Enas Taha S, Khaled E, Abdelkareem M. (August 2020) Prospects of Fuel Cell Combined Heat and Power Systems. Energies Journal, 13, 4104;

[7] Alidadi H, Etemadi Mashhadi S, Najafpour A, Mohebrad B, Dehghan A. (July 2017) Investigation of Biogas Production Process by the Mixture of Landfill Leachate and Animal Waste. Journal of Health Research in Community, Volume 3, Issue 2. Summer 2017;3(2): 44-54.

[8] kupecki J, Badyda K. (2013) Mathematical model of a plate fin heat exchangeroperating under solid oxide fuel cell working conditions. Research Gate articles, Archives of thermodynamics, Vol 34, (2013), No. 4, 3–21. DOI: 10.2478/aoter-2013-0026.

[9] Rafi S, Sharifi M, Maleki E. (Fall 2016) Economic feasibility of energy production from animal waste using Dranco's anaerobic digestion process . Biosystem Engineering of Iran, Volume 48, Number 3, (pp. 379-387).

[10] [Soltani A, Karbasi A, Manoori M. (Fall 2011) Capacity measurement of methane gas production from urban

solid waste materials in the city of Langrod. Environmental Science and Technology, Volume 14, Number 3.

[11] [Mohammadi Majd J, Khodabakhshipour M. (Winter 2018) Investigation and evaluation of methane gas production from the combination of buffalo manure and corn stubble in Khuzestan province. Scientific Quarterly Journal of Promotion of Renewable and New Energy, Year 6, Number 2, Page 19-24.

[12] Shaygan J, Bazdar E. (2018) An overview of biogas production and purification. Iranian Journal of Chemical Engineering, Voulme 17, Number 98.

[13] Venkatesh G, Abdi Elmi R. (2013) Economic–environmental analysis of handling biogas from sewage sludge digesters in WWTPs (wastewater treatment plants) for energy recovery: Case study of Bekkelaget WWTP in Oslo (Norway). Energy. 58: 220-235 DOI: 10.1016/j.energy.2013.05.025

[14] Davoudinejad M, Biparva P, Akbarpour tolooti A. (2014) Estimating the potential of producing biogas and electricity from municipal sewage in the country. Journal of Water recycling. 2: 41-48

[15] Hosseini H, Shafiei pour R, Shahraki M, Shojaei pour M. (2015) Gas production potential in the country's refineries and investigation of factors and methods to increase its production. The 9th renewable, clean and efficient energy conference

[16] Sadeghi Z, Mehdizadeh S, Horri H. (2015) Economic and environmental evaluation of energy production from sewage in Kerman city. Agricultural economics research. 8: 113-131

[17] [Salmani F, Amiri Rad E, Salimi M. (2015) Feasibility of constructing two units of simultaneous production of heat and electricity with biogas in the municipal wastewater treatment plant. Journal of mechanical engineering. 47: 325-331

[18] MosayebNezhad M, S. Mehr A, Gandiglio M, Lanzini A, Dantarelli M. (2017) Techno-economic assessment of biogas-fed CHP hybrid systems in a real wastewater treatment plant. Applied Thermal Engineering. DOI: 10.1016/j.applthermaleng.2017.10.115

[19] Talebi A, Mohammadzadeh B. (2019) Investigating the use of CHP to obtain electrical energy, a case study: Tabari Wastewater Treatment House. The 3rd Congress of Iranian Water and Wastewater Engineering and Science, Shiraz University

[20] S. Mehr A, Adibi T. (2020) Feasibility of creating a power plant for simultaneous production of electricity and heat with biogas fuel by solid oxide fuel cell and solar system in Tabriz urban wastewater treatment plant. Journal of mechanical engineering. 51:103-112

[21] Borelli D, Devia F, Schenone C, Silenzi F, Tagliafico L. (2021) Combined Heat and Power generation exploiting the biogas production from urban wastewaters treatment: the Genoa case study. EDP Sciences

[22] Combined Heat and Power Basics. Office of Energy Efficiency &

Renewable Energy (EERE).

[23] (2023) Combined heat and power generation. GE Gas Power

[24] Demirbas A, Taylan O, Durmus K. (2016) Biogas production from municipal sewage sludge (MSS). Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 38:20, 3027-3033,

[25] Tabatabayi SA. (2016) What is happening in the refinery south of Tehran. Science News Agency (Sina).

[26] Asgari S, Ghvami B, Rastgoo H. (2016) Technical and financial analysis of electricity and heat extraction systems from sludge of municipal sewerage refinery. Proceedings of the 10th National Conference on Renewable,Clean and Efficient Energy.

[27] Otto Cycle – Otto Engine. Nuclear power.

[28] Awais Salman C, Thorin E, Yan J. (Oct 2020) Opportunities and limitations for existing CHP plants to integrate polygene ration of drop-in biofuels with onsite hydrogen production. Energy Conversion and Management (ENERG CONVERS MANAGE). 221:113109.

[29] European Commission. Cogeneration, or Combined Heat and Power (CHP). SETIS

[30] Braimakis K, Grimekis D, Karellas S, Magiri-Skouloudi D. (2020) Energy-exergy analysis of ultra-supercritical biomass-fueled steam power plants for industrial CHP, district heating and cooling. Renewable energy. 154: 252-269

[31] (January 2007) Biomass for Power Generation and CHP, IEA Energy Technology Essentials.

[32] Nitkiewicz S. (2015) The Demand Analysis of the Biogas Plant with CHP System On Substrate, The Aim to Obtain Required Electrical and Thermal Power. Journal of KONES.

[33] Zarrati M. (2014) Optimal use of biogas in sewerage refinery south of Tehran. The first new findings in the environment and agricultural ecosystems.

[34] [Afshari E. (2014) Co-generation of heat and power (mCHP) micro system with fuel cell. Journal of Renewable and New Energy, No. 1.

[35] Mohammadian J, Shirkavand Hadavand B. (2021) A Review of Polymer Fuel Cells. Polymerization. 4: 3-15.

[36] Jamali Paghale S, Rahimi M, Marashi M.B, Alibeigi A, Kafi M. (2015) Advantages of high temperature polymer fuel cell and simulation of different cathode parameters. Fourth International Conference on New Approaches to Energy Conservation.

[37] (March 2008) Combined Heat and Power-Evaluating the benefits of greater global investment. International Energy Agency (IEA). France.

[38] Joronena T, Pääkkönena A. (2019) Revisiting the feasibility of biomass-fueled CHP in future energy systems – Case study of the Åland Islands. Energy Conversion and Management. 188: 66-75.

[39] (2022) Forecast to increase the country's electricity production capacity up to 1800 megawatts and provide stable electricity this summer.

Kimiaye Shomal NEWS.

[40] Natural gas tariff in 1401. National Iranian Gas Company 2022.

[41] Shalbaf S. (2010) Thermodynamic analysis of the performance of a PEM fuel cell system in simple mode and dual generation of power and heat. Scientific information data base. Volume 1 No. 2.

[42] (2020) Renewables 2019 Global Status Report, Market and Industry Trends, Bioenergy. Bio-Heat Markets.