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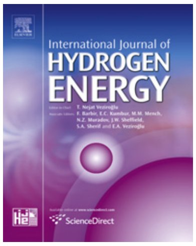

Energy analysis of hydrogen production using biogas-based electricity

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ABSTRACT

In this study, we perform energy analyses of hydrogen production with biogas-based electricity. In this study, a factory generating its own electricity from biogas obtained from wastewater treatment plant is considered for investigation. Hydrogen production process conducted using biogas-based electricity is examined by three methods of electrolysis. The energy analyses of hydrogen production with electricity generated by biogas-based sources are carried out using the actual data obtained from a factory. The results of this study indicate that outdoor temperature greatly affects biogas and hydrogen production. The cities with high-temperate climate may achieve higher overall system energy efficiency. The overall energy efficiencies of the system for the three types of electrolysers vary between 7.86% and 86.90%. Installing a PEM electrolyser in the plant will yield 110 kg/day of H_2 production.

1. Introduction

Hydrogen is a sustainable fuel and regarded as one of the most promising potential solutions for the current problems on the Earth, concerning energy and the environment. Eco-friendly method of production makes hydrogen one of the key features for ensuring a better environment as well as for the successful implementation of sustainable development policies [1]. There are many various methods to produce hydrogen. Electrolysis is one of the most well-known methods. During the electrolysis, the electricity required is supplied from renewable energy sources most of the time. Hydrogen production via electricity could be applicable in practice only if a significant part of the electricity was produced from renewable sources, such as biomass, biogas, wind, sun and similar sources. The importance of the electricity obtained from renewable energy sources increases in the production of hydrogen. Although several methods have been developed and/or are under development for the production of hydrogen from renewable energy sources, the only one that is currently practical is the one by the electrolysis of water. The electrolysis of water is a technology having solid grounds and has widely been used for a long time for the production of hydrogen in capacities ranging from a few cm^3/min to thousands of m^3/h [2].

Many researchers [3–9] have focused on the feasibility and the system performance of fermentative hydrogen production from different sources like wastewater treatment and from

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biogas in different perspectives. In addition, more attention is being paid by the European countries on the generation of biogas and biogas-based electricity produced from the organic wastes. Germany has become the largest biogas producing country in the world. At the end of 2008, approximately 4000 agricultural biogas production units were operated in German farms. Within the agricultural sector in the European Union (EU), 1500 million tons of biomass could be digested anaerobically each year, and energy crops accounted half of this potential [10]. Several applications of electricity generation from biogas are available in Europe. Switzerland has produced 112 million kWh of electricity from biogas. In addition, France and Switzerland provide huge amounts of incentives and financial supports to biogas applications. Italy produces biogas mainly from agricultural wastes. There are 160 currently running biogas production plants in the north of Italy. The electricity generation capacity of the installed systems ranges between 500 kW and 1 MW, respectively. The number of systems utilizing wastewater for the production of electricity is 130, whereas 22 systems utilize different types of industrial wastes. The total electricity generation from biogas is expected to increase up to 300 MW in Italy [11].

Industrial wastewaters are becoming increasingly useful in the production of biogas through the utilization of the anaerobic biotechnology in the developed and developing countries. Anaerobic digestion (AD) is a major category of biological treatment systems, referring to bacteria that operate optimally in the absence of oxygen. At present, anaerobic digestion is a popular option and a widely used wastewater treatment method for a number of wastewater treatment applications. Suitable industrial applications for anaerobic wastewater treatment can be divided into two groups: (i) agricultural companies (pig farms, cattle farms, poultry farms, crop production companies), and (ii) food processing companies (distillery and bioethanol plants, brewery plants, sugar mill, meat processing factories, veterinarian and sanitation plants, starch and treacle plants, yeast plants, milk plants, bakery plants, chips and potato processing plants, juice and tinned food producers, winery and fish processing plants) [12].

In Turkey, industrial wastewaters, specifically emanating from the food industry, have attracted reasonable attention for anaerobic digestion and biogas production. Biogas production from waste has not much developed in Turkey over the years. In the year of 2008, there were 32 municipal landfills. In addition, 76 plants are currently under development. A total of 108 landfills are planned for 2012. The number of license applications for the production of electricity from biogas is 8 with a capacity of 17 MW at the end of 2008 [13]. The technology of biogas production at wastewater treatment plants via anaerobic digestion is older and more mature than with solid waste. Yet, few wastewater treatment plants in Turkey produce biogas. The main barriers to the development of biogas in Turkey are a crucial lack of expertise and a great requirement for capacity buildings. General information about the wastewater indicators between 2001 and 2006 is given in Table 1 [14].

As the studies available in the literature show, utilization of electricity generated from biogas in the production of hydrogen has not gathered generous attention. The aim of this study is to conduct energy analyses of hydrogen production process driven by electricity generated from biogas resources with anaerobic digestion of sludge in an industrial wastewater treatment plant in Turkey.

2. System description and biogas production

Biogas and electricity are produced from wastewater conducting anaerobic refinement process using an up-flow sludge bed (UASB) reactor in the actual plant. Anaerobic microbial matter works in temperatures ranging from 10 to 90 °C. There are two broad categories of bacteria: Mesophilic, or bacteria that work optimally at human body temperature; or thermophilic, bacteria that operates optimally in high-temperature conditions above 40 °C and nearly to boiling point. In the plant process, mesophilic bacteria are used. Mesophilic bacteria are robust and adaptable to the changes in conditions. They are easy to control and cultivate in an anaerobic climate of at least 30 °C. In the factory, process temperature in the anaerobic digester reactor varies throughout the year from 30 °C in winter until 35 °C in summer. Required heat demand for reactor is supplied by both micro turbine (flue gas) and steam boiler (flue gas + steam). This heat is used to keep the reactor at constant process temperature up to 36 °C.

Anaerobic bacteria are water-loving bacteria and thrive in an intensive hydrogen environment. These bacteria can be developed as flocculant bacteria that readily leave the reactor and are either replaced or recirculated to the digester; or a sludge mobilization process that maintains the bacteria in a sludge blanket along the bottom and walls of the cell. Neutral pH is the rule of thumb for healthy anaerobic environments. If acid-forming bacteria are too prevalent in the digester tank, the wastewater conversion of Volatile Suspended Solids (VSS) will diminish substantially. Other competitors for hydrogen and

Table 1 – Wastewater indicators between 2001 and 2006 [13,14].

	Year				
	2001	2002	2003	2004	2006
Number of municipalities served by sewerage system	2003	2115	2195	2226	2321
Amount of wastewater discharged (million m^3/year)	2301	2498	2861	2923	3367
Number of municipalities served by wastewater treatment plants	238	248	278	319	362
Number of wastewater treatment plants	126	145	156	172	184
Biological treatment plants	98	114	121	133	135
Total capacity of wastewater treatment plants (million m^3/year)	2287	2358	2805	3410	3648
Amount of wastewater treated by treatment plants (million m^3/year)	1194	1312	1586	1901	2140

Table 2 – Composition of biogas.

State no.	Volumetric composition (%)			
	CH_4	CO_2	H_2S	H_2O
2	67.0	30.0	2.0	1.0
5[a]	72.0	27.5	0.5	–

a After reduction of H_2O, H_2S and CO_2.

carbon dioxide within the reactor will become more aggressive, reducing biogas yields. Before the operator is aware of it, the acid-forming bacteria may cause the methanogenic and other types of anaerobic microbes to become dormant. Mostly, this is a result of intolerably low pH levels in the tank over the course of time [15].

The chemical composition of the wastewater stream is a very important factor for an anaerobic reactor design. That is the reason of the proper testing and analysis executed in the wastewater stream. In the analysis, the key elements of the chemical composition of the organics in the wastewater are respectively: biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS), Volatile Suspended Solids (VSS), Volatile Fatty Acids (VFA), Fats, Oils and Greases (FOG). To determine the biogas yields, the most important factor is COD. The degree of presence of the factors in the wastewater will determine the ability of anaerobic microbes to disintegrate them. For example, a high VFA may inhibit biogas conversion, even if COD levels are relatively high and uniform. Anaerobic bacteria have natural methods to break down organic compounds to the base elements. In the process, suspended solids in the waste streams are converted into gases. A treatment system that contains this activity improves both water (as organic contamination is the basic environmental problem of organics in the waste streams as measured by COD and BOD) and air (as biogas usually has constituent gases that cause odor vectors).

When UASB reactor is used, wastewater enters the reactor via the header pipe network beneath the sludge bed. The recycled sludge mixes with the feed in accordance with an adjustable pumping schedule. As the wastewater passes upwards throughout the sludge blanket, the microorganisms attack to the feed while generating biogas. The biogas rises through the liquid emerging in the gas–liquid interface just beneath the membrane cover. An insulated floating membrane cover is used to collect biogas and to minimize the heat loss. The loading capacity is changing between 1000 and 1200 m^3/day with 8 kg COD/m^3.day. The UASB reactor volume is 19,600 m^3. It is operating at full capacity within 21 days from start-up. The UASB reactor works under optimized conditions. Daily average biogas production achieves about 10,000 m^3/day for the given system. Volumetric composition of biogas produced is 67% CH_4, 30% CO_2, 2% H_2S and 1% H_2O (see in Table 2). Following biogas generation in the reactor, it is transferred to the blower and the water separator unit. Then the biogas is transferred to the steam boiler or to the micro turbines. H_2S and CO_2 are not removed from biogas that is transferred to the steam boiler. The biogas transferred to micro turbine enters the H_2S and CO_2 reduction column. After reduction of H_2S and CO_2, it is transported to the micro turbine to produce electricity.

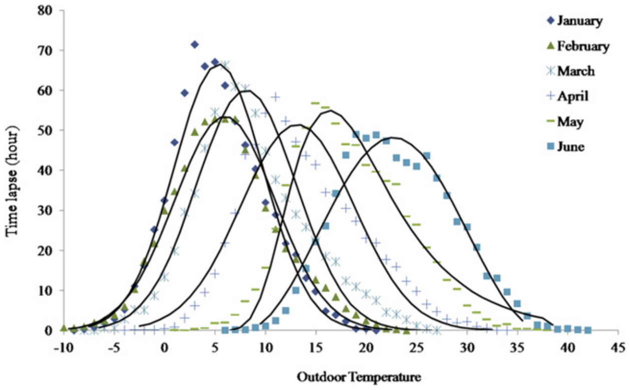

Fig. 1 – Outdoor temperature distribution for region.

2.1. *Determination of reactor heating demand*

The wall composition of UASB type reactor is given in Table 3. The outdoor temperature distribution is determined using the technique given in Ref. [16] and demonstrated in Fig. 1 for the first six month. Depending on the outdoor temperature distribution, the monthly heat loss is calculated for 30 °C reference temperature and given in Fig. 2. It changes between 155 and 335 MWh/month during the year. Both micro turbine flue gases and steam boiler (flue gas + steam) supply heat demand required for the reactor. The outdoor temperature directly affects energy efficiency of the biogas production system.

2.2. *Electricity production*

Produced biogas enters the compressors before the electricity generation. Following this process, the remaining moisture is removed in a water separator unit. Finally, the compressed biogas and the air enter the micro turbine for the generation of electricity. The exhaust gases leave the micro turbines at 275 °C. Flue gas leaving micro turbine enters a heat exchanger

Table 3 – Some properties for UASB type reactor and total heating requirement calculation procedure for 30 °C base temperature.

Element type	Area (m^2)	U (W/m^2 °C)	UA (kW/°C)	Degree–hour (°C–h)	Heating requirement (MWh)
15 cm Concrete	3534	3.58	12.65	131,352	1661.6
	1963		7.03	175,200	1231.7
Total					2893

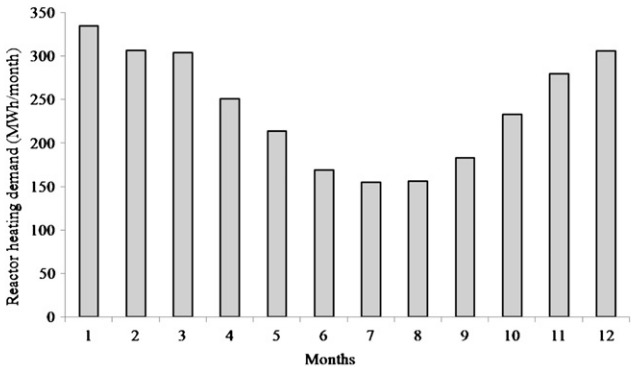

Fig. 2 – Heat demand of the reactor.

to transfer its energy to the reactor heating system. Flue gas leaves the heat exchanger at 110 °C. System has a 330 kW of electricity generation capacity produced via micro turbines.

2.3. System integration

The real process corresponds to the production of biogas and electricity. In this case study, water electrolysis system is integrated to the actual process. It is assumed that excess electricity produced can be utilized for H_2 production. Electricity demand of the factory decreases during the nighttime. Therefore, electricity produced during the nighttime can be used for H_2 production and subsequent storage. The H_2 produced is utilized for the electricity production using fuel cell during the daytime. If there is a fluctuation in biogas production because of any problem in the digestion reactor, the hydrogen stored can be utilized for the electricity production. In addition, since electricity demand of the factory fluctuates during the daytime, electricity produced do not utilized completely. Since excess electricity cannot be stored, it is wasted. However, it can be utilized to produce hydrogen via electrolysis and then stored as a fuel to use for peak demand time. Oxygen produced during the electrolysis process can also be utilized for better combustion in gas turbines. In this case, total system efficiency increase as gas turbine efficiency is improved. A schematic outline of the integrated water electrolysis system to the actual processes is given in Fig. 3.

3. Energy analysis

The actual operational thermodynamic data for a factory are listed in Table 4. The temperature, pressure, mass flow rate, enthalpy, entropy, energy rates for water and biogas are given according to their state numbers as specified in Fig. 3. EES (Engineering Equation Solver) software program is utilized for the determination of the thermodynamic properties of the water and biogas. This program is commonly utilized for the determination of many material thermodynamic properties. Flue gas enthalpy is calculated the procedure given in Ref. [17]. Energy flow diagram for hydrogen production is shown in Fig. 4 for a chosen day.

3.1. Energy efficiency of biogas production

The energy efficiency equations for biogas production process are given below:

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} \tag{1}$$

$$\dot{E}_{in} = \dot{W}_{pump} + \dot{E}_{Rh} + \dot{E}_{Rf} \tag{2}$$

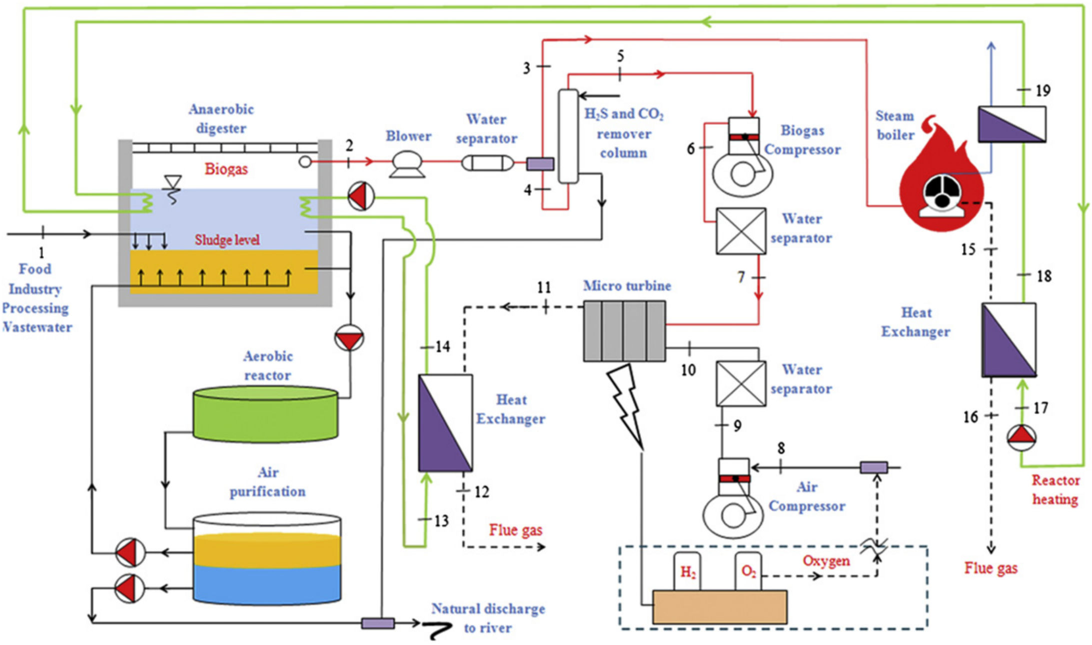

Fig. 3 – Schematics of water electrolyser integration of the actual system.

Table 4 – Input data utilized for energy analyses.

	Fluid type	State	Mass flow rate, $\dot{m}$ (kg/s)	Temperature, T (°C)	Pressure, P (kPa)	Energy flow, $\dot{E}$ (kW)
Ref. state	Air	G	–	12	101	–
	Water	L	–	12	101	–
1	Wastewater	L	11.60	25	150	631.9
2	Biogas	CH_4	0.0526	12	111	2460.6
		CO_2	0.0648	12	111	579.6
		$H_2S + H_2O$	0.0063	12	111	56.3
3	Biogas	CH_4	0.0263	12	120	1230.3
		CO_2	0.0324	12	120	289.8
		$H_2S + H_2O$	0.0032	12	120	28.6
4	Biogas	CH_4	0.0263	12	120	1230.3
		CO_2	0.0324	12	120	289.8
		$H_2S + H_2O$	0.0031	12	120	28.6
5	Biogas	CH_4	0.0263	12	115	1230.3
		CO_2	0.0276	12	115	246.9
		H_2S	0.0005	12	115	4.61
6	Biogas	G	0.0544	210	650	1493.8
7	Biogas	G	0.0544	8	630	1486.7
8	Air	G	0.9313	12	101	–
9	Air	G	0.9313	37	650	23.3
10	Air	G	0.9313	8	630	−3.9
11	Flue gas	G	0.9857	275	120	311.1
12	Flue gas	G	0.9857	110	108	115.9
13	Water	L	2.4760	35.0	110	238.6
14	Water	L	2.4760	52.0	160	415.0
15	Flue gas	G	0.9850	210	118	234.0
16	Flue gas	G	0.9850	110	106	115.8
17	Water	L	5.10	35.0	200	491.5
18	Water	L	5.10	40.0	180	598.3
19	Water	L	5.10	44.7	160	698.8

G: gas, L: liquid.

$$\dot{E}_{Rh} = \dot{m}_{13} \cdot (h_{14} - h_{13}) + \dot{m}_{19} \cdot (h_{21} - h_{19}) \quad (3)$$

$$\dot{E}_{out} = \dot{E}_{Biogas} \quad (4)$$

where η is the energy efficiency. $\dot{E}_{Rh}$ indicates energy amount for reactor heating. $\dot{W}_{pump}$ refers to pump work in anaerobic reactor, aerobic reactor and air purification systems. $\dot{E}_{Rf}$ is the energy rate of wastewater entering the reactor.

3.2. *Energy of electricity production from produced biogas*

The energy efficiency equation for electricity production is given below:

$$\eta = \frac{\dot{E}_{usefull,out}}{\dot{E}_{in}} \quad (5)$$

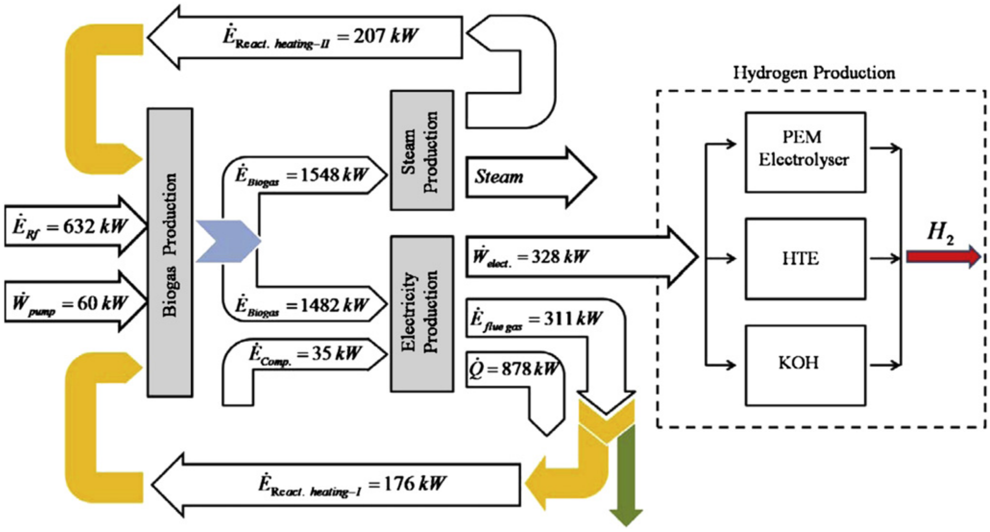

Fig. 4 – Energy flow diagram for the case study.

$$\dot{E}_{in} = \dot{E}_{Biogas} + \dot{W}_{comp} + \dot{E}_{air} \quad (6)$$

$$\dot{E}_{usefull,out} = \dot{W}_{elect} + \dot{E}_{fluegas} \quad (7)$$

$$\dot{E}_{fluegas} = \dot{m} \cdot (h_{12} - h_{11}) \quad (8)$$

where $\dot{W}_{elect}$ and $\dot{W}_{comp}$ stand for electricity generated in micro turbines and compressor work. $\dot{E}_{fluegas}$ is the utilized flue gas energy. $\dot{E}_{Biogas}$ shows energy amount of produced biogas. In the calculations, all energy inputs are taken as the rates in kW. The energy efficiency values are calculated for the electricity generation and hydrogen production (three techniques) and given in Fig. 5.

3.3. *Energy efficiency of hydrogen production*

The calculations are done for three electrolysis techniques as taken into consideration. The electrolysis of water can be carried out in conventional or advanced alkaline electrolysers, solid-polymer electrolysers, or high-temperature, water-vapor electrolysers. Each of these configurations uses electrical energy to split water into hydrogen and oxygen ions in an electrochemical cell consisting of an anode, a cathode and an electrolyte. Hydrogen is collected at the cathode and oxygen at the anode. The differences between the electrolysis systems are evaluated in terms of their operating temperatures, electrolyte properties, and to some extent, their operating pressures [18]. In calculation, output pressure and temperature of hydrogen are considered as 1 bar and 35 °C, respectively.

3.3.1. *PEM electrolyser*

PEM electrolysis is a process operating in a reverse manner of a PEM fuel cell process. The water is split into oxygen, protons and electrons on one electrode (anode) by applying a DC voltage higher than a thermo neutral voltage (1.482 V). The protons pass through the polymer electrolyte membrane and combine with electrons on the cathode to form hydrogen. The passage of protons through the membrane is accompanied by water transport. The typical industrial electrolysers have electricity consumption between 4.5 and 6.0 kWh/Nm^3, corresponding to an efficiency of 65–80%. Production capacity changes between 1 and 100 Nm^3/h H_2. Hydrogen can be produced at 15 bar in this technique. Many parameters affect the efficiency of the PEM electrolysis including the output pressure, the average cell potential, the operating current density, the internal current and the hydrogen loss, the efficiency of DC/DC voltage regulator and as such [19]. It is suitable for stationary and mobile applications. System has a quick start-up and limited lifetime of membranes.

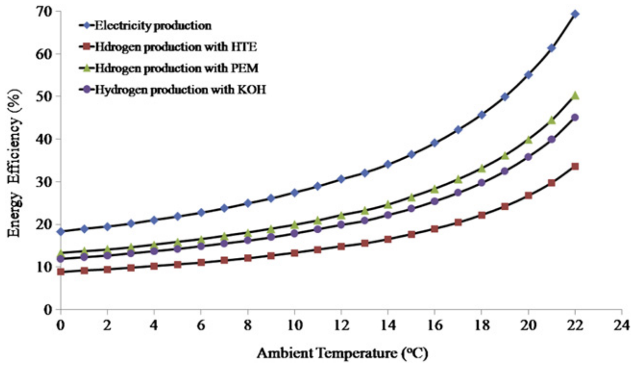

Fig. 5 – Variation of electricity production energy efficiency for overall system.

3.3.2. *High-temperature electrolysis (HTE)*

Hydrogen production efficiency of the high-temperature solid oxide electrolyser system is taken to the range between 43% and 54% as stated in Ref [19]. It is suitable for stationary applications. The system is less resistant to the catalyst poisoning.

3.3.3. *Alkaline (KOH) electrolyser*

The alkaline electrolysers with potassium hydroxide (KOH) electrolyte are commercially available. The optimum efficiency could be higher than 85%, however, the commercial devices achieve between 55% and 75% efficiency. Production capacity changes between 10 and 1000 Nm^3/h. New advanced electrolysers may approach the upper limit [20]. It is suitable for industrial and stationary applications. System has a low operating pressure. During hydrogen production, the efficiency value is assumed as 65–80% for PEM electrolysis, 55–75% for alkaline (KOH) electrolyser and 43–54% for high-temperature electrolysis (HTE).

4. Results and discussion

The purpose of this study is to analyze the energy obtained by hydrogen production from electricity generated using the anaerobic digestion of sludge from industrial wastewater to obtain biogas as the energy source from an industrial wastewater treatment plant in Turkey. Mesophilic bacteria are very sensitive to the changes of the reactor temperature. Therefore, reactor temperature should be kept at the constant temperature. Outdoor temperature directly affects the reactor heating demand. Reactor heating demand is one of the most important inputs for overall system efficiency. Accordingly, cities those have temperate climate achieve higher overall system energy efficiency. This study deduces that there is an increasing potential in Turkey for the production of hydrogen from the electricity generated by the biogas available from wastewater treatment plants. The minimum and the maximum efficiencies are calculated for 0 and 25 °C outdoor temperatures and given in Table 5. The energy efficiency changes between 7.86 and 86.90%.

Table 5 – Comparison of the energetic hydrogen production performance.

Hydrogen production efficiency		Electrolysis technique		
		PEM electrolyse	HTE	KOH
Energy efficiency (%)	Min.	11.87	7.86	10.04
	Max.	86.90	58.68	81.51

5. Conclusions

Hydrogen production using the electricity generated from biogas appears to be a suitable application for industrial wastewater plants. Installation of such biogas production system for hydrogen production purpose becomes viable. According to the results of analyses, outdoor temperature has a great effect on the efficiency of hydrogen production. Efficiency increases with the increase in outdoor temperature. Therefore, selection of the region is very important for overall system performance. Some concluding remarks of this study are given below:

- Electricity demand of the factory decreases during the nighttime. Therefore, electricity produced during the nighttime can be used for H_2 production and subsequent storage. Produced H_2 can be utilized for electricity production using fuel cell during daytime. If there is a fluctuation in biogas production because of any problem in the digestion reactor, stored hydrogen can be utilized for electricity production. In addition, during daytime, since the electricity demand of the factory fluctuates, produced electricity cannot be utilized completely. Excess electricity is converted to hydrogen for storage.
- PEM electrolyzing system has higher overall system efficiencies than the efficiencies of the other two electrolyzing systems. The installation of a PEM electrolyzing system in the plant can achieve a 110 kg/day H_2 production. Energy efficiency of the hydrogen production changes between 11 and 87%, respectively.
- Oxygen produced during the H_2 production can be mixed with ambient air. Oxygen rich air can be utilized in the micro turbine. Oxygen rich air in micro turbine can reach to higher burning efficiency. Electricity generation efficiency can also be improved by this approach.
- The hydrogen production potential using electricity generated from biogas by the municipal wastewater treatment plants or the industrial wastewater treatment plants is substantial. This process appears to be a promising option that should be taken into consideration for the future.

Nomenclature

$\dot{E}$	energy, kW
$\dot{W}$	work rate, kW
Greek letters	
η	energy efficiency
Subscripts	
comp	compressor
elect	electricity
in	input
out	output
Rh	reactor heating
Rf	reactor feeding

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