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TECHNICAL NOTE

Techno-economic assessment for energy generation using bagasse: case study

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SUMMARY

Bagasse is selected as the biomass source that is studied because of its annual significant rate production in Iran and potential for energy generation. Bagasse has been as an energy source for the production of energy required to run the sugar factory. The energy needed by factories was supplied by burning bagasse directly inside furnaces, which had an exceptionally low output. To this end, today, a secondary use for this waste product is in combined heat and power plants where its use as a fuel source provides both heat and power. In addition, low efficiency of traditional methods was caused to increase the use of modern methods such as anaerobic digestion, gasification and pyrolysis for the production of bio-fuels. In this paper, the energy conversion technologies are compared and ranked for the first time in Iran. Therefore, the most fundamental innovation of this research is the choice of the best energy conversion technology for the fuel production with a higher efficiency.

To assess the feasibility application and economic benefit of biogas CHP plant, a design for a typical biogas unit is programmed. The results show the acceptable payback period; therefore, economically and technically, biogas CHP plant appears to be an attractive proposition in Iran.

KEY WORDS
bagasse; biogas; CHP; economic; energy conversion technology; energy generation

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1. INTRODUCTION

Today, the sugar cane industry has attained a prominent role not only in Iran but also in the world [1]. The importance of this industry is because of its by-products, one of which is bagasse. Bagasse has been of particular interest for two reasons: first, bagasse is produced in large quantities (each tonne of sugar cane produces almost 250 kg of bagasse) [2,3], and second, because of its diverse applications [2,4,5].

A study of the experiences of countries with a sugar cane industry shows that the first use of bagasse has been as an energy source for production of the heat and power required to perform a sugar factory [6–8]. The energy needed by the factories was supplied by burning bagasse directly, which had an extremely low efficiency. Therefore, pay attention to technologies with higher energy efficiency is a crucial factor. Moreover, technologies such as gasification, anaerobic digestion, pyrolysis and combustion can be joined with combined heat and power (CHP), which has a higher efficiency as compared with the older energy generation technologies [7,9–14]. As the survey on energy generation from biomass has been improved, attention is paid to modelled economic analysis. Nowadays, different models were developed in the world to analyse cost of electricity generation from various sizes and types of biomass energy conversion technologies [15,16].

Selection of bagasse as a biomass source for this research is based on two reasons. First, despite the fact that bagasse is used in side industries, a large amount (more than 1 500 000 tonnes) is destroyed annually without being used. Second, sugar cane production industries in Iran depend on fossil fuels, in particular natural gas. Therefore, using the high-efficiency technology for additional bagasse would improve this industry economically by converting it into power and heat. Therefore, determining the most appropriate technologies for Iran with regard to existing experience and facilities could increase the efficiency of energy production from bagasse.

This paper has studied the economic merit of bagasse as an energy source using a selected energy conversion technology supplying CHP fuel. An important component of this research has involved the comparison, ranked and chosen of the most suitable energy conversion technologies for bagasse. Then designing a typical small scale of this technology is carried out by computer program in MATLAB software. To enable the design of a typical energy conversion technology for this project, the necessary components for the system are identified. The best typical energy conversion technology was envisaged to be linked to a CHP unit, and then, it was studied from the economic point of view.

2. THE CURRENT STATUES OF SUGAR CANE AND BAGASSE PRODUCTION IN IRAN

At present, the main sugar cane plantation and industry complexes in Iran are Haft Tapeh, Karun, and Sugar Cane and Side Industry Development. The overall area under sugar cane is 114 000 hectares, and there is a capacity to increase this in the future. The annual production of sugar cane in recent years is about 10 000 000 tonnes, and bagasse production is about 3 000 000 tonnes. Although half of the bagasse (about 1 500 000 tonnes) is already being used in various ways, some is used inefficiently, and about 1 500 000 tonnes remain unused and are destroyed annually.

3. COMPARING ENERGY CONVERSION TECHNOLOGIES

By comparing different energy conversion technologies based on some factors, such as a type of raw materials, temperature and pressure of operations, energy efficiency, facilities to convert energy consumption and need to auxiliary material, it will be possible to determine which of these technologies are the most advantageous. In this research, technologies like ethanol production and pyrolysis with liquid fuel as a main product has not been compared.

To assess the technologies' complexity, they will first be compared with the need to process the raw materials (presented in Table I). The complexity of each possible operation has been ranked on a range of 1–10 (see bottom row of Table I). This ranking is carried out according to the simplicity (1) and complexity (10) of the technology. The complexities associated with each technology can then be calculated (see right hand column of Table I).

To dry biomass, there is a need to use a dryer or kiln. To optimise the size of material sieves, mills and chopping equipment are required. These kinds of processes have an effect on the complexity of technologies.

The complexity of the operational temperature is ranked from 1 to 10 in Table II. With the increase of temperature, the performance of materials such as steel comes closer to its performance limits. Consequently, the need to adopt protective measures, such as liming with refractory materials, increases, and this adds to the complexities of the setup. A similar situation also applies

Table I. Comparing technologies from the viewpoint of raw material processing needs.

Type of technology	Need to dry	Size limitation: Small	Size limitation: Average	Size limitation: Unlimited	Need to change the nature of raw materials	Complexity of technology
Fixed bed combustors	__	__	__	×	__	1
Atmospheric fluidised bed combustors	×	×	__	__	__	12
Pressurised fluidised bed combustors	×	×	__	__	__	12
Pyrolysis	×	×	×	__	__	16
Gasification	×	×	×	__	__	16
Anaerobic digestion	__	__	×	__	__	4
Complexity	5	7	4	1	10	__

Table II. Comparing the technologies from the viewpoint of temperature and operational pressure.

Type of technology	Temperature (°C): < 70	70–250	250–500	500–900	> 900	Pressure: Normal	High	Complexity of technology
Fixed bed combustors	__	__	__	__	×	×	__	11
Atmospheric fluidised bed combustors	__	__	__	×	__	×	__	8
Pressurised fluidised bed combustors	__	__	__	×	__	__	×	14
Pyrolysis	__	__	×	__	__	×	__	6
Gasification	__	__	__	×	__	×	×	15
Anaerobic digestion	×	__	__	__	__	×	__	2
Complexity	1	3	5	7	10	1	7	__

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in terms of pressure, and its increase requires the reinforcement of reservoirs, pipes and other components. This also increases the complexity of the system.

Table III shows comparisons of technologies from the viewpoint of the control of the processes required. In addition, raw materials compare as physical and chemical status, co-substrate, and limitation, the results of which are presented in Table IV.

The efficiency of energy conversion (efficiency here, means the recoverable heat energy with the heating value of the produced fuel to the thermal value of raw biomass) is presented in Table V. In this table, the ability of energy transfer or energy products also has been compared. The thermal energy resulting from combustion has a low capability of transfer to other locations. In contrast, liquid fuel can be easily transferred and transported to other locations.

The compatibility of the produced energy has been compared in Table VI with the methods of conversion and consumption of energy. Electricity has been allocated the highest score because of the simplicity of its transfer and its vast application in various uses. Gas fuel also can be transferred by pipelines or in pressured portable tanks. Solid fuel is easily portable but often tends to occupy larger volume because of its low specific mass [17].

Summing up of the technical comparisons of technologies for converting bagasse into energy has been reached by scoring and summing to obtain a total score. Scoring for technology complexity has been made in accordance with Table VII.

Scoring based on the limitations of compatibility with raw materials and special limitation has been performed as presented in Table VIII.

The final results of scoring for technical comparisons are presented in Table IX. The result of the technical study gives two technologies as joint leaders (gasification and anaerobic digestion). However, to choose which one is

Table III. Comparing the technologies from the viewpoint of managing the process.

Type of technology	Process control		Adding co-substrate				Pre-treatment		Complexity of technology
	Continuous	Split	Continuous	Split	Normal	High pressure	Physical	Chemical	
Fixed bed combustors	×	__	×	__	×+	×+	__	__	16
Atmospheric fluidised bed combustors	×	__	×	__	__	×	×	__	23
Pressurised fluidised bed combustors	×	__	×	__	__	×	×	__	23
Pyrolysis	×+	×+	__	×	×+	×+	×	__	14
Gasification	×	__	×	__	__	×	×	×+	28
Anaerobic digestion	__	×	__	×	×	__	__	×+	9
Complexity	8	2	5	1	1	5	5	10	__

Note: In the boxes with the signs ×+, the average complexity has been considered.

Table IV. Comparing the technologies from the viewpoint of compatibility with raw materials and auxiliary material needs.

Type of technology	Physical status of material	Chemical status of material	Type of main co-substrates	Specific limits
Fixed bed combustors	Dry or semi dry	Almost unlimited	Air (oxygen)	—
Fluidised bed combustors	Dry	Cellulose and lignocellulose	Air (oxygen)	—
Pyrolysis	Dry	Cellulose and lignocellulose	Types of gases (optional)	—
Gasification	Dry	Almost unlimited	Types of gases (obligatory)	—
Aerobic digestion	Dry or wet (unlimited)	Degradable	Water	—

Table V. Comparing the technologies from an energy efficiency viewpoint.

Technology (Tech.)	Efficiency (%)			Products transportability			Tech. score
	<40	40–70	>70	Good	Medium	Weak	
Fixed bed combustors	__	×	__	__	__	×	7
Fluidised bed combustors	__	__	×	__	__	×	10
Pyrolysis	__	__	×	×	__	__	14
Gasification	__	__	×	__	×	__	12
Anaerobic digestion	__	×	__	__	×	__	9
Score	2	5	8	6	4	2	__

Table VI. Comparing the technologies from the viewpoint of compatibility with the methods of conversion and consumption of energy.

Technology	Electricity production				Residential consumption	Industrial consumption		Transport	Total score
	Internal combustion engine	Steam turbine	Gas turbine	Fuel cell		Steam	Heat		
Fixed bed combustors	__	×	__	__	__	×	×	__	11
Atmospheric fluidised bed combustors	__	×	__	__	__	×	×	__	11
Pressurised fluidised bed combustors	__	×	×	__	__	×	×	__	17
Pyrolysis	×	__	__	__	×	×	×	__	18
Gasification	×	×	×	×	×	×	×	__	38
Anaerobic digestion	×	__	__	×	×	×	×	__	27
Rating	4	5	6	9	8	3	3	5	__

Table VII. Scoring the technologies based on complexity.

Total complexity	Score
Under 20	20
21–35	15
36–50	10
Up to 51	5

Table VIII. Scoring the technologies based on compatibility with raw materials and specific limitations.

Limitations in physical state of raw material	Limitations in chemical state	Special limitations	Score
—	—	—	20
+	—	—	15
+	+	—	8
—	+	+	5
—	+	—	13

the best possibility of using, existence experiences about these technologies in Iran should be considered.

Since 1974, sporadic studies have been conducted by research and academic institutions in Iran, which have led to the construction of several biogas plants in an experimental form. However, gasification is still a new technology in Iran, and there is little understanding of it. Therefore, the priority technology for Iran will be anaerobic digestion.

4. THE DESIGN CALCULATION FOR A TYPICAL BIOGAS PLANT

It is assumed that a part of extra bagasse may be used as substrate in anaerobic digestion bioreactor for biogas production. Moreover, assume that biogas produced is used as fuel in CHP. With this assumption, based on the daily rate of biogas and some additional assumptions, such as Ms of bioreactor will consider 5 Mg/d (million grams per day) of liquid manure, 4 Mg/d of bagasse, and 2.5 Mg/d of feedstock from residues storage [18], the equipments of a complete biogas plant can be designed using the program that is coded in MATLAB software. In addition, 4 Mg/d of bagasse, and 2.5 Mg/d of feed stack from residues storage [18], the equipments of a complete biogas plant can be designed using the computer program that is coded in MATLAB software.

The calculations of bioreactor and preparation tank, which are the main parts of typical biogas plant, are presented as follows. However, other calculations have been omitted for limitation space in the paper. However, the result of designing calculations for other parts of biogas plant is presented clearly in Table X. Also, the components of designed biogas CHP are shown in Figure 1

Table IX. Summing up the technical scores for technologies of conversion of biomass into energy.

Kind of technology	Complexity score	Score of technology based on complexity	Score of compatibility with raw material	Score of energy efficiency	Score of compatibility with facilities	Total score
Fixed bed combustors	28	15	20	7	11	53
Atmospheric fluidised bed combustors	43	10	8	10	11	39
Pressurised fluidised bed combustors	49	10	8	10	17	45
Pyrolysis	36	10	8	14	18	50
Gasification	59	5	15	12	38	70
Anaerobic digestion	15	20	13	9	27	69

Table X. Specifications of equipments designed the biogas plant.

Equipment	Specifications
Bioreactor	Volume (V_{BR}) = 431 m^3, D_{BR} = 10 m, H_{BR} = 5.5 m, D_{AG} = 0.5, n_{AG} = 150 RPM
Agitator power	13.4 kW
Preparation tank	Volume (V_{PT}) = 62.5 m^3, H_{PT} = 6.8 m, D_{PT} = 4.8 m
Bagasse reservoir	Volume (V_s) = 1100 m^3, 10 × 3.5 × 32 m^3($W_s \times H_s \times L_s$)
Pump of preparation tank (centrifugal pump)	P_{AG} = 5 kW, Volume rate = 86 m^3/h, pressure head = 1 bar
Reservoir conveyors	P_{SC} = 0.8 kW (Two screw conveyors)
Heating	Q_{SU} = 17 kW, A_{BR} = 250 m^2, Q_{BR} = 5 kW, Q_{supply} = 22 kW, D_{HP} = 0.025 m, L_{HP} = 25 m
Aeration	$\dot{V}_a$=1.6 Nm^3/h, D_a = 0.02 m
Compressor	P_c = 0.5 kW, $\dot{V}_{CPV}$ = 1.7 m^3/h, pressure head = 1 to 6 bar
Gas holder	V_{Gh} = 862 m^3
Residue storage tank	V_{Res} = 990 m^3, H_{Res} = 5.5 m, D_{Res} = 15 m

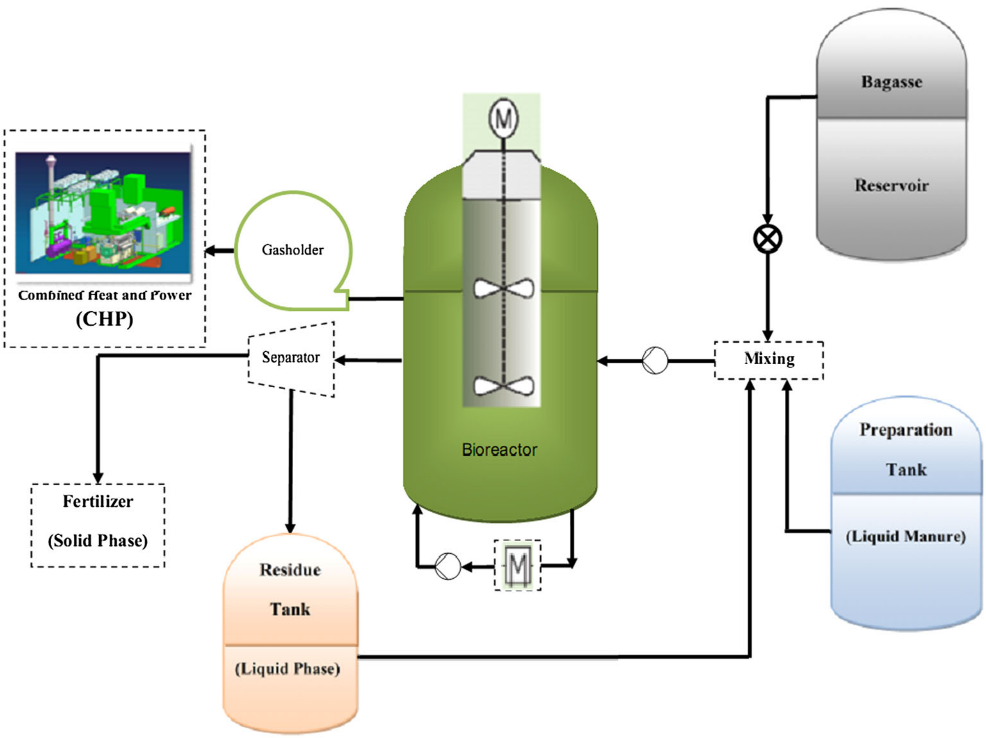

Figure 1. The layout of the biogas CHP plant.

4.1. Bioreactor

A vertical concrete cylindrical tank is designed as a bioreactor. The substrate residence time in the bioreactor is assumed, t_{RBR} = 30 days. The factor to increase the bioreactor volume (f_{VBR}) is chosen to be equal to 1.25 based on the assumption of volume for air and fixtures in the bioreactor. The filled bioreactor is assumed unfilled, at a flow rate of v_{DBR} = 0.5 m/s within the t_{DBR} = 5 h. In addition, the suitable relation between the bioreactor's height and diameter is H_{BR}/D_{BR} = 1/2. Therefore, the volume, height and diameter of bioreactor are as follows:

$$\begin{aligned}\text{Volume}: V_{BR} &= \dot{M}_{SU}/\rho_{SU}.t_{RBR}.f_{VBR}\\ &= (11.5\text{Mg/d})/(1000\text{kg/m}^3).30\text{d}.1.25\\ &= 431\text{m}^3\end{aligned}$$

$$\text{Height}: \quad H_{BR} = 5.5\text{m}$$

$$\text{Diameter}: \quad D_{BR} = 10\text{m}$$

where $\dot{M}_{SU}$is substrate mass rate of in Mg (million grams).

4.2. Preparation tank

The preparation tank is assumed to be a vertical concrete cylindrical container. In the preparation tank,

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to fulfill cleaning and maintenance work at the bioreactor, the daily liquid manure will be stored for residence time in preparation tank (t_{RPT}), equal to 10 days. The liquid manure density is $\rho_{lm} = \rho_w$. A factor to increase the preparation tank volume $f_{VPT} = 1.25$ is assumed to take into consideration the volume for air and fixtures. The suitable relationship between height (H) and diameter (D) of the tank shall be $H_{PT}/D_{PT} = 2$. Therefore, the volume, height and diameter of bioreactor are as follows:

$$\begin{aligned} \text{Volume}: V_{PT} &= M \cdot K_{lm}.(t_{RPT}/\rho_{lm}).f_{VPT} \\ &= (5\text{Mg/d}).(10\text{d}/1000\text{kg/m}^3).(1.25) \\ &= 62.5\text{m}^3 \end{aligned}$$

$$\text{Height}: H_{PT} = 6.8\text{m}$$

$$\text{Diameter}: D_{PT} = 3.4\text{m}$$

5. ECONOMIC STUDY OF A TYPICAL BIOGAS COMBINED HEAT AND POWER

The typical designed biogas CHP is studied as economic aspect. The results of this study would be useful for making a decision about investment on the development of biogas CHP in Iran. The most basic challenge facing biomass energy is its economic cost [19]. To make an economic analysis of CHP power plants with biogas fuel, the data relating to the cost of a plant are presented in Table XI.

In this case study, the volume of the sample bioreactor and the nominal capacity of CHP power plants with biogas fuels have been set as 431 m^3 and 111 kW_e, respectively. Here, the size of biogas CHP is assumed to be small because if it is proved that small scale is attractive and economic, so large scale will appear more attractive and economic [15].

According to Table XI, the cost of investment for a reactor is $464/m^3. In addition, the cost of investment in an electrical energy unit for CHP for a CHP power plant is determined to be about $650/kW$_e$ (according to the data from companies such as Gascore, Duetch and Perkins). In the economic calculations, the cost of investment without considering CHP is estimated to be about $200 000 and for the installations related to CHP $72 000. The costs of the CHP system include the costs of electrical connection between the power plant and the electrical network based on a connection being available at a short distance; therefore, the total cost is estimated to be equal to $272 000. In the designed biogas CHP plant, energy is produced as electricity and heat, and the power consumption of electricity and heating estimated for the entire plant is 15.3 and 22 kW, respectively.

Figure 2 shows the annual capital cost in detail that is calculated for the typical biogas power plant.

This power plant is the suitable compression ignition (CI) engine type, which, in a small biogas power plant, will require about 10% of natural gas to be used.

In Figure 3, the rate of natural gas consumption is 0.1 m^3 per day at a cost of $0.006/m^3 (according to the contract between the client (Power Generation, Transmission & Distribution Management Company) and contractor). Moreover, each kWh_e is sold for industrial application at $0.034, and each 10 kWh_{th} is calculated equal to the price of 1 m^3 of natural gas at $0.07 (according to the directive of the Ministry of Energy).

In addition, Figure 4 shows the annual operating cost in detail that is used for calculation of the annual expenditures. With regard to the estimated costs (capital, consumption and operating), the annual expenditures of this biogas power plant is estimated to be $88 055. The power plant will be able to sell electricity, heat and the residue from the process of fermentation, which will be useful as fertiliser. All these outputs will generate income as shown in Figure 5.

In calculating this value, it has been assumed that the power plant operates for 8640 hours per year, and the rates of electrical and thermal practical generation capacity are 85.4 kW_e and 142 kW_{th}, respectively (electrical and thermal efficiency of engine considered being 30% and 50%). Therefore, in respect of the biogas power plant annual income, and the rate of electricity purchase for renewable energies, each kWh_e is calculated as $0.13. In addition, for thermal energy, each 10 kWh_{th} is calculated equal to the price of 1 m^3 of natural gas as $0.07 (according to the directive of Ministry of Energy). After deduction of the annual expenditures ($88 055 per year) from the annual income

Table XI. Typical figures for the costs of agricultural biogas plants [18].

Investment cost basis	Typical figure
CHP per kW_{el}	$500–1500
per 1 m^3 reactor volume	$300–500
per 1 animal unit	$450–700 (self construction)
	$650–1800 (industrial construction)
per 1 kW installed power	$2400 (large plants > 300 kW)
	$6000 (small plant)
per 1 m^3/h biogas	$4000–7000 (plant alone)
	$5500–9000 (including silo for maize silage)

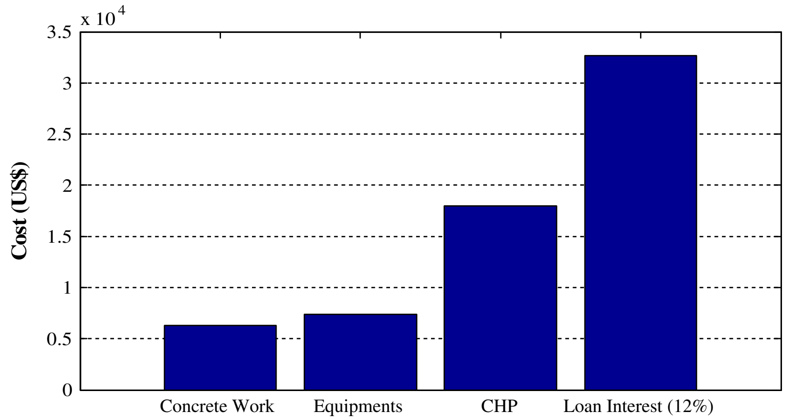

Figure 2. The annual capital costs (US$).

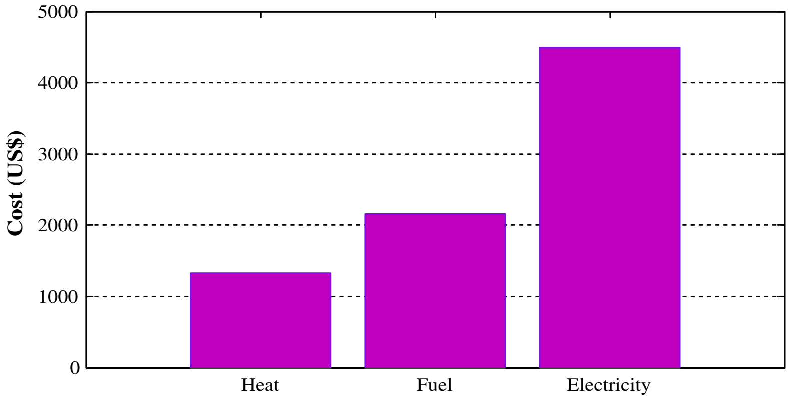

Figure 3. The annual consumption costs (US$).

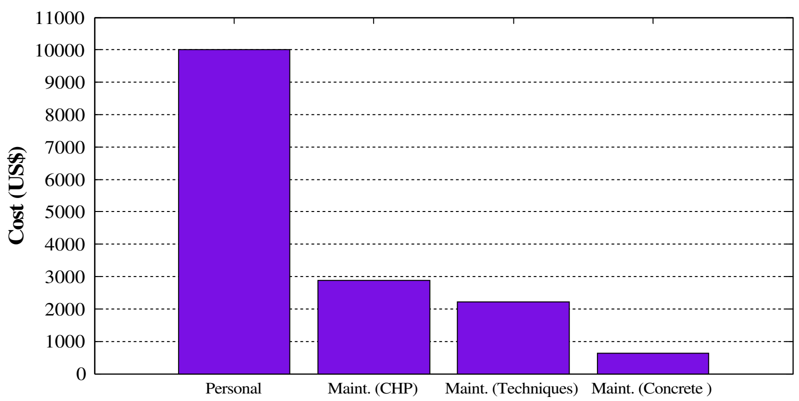

Figure 4. The annual operating costs (US$).

($105 509), the annual benefit of the power plant will be $17 454 per year, which is justifiable economically. In terms of capital payback, the plant should pay for itself in about 5.5 years even without considering the benefits from the reduction of greenhouse gases and natural gas saving.

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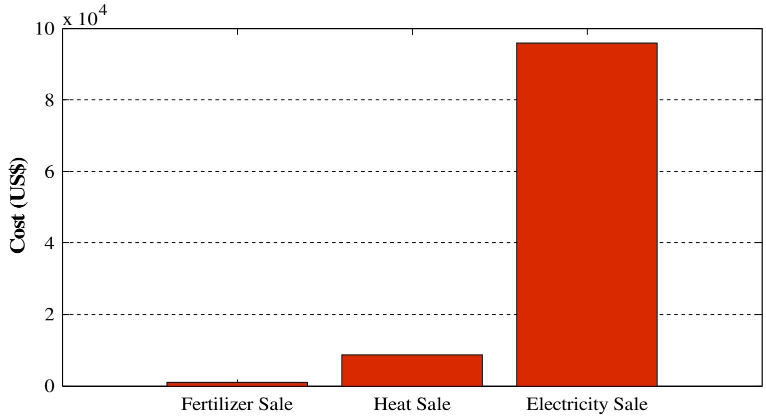

Figure 5. The annual income (US$).

6. RESULTS AND DISCUSSION

More than 1.5 million tonnes of additional bagasse is destroyed annually. In addition, bagasse has the potential for many different applications, such as an energy resource. Moreover, sugar cane industry consumes energy as power and heat. Therefore, energy generation from this extra bagasse ought to be economic for sugar cane factories. In this research, different types of energy conversion technologies such as combustion, anaerobic digestion, pyrolysis and gasification were compared and ranked. Many factors influence the complexity and ability of technology performance, such as operational temperature, need for pre-treatment, need for continuous control of the procedure, need for addition of auxiliary materials, need for purification of improvement of energy products, and efficiency, all of which are considered in this comparison. The results of a comprehensive technical comparison suggest that two technologies compete to be the most attractive (gasification and anaerobic digestion). To prioritise one, the possibility of applying these technologies was reviewed, and anaerobic digestion was chosen as the favoured option. Biogas production technology is particularly valuable, when the resulting biogas is used in CHP plants as a fuel. With the establishment of these types of power plants, large quantities of electricity and heat could be produced; however, they also will produce thousands of tonnes of natural fertilisers for agriculture. Moreover, CHP plants' economic benefits will be remarkable. Therefore, a typical of biogas CHP was assumed, and its equipments were designed using the computer programme in MATLAB software. The computations are carried out for different parts of biogas plant, according to the biogas plant process for obtaining output. Economic calculations were carried out on a typical designed biogas CHP plant with a capacity of 111 kW_e, which consumed biogas from a designated bioreactor of 431 m^3. The calculations show that the establishment of biogas CHP plants should be economic with a payback period of about 5.5 years. In addition, by increasing the scale of such plants (biogas CHP plants), economies of them grow up, and greater cost benefits should be obtained.

7. CONCLUSION

Sugar cane industry has found a significant position in Iran because of its by-products. Out of these by-products, bagasse has been of particular interest for two reasons: first, bagasse is produced in large quantity production, and second, because of its diverse applications. The first application of bagasse has been as an energy source for the production of the heat and power required to run the sugar factory. The sugar industry requires both heat and power, so CHP is a potent energy (power and heat) generation technology for these industries. The technical study of the energy conversion technologies applicable for bagasse illustrated that the priority in Iran is anaerobic digestion.

Therefore, the typical biogas plant was envisaged to be linked to a CHP unit, and then, this biogas CHP plant was designed and considered from economic aspect. It is worth mentioning that for demonstrating the attraction and feasibility of this research, a small scale of biogas CHP plant was selected and designed. In addition, it would be even more attractive and feasible if implemented at a larger scale. The importance of this study is limited to technical study of different energy conversion technologies for comparison and selection of the most applicable and suitable for bagasse in Iran.

NOMENCLATURE

A	= Surface (m^2)
D	= Diameter (m)
f	= Factor to increase
H	= Height (m)
L	= Length (m)
$\dot{M}$	= Mass rate ($Mg\,d^{-1}$)
n	= Revolutions (rpm)

P	= Power consumption (kW)
Q	= Heat (required or losses) (kW)
t	= Time (day (d) or h (hour))
$\dot{V}$	= Volume (m^3)
V	= Volume (flow) rate ($Nm^3.h^{-1}$ or $m^3.d^{-1}$)
W	= Width (m)

Greek letters

ρ	= Density ($kg.m^{-3}$)
v	= Velocity ($m.s^{-1}$)

Superscripts

.	= Rate

Subscripts

a	= Aeration pipe
AG	= Agitator
BR	= Bioreactor
C	= Air compressor
CPV	= Compressor pressure vessel
DBR	= Discharging the bioreactor content
Gh	= Gas holder
HP	= Heating pipe
lm	= Liquid manure
PT	= Preparation tank
RBR	= Residence in bioreactor
Res	= Residue storage tank
RPT	= Residence in the preparation tank
S	= Bagasse reservoir
SC	= Bagasse conveyor
SU	= Substrate
Supply	= Heat supply to bioreactor
VBR	= Volume of bioreactor
VPT	= Volume of preparation tank
w	= Water

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