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Environmental-economic evaluation of sugar cane bagasse gasification power plants versus combined-cycle gas power plants

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ABSTRACT

Approximately 2.4 million tons of bagasse are produced each year in Iran, most of which are currently treated as waste adding to serious environmental concerns. Application of bagasse for energy production is a sustainable solution to supply the required energy within the sugar refineries and export the surplus electricity to the grid. Currently, the energy demand in Iranian sugar mills is mainly supplied by fossil fuels (natural gas or mazut). Bagasse fluidized bed and fixed bed gasification plants would respectively lead to save 59,250 and 21,750 tons of CO_2 annually, compared to gas power plants of the same scale. The present study aims to compare the environmental economic analysis of electricity generation in 10-MW gas-fired power plants with that electricity generation in bagasse gasification plants (with fluidized bed and fixed bed reactors) exemplarily in Iran. The bagasse fluidized bed gasification option (with IRR of 28.6%) showed the most promising economic viability compared to bagasse fixed bed gasification and gas power plant cases with IRR values of 25.09 and 21.94%, respectively. Furthermore, bagasse gasification options were potentially characterized by a better environmental performance compared to fossil-fuelled options. On the other hand, the obtained levelised cost of electricity at gas power plants (2 cents/kWh) was lower than the global range and lower than bagasse gasification cases (7-9 cents/kWh). The results revealed the vital need of biomass power plants to governmental support in order to compete with fossil power plants by participation of private sector.

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INTRODUCTION

The global sugar production in 2019 (181 million tons) accounts for about 80% sugar cane and 20% sugar beet (USDA, 2019). The largest sugar cane producer countries are Brazil, India, Thailand, China, Mexico and Pakistan, respectively (ISO, 2019). Around 88,300 hectare of sugar cane farm area in Khouzestan province of Iran is under cultivation with an average yield of 84.1 tons/hectare annually, producing 7.4 million tons of cane which is equal to sugar production capacity of 772,000 tons/year (ISFS, 2017). The current energy demand in the Iranian sugar plants is supplied by fossil fuels such as mazut and natural gas (NG) (Avami and Sattari, 2007). On the other hand, the amount of bagasse produced in Iran reaches 2.44 million tons annually, which can be used to produce energy along with 0.5 million tons of cane trash (Mohammadi *et al.,* 2020). Bagasse is currently disposed as waste in the country and only a small portion of it is used to produce medium density fiberboard (MDF). Cane trash remains on the field and decomposes to improve the soil quality. Gasification is regarded as one of the most promising technologies for converting biomass into energy due to its higher efficiency as compared to the combustion technology commonly used in the sugar cane industry (Anukam *et al.,* 2016). Gasification process converts the carbonaceous materials into carbon monoxide (CO), hydrogen and carbon dioxide (HO_2 and CO_2) which react at high temperatures (more than 700 °C) without combustion and provide a controlled amount of oxygen and/or steam. The produced syngas is converted into energy in a combined cycle consisting of a gas turbine and a steam turbine. Fluidized bed (FLB) and fixed bed (FXB) gasifiers are typically used for small-scale gasification. FLB gasification technology is suitable for capacities of 100 kW to 1 MW, while FXB type is more suitable for capacities of 10 to 100 MW (Ciferno and Marano, 2002; NNFCC, 2009; Puig-Arnavat *et al.,* 2010). Gasification is assessed from different points of view by Niroo Research Institute (NRI) and various researchers as an appropriate technology to generate energy from bagasse (Amin Salehi *et al.,* 2012; Asadullah, 2014; Safari *et al.,* 2016; Sheikhdavoodi *et al.,* 2015; Tavasoli *et al.,* 2016). Mohammadi, *et al.,* (2020), in a most recent study, carried out the life cycle assessment of energy production by bagasse in different Iranian sugar cane industries and investigated the environmental impacts. Some of the environmental impacts of electricity generation in combined heat and power (CHP) gas and bagasse gasification plants are presented in Table 1. As can be seen in Table 1, the gas power plant has the highest acidification potential due to its higher emissions of sulphur and nitrogen oxides (SO_x and NO_x). In gas power plants, the engine adjustment is often a trade-off between NOx and other emissions. Adjustments of gas engines to lower NOx emissions normally lead to increased emissions of unburned hydrocarbons and CO (Kvist *et al.,* 2011). A dry low NOx burner or selective catalytic reduction, which uses ammonia and a catalyst, can be used to reduce NOx emissions (NREL, 2017). Bagasse FXB gasification and CHP gas plants have the least and the highest eutrophication impacts due to their release of NOx and phosphate, respectively. Providing zeolite and sulphuric acid in FLB gasification process has a considerable influence on this impact category. The human toxicity potential of bagasse FLB gasification is the highest due to toxic effects of chemicals during the total chain, especially chromium, arsenic and NOx emissions. The photochemical oxidation potential generally depends on the amounts of released SOx and CO. In this category, CHP gas

Table 1: Environmental impacts of production of 1 kWh electricity in different power plants (Mohammadi *et al.,* 2020)

Environmental impacts	Unit	Values in CHP gas	Values in bagasse FLB gasification	Values in bagasse FXB gasification
Acidification potential	kg SO_2 equal	4×10^{-4}	2×10^{-4}	6×10^{-5}
Eutrophication potential	kg PO_4 equal	7×10^{-5}	6×10^{-5}	1×10^{-5}
Human toxicity potential	kg 1,4- DB equal	9×10^{-3}	3×10^{-2}	5×10^{-3}
Photochemical oxidation potential	kg SO_2 equal	1×10^{-5}	9×10^{-6}	2×10^{-6}
GWP	kg CO_2 equal	0.90	0.38	0.70

plant has the highest impact. Moreover, gas power plant and bagasse FLB gasification have the highest and the lowest global warming potentials (GWPs), respectively, due to CO_2 emissions released from co-generation unit (Mohammadi *et al.,* 2020). Using bagasse energy in sugar cane factories could reduce GHG emissions in line with the Kyoto protocol limitation on Iran (Hosseini *et al.,* 2013; Mohammadi *et al.,* 2020).

Many studies have focused on economic feasibility of bagasse gasification plants (Ahmad *et al.,* 2016; Broek *et al.,* 2000; Caputo *et al.,* 2005; Ciferno and Marano, 2002; Patel *et al.,* 2016). However, neither of them has compared bagasse gasification plants with gas-fired power plants from environmental-economic perspective in the Iranian sugar cane industries. There are clear incentives to efficient use of energy alongside with developing alternative energy sources. Assigning parts of the country's energy mix to renewable sources of energy has become a vital issue for Iranian policy makers and stakeholders due to the increase of the related environmental problems caused by wasteful consumption of fossil energy in the country (Mohammadi *et al.,* 2020). Power generation in Iran heavily relies on NG, which covered 85% of the power sector in 2016. Moreover, the CHP NG power plants capacity will likely increase significantly in the near future in response to low NG prices, low carbon content, excellent dynamic response in operation, short construction period and lower cost of installation of CHP gas-fired power plants (Azadi *et al.,* 2017; EIA, 2019; Falode and Ladeinde, 2016). Considering the challenges of GHG reduction efforts in one hand and the environmental concerns caused by the current treatment of bagasse as waste on the other, it seems essential to investigate the possibility of using bagasse for energy production in the existing cane industry in Iran. The goal of this study is to compare the environmental-economic viability of gas power plants with that of bagasse gasification power plants in the sugar cane industry in Iran. This study has been carried out in the department of environmental engineering, University of Tehran in 2019.

MATERIAL AND METHODS

In this study, electricity generation in three cases of gas CHP, bagasse FLB and FXB gasification power plants was evaluated and compared from the environmental-economic points of view. The discounted net present value (NPV) and internal rate of return (IRR) were calculated using Comfar software. NVP indicates the value the project adds to the investment by discounting the cash flow to the present time value as presented by Eq. 1. IRR reflects the actual profit rate of an investment project. The moderated IRR is a discount rate at which the project NPV becomes zero. A project is economically attractive if it has the highest IRR (higher interest rate on long-term loans in the bank deposit market) and a positive NPV. However, the government generally invests in the projects which generate electricity with lower levelised cost of electricity (LCOE) (IRENA, 2015) as estimated using Eq. 2. Moreover, the revenues earned from carbon reduction in the renewable cases were considered to clarify the path for both environmental and economic aspects.

$$PV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{1}$$

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + C_{O\&M\,t} + C_{fuel\,t}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{pro\,t}}{(1+r)^t}} \tag{2}$$

Table 2: Assumptions used in the economic evaluation of power plants in the studied cases

Parameters	Values
Electrical power capacity	10 MW
Construction time	1 y
Lifetime of the power plant	20 y
Tax	25% on income
Inflation and discount rate	20%
Annual depreciation rate	5%
Scrap value after useful life	10%
Carbon emission reduction credit sailing rate	USD 20 per ton of CO_2 reduction

Where, CF_t is net cash flow at the end of year t; I_t is investment expenditures in the year t (USD/y); $C_{O\&M\ t}$ is operations and maintenance expenditures in the year t (USD/y); $C_{fuel\ t}$ is fuel expenditures in the year t (USD/y); $E_{pro\ t}$ is electricity generation in the year t (kWh/y); r is discount rate (%); and n is lifetime of the project (y).

Assumptions

The heat and electricity produced in the co-generation process were assumed to fulfill the energy demand within the sugar refinery and processes. The remaining heat was released to the atmosphere as waste heat, while the surplus electricity was sold to the grid. The cane factories in Iran, with an annual sugar production capacity of 100,000 tons, have a potential to annually produce 381,000 tons of bagasse and cane trash blend, which are suitable for fuel gasification plants. 0.35 and 0.30 kWh surplus electricity can be fed into the grid per kg bagasse via FLB and FXB gasification systems, respectively (Gabra *et al.,* 2001; Mohammadi *et al.,* 2020). By assuming 70% feedstock accessibility and 7,500 operating hours (OH) annually, the estimated capacity of gasification plants in each cane factory would be about 10 MW. The assumptions considered in the economic analysis are presented in Table 2.

The required data were collected from the previous studies mainly conducted by Broek *et al.,* (2000); Caputo *et al.,* (2005); Ciferno and Marano, (2002); Mohammadi *et al., (*2020); and Patel *et al.,* (2016), and also from NRI technology suppliers and consultants. The expenses and revenues were estimated at the current study.

Costs

Estimation of cost components including capital expenditures (CAPEX) and operation and maintenance (O&M) costs (Blok *et al.,* 2013; IRENA, 2013 and 2015) is presented in Table 3. In terms of CAPEX, according to the data retrieved from Iran's Ministry of Energy, equipment costs were taken as 375, 2500 and 2000 USD per kW for CHP gas, FLB and FXB gasification power plants, respectively. The costs of design, land purchase, preparation, construction and civil works were taken as 10% of the equipment costs (Worley and Yale, 2012). O&M costs include costs of personnel, routine replacement, maintenance of equipment, insurance, raw materials, water and electricity, environmental actions, ash disposal and fuel costs. Based on the data obtained from NRI, NG consumption is approximately 0.25 m^3/kWh or 18.75 million m^3/y at 10-MW gas power plants. The price of NG is 0.008625 USD/m^3 according to Iran's energy balance sheet of 2015. The cost of supplying bagasse is neglected due to the abundance of this resource in the Iranian cane factories. The electricity needed in the factory during the start-up phase is provided from the grid, while the rest is to be supplied from the CHP unit (ISFS, 2017). With a rough estimation, O&M costs other than fuel costs were obtained as 6% and 3% of the CAPEX in gas-fired and gasification plants, respectively.

Revenues

Revenues comprising the proceeds from products sale, trading of carbon reduction credits (accounted as environmental criteria in renewable

Table 3: Costs estimated for 10-MW power plants in the studied cases

Cost elements	Unit	Values in case 1: CHP gas	Values in case 2: Bagasse FLB gasification	Values in case 3: Bagasse FXB gasification
Equipment costs	1000 USD	3,750	25,000	20,000
Costs of design, land and civil	1000 USD	375	2,500	2,000
Total CAPEX	1000 USD	4,125	27,500	22,000
Fuel costs	1000 USD/y	161.72	-	-
O&M costs other than fuel cost	1000 USD/y	247.5 (6% of CAPEX)	825 (3% of CAPEX)	660 (3% of CAPEX)
Total O&M costs	1000 USD/y	409.2	825	660

Table 4: Revenues estimated for 10-MW power plants in the studied cases

Revenue elements	Unit	Values in case 1: CHP gas	Values in case 2: Bagasse FLB gasification	Values in case 3: Bagasse FXB gasification
Power plant electricity production (E_{pro} calculated from Eq. 3)	GWh/y	75	75	75
Electricity consumption in sugar factory and process obtained from CHP unit (E_{cons})	GWh/y	34	22.5	40
Excessive electricity exported to the grid (E_{exp} calculated by Eq. 4)	GWh/y	41	52.5	35
Electricity selling price (Pr_{el})				
- In the first 10 y of operation	cents/kWh	1.375	5.088	5.088
- In the second 10 y of operation	cents/kWh	1.375	3.561	3.561
Revenue from selling electricity (R_{el} calculated from Eq. 5)				
- In the first 10 y of operation	1000 USD/y	564	2,671	1,781
- In the second 10 y of operation	1000 USD/y	564	1,870	1,246
Carbon reduction	tons CO_2/y	-	59,250	21,750
CO_2 reduction price	USD/ton CO_2	20	20	20
CDM revenue	1000 USD/y	-	1,185	435
Equipment scrap value (10% of equipment costs)	1000 USD	375	2,500	2,000

cases) and scrap value were estimated in details for the three studied cases, as summarized in Table 4. Equipment scrap value after useful life (R_{scrap}) was taken as 10% of the initial equipment price, according to estimates by NRI. The revenues from selling the excessive electricity to the grid after provision of the electricity demand within the sugar refinery and co-generation process were calculated using Eqs. 3 to 5. OH was considered 7500 hours (h) annually leading to electricity production (E_{pro}) of 75 GWh/y in 10-MW power plants (Eq. 3). The electricity consumptions within sugar factory and co-generation process obtained from CHP unit (E_{cons}) were estimated as 45.33%, 30% and 53.33% of E_{pro} (Mohammadi *et al.,* 2020) or 34, 22.5 and 40 GWh/y in CHP gas, bagasse FLB and FXB gasification power plants, respectively. Therefore, these cases respectively have a potential to export 41, 52 and 35 GWh of the surplus electricity to the grid annually (E_{exp}) (Eq. 4). According to the data obtained from Iran's Ministry of Energy, the electricity selling price (Pr_{el}) was set at 1.375 cents/kWh at CHP gas plants. Renewable electricity purchase is guaranteed by Iran's renewable energy and energy efficiency organization (SATBA) for up to 20 y with a feed-in tariff (FIT) of 4.625 cents/kWh defined for biomass gasification plants. An adjustment factor of 1.1 was applied on this price, estimated averagely over the past 20 y according to the Iranian central bank data. In the gasification cases, Pr_{el} was set at 5.088 cents/kWh in the first 10 y of the operation and 3.561 cents/kWh in the second 10 y (70% of the first 10 y price, due to SATBA's 2018 statement).

$$E_{pro} = P_{el} \times OH \quad (3)$$

$$E_{exp} = E_{pro} - E_{cons} \quad (4)$$

$$R_{el} = E_{exp} \times Pr_{el} \quad (5)$$

Where, E_{pro} is electricity production (kWh/y); P_{el} is power plant's electrical capacity (kW); OH is operating hours (h/y); E_{exp} is excessive electricity exported to the grid (kWh/y); E_{cons} is electricity consumption in sugar factory and process (kWh/y); R_{el} is revenue from selling electricity (USD/y); and

Pr_{el} is electricity selling price (USD/kWh).

Among the environmental impact categories, GWP was taken into account in the economic analysis. The use of bagasse and cane trash blend for energy production in FLB and FXB gasification cases will respectively lead to savings of 0.79 and 0.29 kg CO_2/kWh produced electricity (or 59,250 and 21,750 tons of CO_2 annually at 10-MW power plants), directly and indirectly by substituting the fossil-fuel-based electricity (Mohammadi *et al.,* 2020). The carbon reduction credit rate was assumed as 20 USD/ton CO_2 reduction using the clean development mechanism (CDM).

RESULTS AND DISCUSSION

The results of economic analysis of the cases are presented in Table 5. The positive NPV indicated the profitability of investments in all of the three cases. Bagasse FLB gasification and NG power plant cases showed the highest and the lowest economic profitabilities with the IRR values of 28.60% and 21.94%, respectively. The return of capital (ROC) for CHP gas, bagasse FLB and FXB gasification power plants were calculated as 9.7, 6 and 7.5 y, respectively, showing the least payback period in the bagasse FLB gasification case. Analysis of the techno-economic feasibility of municipal waste gasification plants in Brazil showed that investment in the large gasification power plants can lead to an acceptable IRR (Luz, *et al.*, 2015). In the economic analysis of a 200-MW gas power plant project for the first gas industrial park in Nigeria conducted by Falode and Ladeinde, (2016), a NPV of 10.8 million USD at a discount rate of 15% and an IRR of 16% with a ROC of 9 years was realized. The inconsistency of their results with the the results obtained in the current study can be due to different assumptions of discount and inflation rates. They also assumed NG and electricity prices or the specific capital cost per installed capacity three times higher than their amounts in the current study. Furthermore, due to SATBA's 2018 statement, domestic designing and manufacturing of the power plant will increase the guaranteed purchase price of electricity up to 30%, which was neglected in this study. The CAPEX of biomass gasification power plants in the United States is in the range of 1500 to 5700 USD per kW (IEA, 2007, 2015; IRENA, 2017). Various researches have obtained different ranges for the CAPEX of biomass gasification power plants. For example, it was estimated as 2000-5000 USD per kW by Balat and Osman, (2005), or 3600 USD/kW by Dantas *et al.* (2013). Application of additional equipment such as sound insulators to isolate the engine will lead to rise of prices. Lower cost equipment is accessible in Iran, as it varies considerably depending on the applied technology, pre-treatment methods, level of maturity, plant size, site conditions, regional price changes and local environmental requirements. The highest costs are assigned to small-scale systems, depending on equipment such as fueling system, engine walls and limited production. Therefore, the higher the capacity of the installation, the lower the specific costs (CAPEX per kW) and the higher the benefits (IRENA, 2013). In the economic evaluation of biomass gasification plants conducted by Caputo *et al.* (2005), the NPV trend was investigated over a capacity range of 5 to 50 MW. They found out that only negative NPV values were reached in the capacity range of 5 to 25 MW, while the positive values of NPV were associated with the power plants installed in higher capacities. When the gasification plant size increased from 5 to 50 MW, the investment costs decreased from 4900 to 2200 € per kW. Furthermore, some studies have shown that the small-scale biomass gasification plants present lower electric efficiency compared to large

Table 5: Results of economic evaluation of investment plans for the studied cases

Indicator	Unit	Values in case 1: CHP gas	Values in case 2: Bagasse FLB gasification	Values in case 3: Bagasse FXB gasification
IRR	%	21.94%	28.60%	25.09%
NPV	million USD	0.70	35.17	11.65
ROC	y	9.7	6	7.5
LCOE	USD/kWh	0.02	0.09	0.07

scale ones (Pantaleo, *et al.,* 2015). However, a large number of case studies have confirmed the feasibility and financial viability of using the small-scale units in the decentralized biomass gasification power plants (Luz *et al.,* 2015; Pantaleo *et al.,* 2015; Singh, 2015). The positive NPV obtained from 10-MW bagasse gasification plants in the current study can be due to the availability of free bagasse in the country, while the feedstock costs could be critical for biomass power plants worldwide. The results reported in various studies are consistent with the results obtained in the present on the economic benefits of investment in bagasse-fuelled power plants (Balat and Osman, 2005; Broek *et al.,* 2000; Caputo *et al.,* 2005; Ciferno and Marano, 2002; Matsumura and Yokoyama, 2005). The syngas composition and gasification efficiency depend on gasifier type and conditions (Ardila *et al.,* 2012; Dutta *et al.,* 2012; Hijazi *et al.,* 2016; Indrawan *et al.,* 2017; Othman and Boosroh, 2016). In the United States and Europe, equipment (including gas turbine, heat recycling steam generator, water treatment system, and electrical equipment), engineering services and installation of a 10-MW gas-fired power plants averagely cost about 500-1500 USD per kW (Blok *et al.,* 2013; IRENA, 2012; IRENA, 2013; IRENA, 2017). In addition to considering the low cost of installation in the country, equipment prices of the lower part of the global range were assumed in the current study in order to conform with the earned revenues leading to beneficial economic results in the examined cases. Various researchers have estimated the share of O&M costs in gasification and gas-fired power plants in a wide range accounting for 2-10% of the CAPEX (Blok *et al.,* 2013; Dantas *et al.,* 2013; Falode and Ladeinde, 2016; IRENA, 2013; IRENA, 2015; IRENA, 2017). Considering the effect of the power plant scale, especially on the required workforce, the larger the power plant, the lower the O&M cost per kW (Blok *et al.,* 2013; IRENA, 2013). Typically, CHP gas plants need to be inspected every 4000 h to ensure whether the turbine has additional vibrations. The time duration between major repairs and complete refurbishment of all gas turbine components is approximately 25,000-50,000 h. The maintenance cost of a periodically operated turbine is three times of a continuously operated turbine, which operates for a period of 1,000 h or more. As displayed in Table 5, the estimated LCOE rate for the gas-fired power plant (0.02 USD/kWh) was far lower than the bagasse FLB and FXB gasification plants (0.09 and 0.07 USD per kWh, respectively). The projected LCOE range for gas power plant is estimated in a wide range of 0.01 to 0.24 USD per kWh based on the literature worldwide (DEA, 2016; EIA, 2019; IEA, 2015; NETL, 2015; Nian *et al.,* 2016; NREL, 2017). In the present study, due to the low price of NG in Iran, application of low cost equipment and exchange rate fluctuations in the country, the obtained LCOE in the gas power plant was in the lower part of the global range. In gasification plants, the LCOE range is very wide due to the variety of raw material cost, efficiency and maturity. The LCOE in biomass gasification plants in the United States is typically 0.1-0.2 USD per kWh (IEA, 2007, 2015). Numerous researchers have evaluated the cost of electricity production in biomass gasification plants. For example, Meerman *et al.* (2013) and Patel *et al.* (2016) estimated the cost of electricity production in biomass gasification plants to be in the range of 0.1-0.2 USD per kWh, while, Naqvi *et al.,* (2016) calculated it to be varying between 0.29 and 0.45 USD per kWh. According to IRENA reports, in a small or large scale CHP gasification system, the LCOE range is from 0.06 USD/kWh for FXB gasifiers to 0.24 USD/kWh for a small internal combustion engine as a primary engine (600 kW) which is suitable for off-grid or mini-grids applications due to its high investment cost (IRENA, 2012). In the studied bagasse gasification cases, the LCOE was in the lower part of the global range. LCOE was slightly higher in bagasse FLB gasification plants compared to bagasse FXB gasification plants due to their lower maturity. The discrepancies between the LCOE results obtained in the studied cases and the global ranges could be due to several factors such as availability of low price NG in the country, biomass feedstock prices, utilization of low cost equipment, scale of the studied power plants and the exchange rate fluctuations. Moreover, the costs and benefits of different technological routes can vary based on environmental and social perspectives (Dantas *et al.,* 2013).

This study confirmed that the additional revenues from GHG emission savings by substituting the fossil-

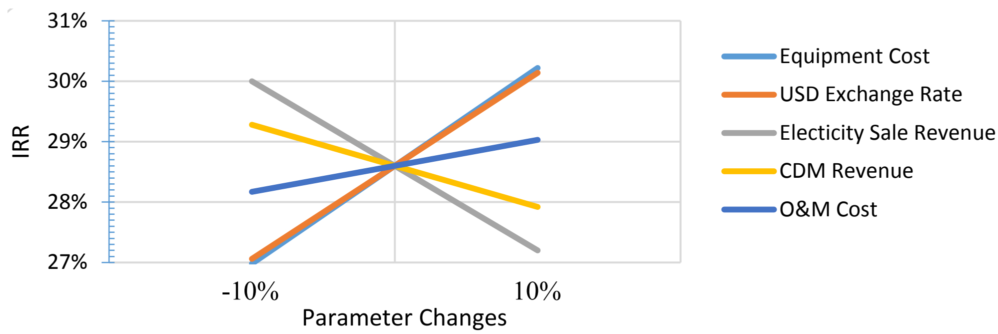

Fig. 1: Diagram of IRR sensitivity to variation of various parameters in the investment plans for power plants

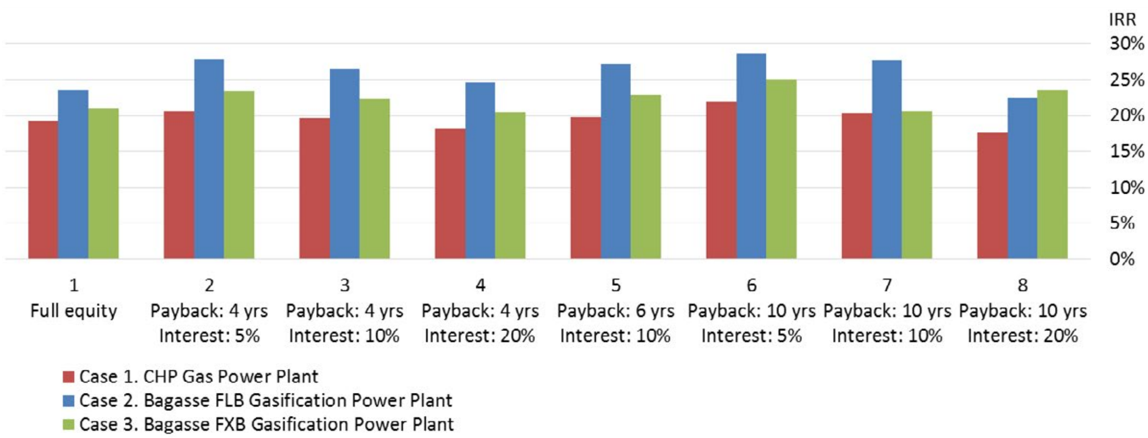

Fig. 2: IRR results of financing scenarios for investment plans for power plants with different loan conditions

based grid electricity will improve the economic viability of the project as previously reported in various studies (Mbohwa and Fukuda, 2003; Patel *et al.,* 2016). However, some local environmental effects, which represent considerable costs, may not be considered in this study. Acidification, eutrophication, human toxicity, photochemical oxidation are among such environmental effects. Such costs could be evaluated based on the local studies and included in the LCOE calculation.

Sensitivity analysis

A sensitivity analysis was conducted to determine the parameters that had the largest effects on the economic results. As shown in Fig. 1, the changes of equipment cost and exchange rate had the largest effects on NPV and IRR values respectively. The results showed that 10% decrease in either of the two parameters would lead to 1.6% increase in the IRR results. Subsequently, raising the electricity sales revenues (by raising FIT or the electricity production efficiency) and increasing the CDM trading rates had the largest effects on increasing the IRR values, respectively. Variation of O&M costs had no significant effect on IRR and NPV values. Moreover, some other factors such as tax-exempt liability, more supporting banking facilities or the possibility of benefiting from immediate governmental plans to use free fuel in the early years of gas power plant operation will improve the economic profitability and attractiveness of the investment plans for the studied cases.

Different financial scenarios were investigated as displayed in Fig. 2. In the first financial scenario, the total capital cost was provided by the investor equity. In the financial scenarios 2 to 8, the investor equity share of the CAPEX was assumed as 15%. The rest (85%) was covered by a bank loan. A breathing period of 1.5 years, different interest rates (5, 10 and 20%) and various repayment periods (4, 6 and 10 years) were considered on the loan (Fig. 2). The highest IRR was allocated to the sixth financial scenario using the bank loan with the longest repayment period and the lowest interest rate on it. Subsequently, financial scenarios 2, 7, 5, 3, 1 and 4 showed the best results, respectively. Financial scenario 8 (financed with the highest interest rate on the loan and the longest payback period) had the least profitability. According to the results, the interest rate had a considerable effect on the profitability of the project. Among the financial scenarios with the same loan interest rates, the cases with the longest payback period showed a better economic viability.

CONCLUSION

Annually, high amounts of bagasse are produced in Iran, most of which are currently treated as waste or burned. The country is facing the challenge of reducing GHG emissions and the necessity for replacing fossil fuels in cane factories. Moreover, Iranian sugar mills energy demand is mainly supplied by fossil fuels (NG or mazut). Each sugar cane factory in Iran, with an annual sugar production capacity of 100,000 tons, has a potential of fueling the 10-MW bagasse gasification power plants which will be able to export the surplus electricity to the grid, considerably save GHG emissions, and replace the grid electricity after satisfying the energy needs of the sugar refinery. A gas-fired power plant of the same scale consumes around 18.75 million m^3 NG annually, which can be avoided using bagasse as renewable source of energy. Therefore, application of bagasse as a renewable source of energy is a feasible solution in terms of waste management in cane factories and contributes to the reduction of GHG emissions, fossil fuel replacement and consequently enhancing the energy security on a national level. This study reveals that the availability of free bagasse in Iran can lead to economical advantage of investment in bagasse gasification power plants compared to gas-fired power plants of the same scale. Although, due to the availability and low price of NG and petroleum products in Iran, the levelised electricity generation costs is significantly higher in biomass gasification plants compared to NG power plants. Therefore, it seems essential for the government to consider the environmental advantages along with the economic profitability of bagasse gasification plants and to support the private sector for improving the incentives to establish the biomass power plants to be able to compete with the fossil power plants.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
€	Euro
USD	United States dollar
1,4- DB	1,4-Dichlorobenzene
CAPEX	Capital expenditure
CDM	Clean development mechanism
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
Eq.	Equation
Fig.	Figure
FIT	Feed-in tariff
FLB	Fluidized bed
FXB	Fixed bed
GHG	Greenhouse gas

GWh	Gigawatt hour
GWP	Global warming potential
h	Hour
HO_2	Hydrogen dioxide
IRR	Internal rate of return
kg	Kilogram
IUE	Institute of environmental technology and energy economics
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelised cost of electricity
LHV	Low heating value
m^3	Cubic meter
MDF	Medium density fiberboard
MJ	Megajoule
MW	Megawatt
NG	Natural gas
NOx	Nitrogen oxide
NPV	Net present value
NRI	Niroo research institute
O&M	Operations and maintenance
OH	Operating hours
PO_4	Phosphate
ROC	Return of capital
SATBA	Iran's renewable energy and energy efficiency organization
SO_2	Sulphur dioxide
SOx	Sulphur oxide
TUHH	Hamburg University of technology
Y	Year

REFERENCES

Ahmad, A.A.; Zawawi, N.A.; Kasim, F.H.; Inayat, A.; Khasri, A., (2016). Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. Renew. Sustain. Energy Rev., 53: 1333–1347 **(15 pages).**

Amin Salehi, F.; Abdoli, M.A.; Shokouhmand, H.; Jafari, H.R., (2012). Techno-economic assessment for energy generation using bagasse: case study. Int. J. Energy Res., 37(8): 982–990 **(9 pages).**

Anukam, A.; Mamphweli, S.; Reddy, P.; Meyer, E.; Okoh, O., (2016). Pre-processing of sugarcane bagasse for gasification in a downdraft biomass gasifier system: A comprehensive review. Renew. Sustain. Energy Rev., 66: 775–801 **(7 pages).**

Ardila, Y.C.; Figueroa, J.E.J.; Lunelli, B.H.; Filho, R.M.; Maciel, M.R.W., (2012). Syngas production from sugar cane bagasse in a circulating fluidized bed gasifier using Aspen Plus: Modelling and simulation. Computer Aided Chem. Eng., 30: 1093-1097 **(5 pages).**

Asadullah, M., (2014). Barriers of commercial power generation using biomass gasification: A review. Renew. Sustain. Energy Rev., 29(C): 201-215 **(15 pages).**

Avami, A.; Sattari, S., (2007). Energy conservation opportunities: Sugar industry in Iran. Int. J. Energy, 1(3): 65–71 **(7 pages).**

Azadi, P.; Nezam Sarmadi, A.; Mahmoudzadeh, A.; Shirvani, T., (2017). The Outlook for natural gas, electricity, and renewable energy in Iran. Stanford Iran 2040 Project, Stanford University, Working Paper 3: 1–27 **(27 pages).**

Balat, M.; Osman, H., (2005). Use of biomass sources for energy in Turkey and a view to biomass potential. Biomass Bioenergy, 29(1): 32–41 **(10 pages).**

Blok, K.; Huijbregts, M.; Roes, L.; Haaster, B.; Patel, M.; Hertwich, E.; Wood, R.; Michael, Z.; Hauschild, Piet Sellke.; Antunes, Paula.; Hellweg, Stefanie.; Ciroth, Andreas.; Harmelink, M., (2013). Handbook on a novel methodology for the sustainability impact assessment of new technologies. Utrecht University-Prosuite project, 1–23 **(23 pages).**

Broek, R.; Burg, T.; Wijk, A.; Turkenburg, W., (2000). Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua: A comparison with fuel oil electricity generation on the basis of costs, macro-economic impacts and environmental emissions. Biomass Bioenergy, 19: 311–335 **(25 pages)**.

Caputo, A.C.; Palumbo, M.; Pelagagge, P.M.; Scacchia, F., (2005). Economics of biomass energy utilization in combustion and gasification plants: Effects of logistic variables. Biomass Bioenergy. 28(1): 35–51 **(17 pages).**

Ciferno, J.P.; Marano, J.J.; (2002). Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. Report prepared for U.S. Department of Energy (DOE) – National Energy Technology Laboratory technical report (NETL), 1: 1–58 **(58 pages).**

Dantas, G.A.; Legey, L.F.L.; Mazzone, A., (2013). Energy from sugarcane bagasse in Brazil: An assessment of the productivity and cost of different technological routes. Renew. Sustain. Energy Rev., 21: 356–364 **(9 pages).**

DEA, (2016). The Danish levelized cost of energy calculator. Danish Energy Agency, 1(1): 1–68 **(68 pages).**

Dutta, A.; Talmadge, M.; Hensley, J.; Worley, M.; Dudgeon, D.; Barton, D.; Groenendijk, P.; Ferrari, D.; Stears, B.; Searcy, E.; Wright, C.; Hess, J.R., (2012). Techno-economics for conversion of lignocellulosic biomass to ethanol by indirect gasification and mixed alcohol synthesis. Environ. Prog. Sustain. Energy, 31(2): 182–190 **(9 pages).**

EIA, (2019). Annual energy outlook 2019. U.S. Energy Information Administration, 1(January): 1–83 **(83 pages).**

Falode, O.A.; Ladeinde, A.O., (2016). Economic evaluation of gas power plant project for the first gas industrial park in Nigeria.

Br. J. Appl. Sci. Technol., 17(1): 1–19 **(19 pages).**

Gabra, M.; Pettersson, E.; Backman, R.; Kjellstrom, B., (2001). Evaluation of cyclone gasifier performance for gasifcation of sugar cane residue - Part 2: Gasifcation of cane trash. Biomass Bioenergy, 21(5): 371–380 **(10 pages).**

Hijazi, O.; Munro, S.; Zerhusen, B.; Effenberger, M., (2016). Review of life cycle assessment for biogas production in Europe. Renew. Sustain. Energy Rev., 54: 1291–1300 **(10 pages).**

Hosseini, S.E.; Mahmoudzadeh Andwari, A.; Abdul Wahid, M.; Bagheri, G., (2013). A review on green energy potentials in Iran. Renew. Sustain. Energy Rev., 27: 533–545 **(13 pages).**

IEA, (2007). Biomass for power generation and CHP. Int. Energy Agency- Energy technology essentials, OECD/IEA, 1–4 **(4 pages).**

IEA, (2015). Projected costs of generating electricity. Int. Energy Agency, 1(1): 1–250 **(250 pages).**

Indrawan, N.; Thapa, S.; Bhoi, P.R.; Huhnke, R.L.; Kumar, A., (2017). Engine power generation and emission performance of syngas generated from low-density biomass. Energy Convers. Manage., 148(15): 593–603 **(11 pages).**

IRENA, (2012). Renewable energy technologies cost analysis series: Concentrating solar power. Int. Renew. Energy Agency, 2(1): 1–60 **(60 pages).**

IRENA, (2013). Renewable power generation costs in 2012: An overview. Int. Renew. Energy Agency, 1: 1–12 **(12 pages).**

IRENA, (2015). Data methodology. Int. Renew. Energy Agency, 2(1): 1–14 **(14 pages).**

IRENA, (2017). Renewable power generation costs in 2017. Int. Renew. Energy Agency, 1: 1–16 **(16 pages).**

ISFS, (2017). Reports of sugar cane and sugar beet mills of Iran. Iranian sugar factories syndicate, 1: 1–58 **(58 pages).**

ISO, (2019). Sugar Yearbook. International Sugar Organization, 1: 1-75 **(75 pages)**.

Kvist, T.; Frohn, L.M.; Jørgensen, L., (2011). Environmental optimisation of natural gas fired engines. International Gas Union Research Conference (IGRC), (19-21 October): 1-10 **(10 pages).**

Luz, F.C.; Rocha, M.H.; Lora, E.E.S.; Venturini, O.J.; Andrade, R.V.; Leme, M.M.V.; Olmo, O.A., (2015). Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. Energy Convers. Manage., 103: 321–337 **(17 pages)**.

Matsumura, Y.; Yokoyama, S.Y., (2005). Current situation and prospect of biomass utilization in Japan. Biomass Bioenergy, 29(5): 304–309 **(6 pages).**

Mbohwa, C.; Fukuda, S., (2003). Electricity from bagasse in Zimbabwe. Biomass Bioenergy, 25: 197–207 **(11 pages)**.

Meerman, J.C.; Knoope, M.M.J; Ramírez, A.; Turkenburg, W.C.; Faaij, A.P.C., (2013). Technical and economic prospects of coal- and biomass-fired integrated gasification facilities equipped with CCS over time. Int. J. Greenh. Gas Control, 16: 311-323 **(13 pages)**.

Mohammadi, F.; Roedl, A.; Abdoli, M.A.; Amidpour, M.; Vahidi, H., (2020). Life cycle assessment (LCA) of the energetic use of bagasse in Iranian sugar industry. Renew. Energy, 145: 1870–1882 **(13 pages).**

Naqvi, M.; Yan, J.; Dahlquist, E.; Raza, S., (2016). Waste biomass gasification based off-grid electricity generation: A case study in Pakistan. Energy Procedia, 103(April): 406–412 **(7 pages)**.

NETL, (2015). Cost and performance baseline for fossil energy plants: Bituminous coal (PC) and natural gas to electricity. National Energy Technology Laboratory (NETL), 1(3): 1–240 **(240 pages).**

Nian, V.; Sun, Q.; Ma, Z.; Li, H., (2016). A comparative cost assessment of energy production from central heating plant or combined heat and power plant. Energy Procedia, 104: 556–561 **(6 pages).**

NNFCC, (2009). Review of technologies for gasification of biomass and wastes. E4-tech, 1: 1–125 **(125 pages)**.

NREL, (2017). Electricity generation baseline report. National Renewable Energy Laboratory, 1: 1–289 **(289 pages).**

Othman, N.F.; Boosroh, M.H., (2016). Effect of H2 and CO contents in syngas during combustion using micro gas turbine. Effect of H2 and CO contents in syngas during combustion using micro gas turbine. IOP Conf. Ser. Earth Environ. Sci., 32(1-No.12037) 1–5 **(5 pages)**.

Pantaleo, A.M.; Camporeale, S.; Fortunato, B., (2015). Small scale biomass CHP: Techno-economic performance of steam vs gas turbines with bottoming ORC. Energy Procedia, 82: 825–832 **(8 pages).**

Patel, M.; Zhang, X.; Kumar, A., (2016). Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. Renew. Sustain. Energy Rev., 53: 1486–1499 **(14 pages)**.

Puig-Arnavat, M.; Bruno, J.C.; Coronas, A., (2010). Review and analysis of biomass gasification models. Renew. Sustain. Energy Rev., 14(9): 2841–2851 **(11 pages)**.

Safari, F.; Tavasoli, A.; Ataei, A., (2016). Gasification of sugarcane bagasse in supercritical water media for combined hydrogen and power production: A novel approach. Int. J. Environ. Sci. Technol., 13(10): 2393–2400 **(8 pages)**.

Singh, J., (2015). Overview of electric power potential of surplus agricultural biomass from economic, social, environmental and technical perspective: A case study of Punjab. Renew. Sustain. Energy Rev., 42: 286–297 **(12 pages)**.

Sheikhdavoodi, M.J.; Almassi, M.; Ebrahimi-Nik, M.; Kruse, A.; Bahrami, H., (2015). Gasification of sugarcane bagasse in supercritical water; Evaluation of alkali catalysts for maximum hydrogen production. J. energy inst., 88: 450–458 **(9 pages)**.

Tavasoli, A.; Barati, M.; Karimi, A., (2016). Sugarcane bagasse supercritical water gasification in presence of potassium promoted copper nano-catalysts supported on γ-Al2O3. Int. J. Hydrogen Energy, 41: 174–180 **(7 pages)**.

USDA, (2019). Report: Sugar: world markets and trade. United States department of agriculture, 1(May): 1–7 **(7 pages)**.

Worley, M.; Yale, J., (2012). Biomass gasification technology assessment: Consolidated Report. National Renewable Energy Laboratory (NREL), 46(NREL/SR-5100-57085): 1-358 **(358 pages)**.

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