The Nucleus **57**, No. 3 (2020) 81-89

www.thenucleuspak.org.pk

The Nucleus

ISSN 0029-5698 (Print)

ISSN 2306-6539 (Online)

Techno-Economic Assessment of Syngas Generation from Municipal Solid Waste in Pakistan: A Simulated Study

H. A. Nawaz*, Q. Abbas, N. Ramzan, and S. Naveed

Department of Chemical Engineering, University of Engineering and Technology, Lahore 54890, Pakistan

ARTICLE INFO

Article history:

Received: *27 May, 2019*

Accepted: *13 January, 2021*

Published: *18 March, 2021*

Keywords:

Municipal solid waste gasification,

Techno-economic assessment,

ASPEN PLUS,

Return on investment,

Discounted payback period,

Net present value

ABSTRACT

The key objective of this work is to analyze the techno-economic feasibility of municipal solid waste (MSW) gasification plant in a small village named Nano Dogar near Lahore, Pakistan. Sampling of MSW was performed in the village indicating feed rate as 83.4kg/hr equivalent to 2 tons/day. The technical assessment was achieved by using process simulator; ASPEN PLUS version 8.1, in terms of material and energy balance. The results attained were associated with equations finding process efficiency, power generation potential, capital and operating costs. For economic appraisal, various cost parameters were taken into account like interest rate, plant life, operating hours, costs of labor, maintenance, supervision and purchase equipment costs (PEC) to estimate the project feasibility indicators like return on investment (ROI), discounted payback period (DPBP), net present value (NPV), internal rate of return (IRR), and profitability index (PI). This hypothetic gasification plant has power generation potential of 0.175 MW/ton when operated at 800°C and 1 atm, with flowrates of MSW, air and steam as 80 kg/hr, 115 kg/hr and 52 kg/hr at 1 atm, respectively. However, the temperature for MSW and air was 25°C and for steam, it was 200°C. ROI and DPBP were found to be 4.6% and 3 years, respectively. NPV was positive followed by 17% IRR and PI was greater than one. This assessment can be useful to study the technical and economic aspects of gasification plant irrespective of feedstock type such as coal, oil and biomass, and plant capacity.

1. Introduction

One of the major challenges faced by living beings is pollution, resulting from excessive use of fossil fuels, harmful industrial emissions, ever increasing solid waste generation level and greenhouse gas emissions leading towards environment degradation and climate change [1]. Waste generation level is becoming critical and alarming worldwide. A World Bank survey showed that world cities generated 2.01 billion tonnes of solid waste annually with footprint of 0.74 kg/person/day and is expected to rise to 3.40 billion tonnes by 2025 due to rapid urbanization and population growth [2]. Solid waste management (SWM) scenario in Pakistan is cautionary. Pakistan is declared as second largest country in South Asia ranking sixth largest in the world with a population of 207.7 million [3]. Solid waste generation in Pakistan ranges between 0.283 to 0.612 kg/capita/day or 1.896 to 4.29 kg/house/day [4, 5]. Based on estimates, Pakistan generates more than 50,000 tonnes of solid waste/day, with annual growth rate of more than 2 percent [6, 7]. Now a days, waste is no more recognized as litter or trash; in future, it might become more valuable and profitable residue as its potential has been explored to produce energy by mitigating environmental degradation impacts.

Energy has become a vital need for human and socio-economic development and playing its role in improving our living standard. In Pakistan, imported oil and gas is being used as a major source for electricity generation. Hence, the commutative cost of power is higher. Average price of natural gas for domestic and industrial sector in Pakistan provided by Oil and Gas Regulatory Authority (OGRA) for October 2020 was 5-6$ per Million British Thermal Unit (MMBTU) [8]. While gasoline price set by OGRA for November, 2020 was 0.65$/litre [9]. Other energy resources include hydel, liquefied petroleum gas, coal, wind, solar and nuclear [10]. Economic Survey 2017-2018 revealed that Pakistan's installed capacity of power has reached up to 29,573 MW uptil February 2018 [3]. Consumer demand was around 23,000 MW in June 2018. There are seasonal fluctuations having energy deficit of 3000-6000 MW. Annual electricity supply and demand is growing at a rate of 7% and 10%, respectively. This shows that by 2030, the power requirement will be greater than 45,000 MW in the country [10, 11]. Pakistan is facing energy crises not only because of its sole dependency on hydel and fossil fuel for power generation but also due to population growth at a fast rate.

China-Pakistan Economic Corridor (CPEC) is contributing its role in the development of energy sector including power generation and transmission projects [12]. However, gas and oil reserves are depleting at a faster rate and are left only for 10 and 19 years, respectively [10]. Country is, now, focused about energy mix to overcome energy deficit; to minimize hazardous environmental impact of waste and fossil fuels; and to have relatively less dependency on expensive oil by relying on renewable energy sources like biomass, wind, tidal, geothermal and solar [13] . The total renewable energy potential in Pakistan is about 179.3 GW by 2030 [10]. Biomass is preferred to other renewable sources in terms of cheap raw material, relatively less environmental impact, global warming, human health concerns and carbon foot print [14]. Various types of biomass like agricultural,

*Corresponding author: ayesha.pu35@gmail.com

forest, animal and municipal solid waste (MSW) can be treated as solid fuel and converted into energy via incineration, pyrolysis and gasification. In 2016, 30 million tons of combustible MSW generated power about 14 billion kWh of electricity in United States [15]. MSW, being a major potential source of energy [16], is considered as a solid fuel to minimize SWM concerns and to produce energy in the form of synthesis gas throughout this paper.

For SWM, appropriate disposal of MSW is as necessary as increasing demand of energy in terms of heat and electricity. Various treatment methods of disposal and utilization of MSW include landfill, recycling, composting, incineration, pyrolysis and gasification. Each strategy has its own pros and cons. Landfill involves gas and leachate generation, leading towards severe health hazards, unpleasant odor, contaminated air, damage to vegetation land and ground water, and explosion in severe cases [17]. Recycling not only saves land, conserves energy but also requires separate factories to process tons of garbage and produce pollutants. Composting improves soil health and fulfills soil need for fertilizers but at the same time accumulation of heavy metals adversely affects plant growth and health of living beings. Incineration has lower thermal efficiencies. It has more carcinogenic and toxic chemicals like dioxins and furans in gas emissions than that of gasification [18]. So, its cleaning system is expensive than gasification. Pyrolysis involves low carbon conversion and produces more char than gasification [19]. Among these, gasification is considered as the most environment friendly process by utilizing waste into energy in terms of landfill space preservation and less hazardous gas emissions [20]. It is considered as cleaner, renewable and sustainable energy choice [21].

Gasification is the conversion of organic part of solid fuel (solid waste) to gaseous fuel (synthesis gas or simply syngas). This thermochemical process occurs in the presence of oxidizing agents (pure oxygen (O_2), steam (H_2O) or air) [22]. Atmospheric pressure and temperature generally ranging between (700-1000)°C are regarded as favorable conditions for the chemical reactions to maximize waste conversion to high heating value fuel gas. Syngas mainly comprises of carbon monoxide (CO), hydrogen (H_2) and some trace amounts of methane (CH_4), carbon dioxide (CO_2) and steam (H_2O) [23]. Undesirable gases like hydrogen sulphide (H_2S) are scrubbed away. In air gasification, auto-thermal gasification starts after the combustion of the part of the fuel to provide necessary heat for this process [24, 25]. Syngas is useful as a fuel for heating purpose in stoves, for power generation and as a raw material source for the production of chemicals. It is much cleaner energy option than fossil fuel combustion. Syngas composition can vary significantly depending on the feedstock and the gasification process involved. Many researchers performed simulation of biomass gasification via commercial softwares like ASPEN PLUS [26–28] and evaluated the technical and economic aspects of biomass gasification plant [29–32]. Extensive detail of ASPEN PLUS blocks are discussed by Moshi et al. [33].

The objective of this paper is to assess the technical and economical perspectives of a small scale gasification plant in a village near Lahore by utilizing the potential of available MSW to meet their energy demand in the form of synthesis gas and to minimize perilous environmental issues. For this, a model was simulated on ASPEN PLUS version 8.1, which assisted in technical assessment for gasification plant. Another aim of this study is to evaluate plant’s economics, feasibility and socio-cost benefit analysis.

2. Methodology

In this research, MSW was collected from a small village named *Nano Dogar* near Lahore. MSW generation rate was found to be 2 tons/day by performing sampling of MSW in the village for one week. Estimated composition of collected MSW has been shown in Fig. 1. Typical ultimate and proximate analysis including estimated low heating value (LHV) of MSW is given in Table 1. Gasification plant can be split up into three main areas: pre-treatment includes screening, grinding, drying; main treatment has gasification process; and post treatment includes gas cleaning (see Fig. 2). After screening, the moisture of MSW is removed in a dryer. Then, it goes to a mill where 5-20mm particle size is achieved. Afterwards, MSW passes through different zones of gasifier where gasification reactions occur and syngas is produced which is cleaned either by physical or chemical absorption [34, 35].

Commercial software ASPEN PLUS version 8.1, process simulator, was used to model gasification process in terms of material and energy balances [36]. Fig. 3 demonstrates an ASPEN PLUS simulation model. In ASPEN PLUS, MSW and Ash were declared as non-conventional feed. PENG-ROB was considered as physical property method [37]. HCOALGEN and DCOALIGT were selected as enthalpy and density model for both MSW and Ash. Moisture of MSW was removed in R Stoic followed by Flash-2 as a separator. In R Stoic, PROXANAL, ULTANAL and SULFANAL analysis were entered for MSW and Ash. Then, this dried MSW was decomposed in R Yield followed by R Gibbs to simulate gasification of MSW. Temperature and pressure conditions for Gasifier were 800°C and 1 atm.

Flowrates of MSW and air were 80kg/hr and 115 kg/hr at 1 atm and 25°C respectively. Steam was also introduced at 1 atm and 200°C with flowrate of 52 kg/hr. In the last step of simulation process, syngas is cleaned from Ash via Flash-2 as a separator. This integrated fixed bed gasifier model can be used for different biomass feedstocks.

2.1 Technical and Economical Assessment of Gasification Plant

Eqs. (1) to (4) were used to calculate total annual syngas

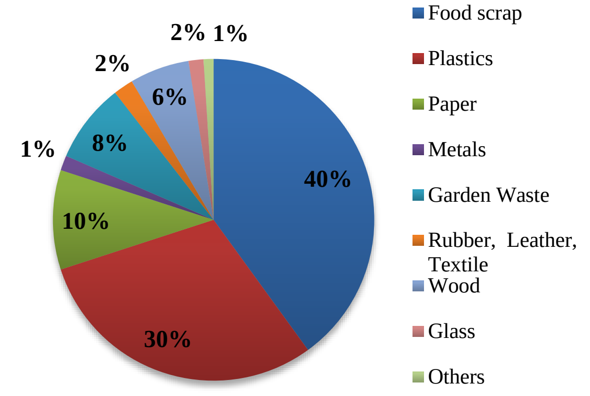

Fig. 1: Composition of collected MSW.

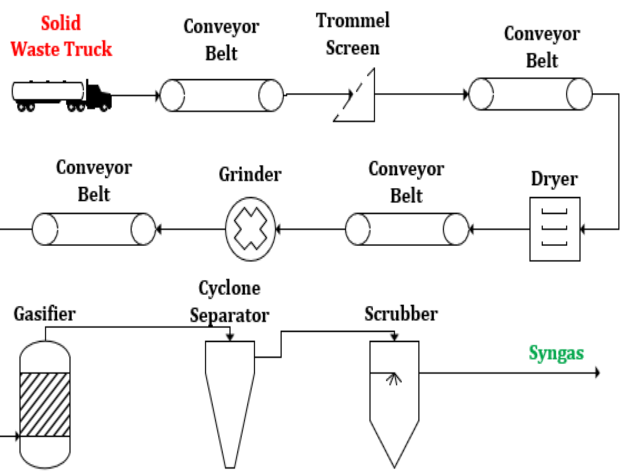

Fig. 2: Process flow diagram of waste to syngas.

yield, low heating value of syngas, energy recovery potential (ERP) and power generation potential (PGP) of MSW [21, 38–40].

$$Ys = Pc \times H \tag{1}$$

Where Ys is the total annual syngas yield (m^3), Pc is the production capacity (m^3/hr) and H is the running hours (hr). The value of Pc has been calculated from Aspen Plus.

$$LHV = \frac{H2\% \times 107.98 + CO\% \times 126.36 + CH4\% \times 358.18)}{1000} \tag{2}$$

Where LHV is the low heating value of syngas (MJ/Nm^3), H_2%, CO%, and CH_4% are the volume percentages of these components in the gaseous products.

$$ERP = \frac{NCV \times Ws \times 1000}{860} \tag{3}$$

$$PGP = \frac{1.16 \times NCV \times Ws}{24000} \tag{4}$$

Where ERP is the energy recovery potential of MSW (kWh), PGP is the power generation potential (MW), NCV is the net calorific value (kcal/kg) and Ws is the weight of combustible MSW (ton/day).

Table 1: Proximate and ultimate analysis of MSW [41].

Proximate Analysis	(Mass %)
Fixed carbon	15.47
Volatile matter	38.29
Moisture	12
Ash	46.24
Ultimate Analysis	(Mass %)
C	65
H	22
O	6
N	4
S	1
Ash	2
MSW low heating value	15 MJ/kg[a]

a. Source of calculating low heating value of MSW [42, 43].

The economic evaluation of the process includes: preparing a process flow diagram, calculating mass and energy flows, estimating the capital and operating cost, annual product income (API), forecasting the product sales price and estimating profitability indicators [44]. The economic assessment was done by estimation models and rules of thumb given by Towler and Sinnott [45] in order to estimate key financial indicators such as fixed capital investment (FCI), working capital (WC), total capital requirement (TCR), fixed production costs (FCOP), variable costs of production (VCOP), annual product income, annual operating costs (AOC), and depreciation. Basis of these cost parameters are presented in Table 2. FCI comprises of offsite battery limit investments (OS), engineering and construction costs (D&E), contingency charges (X) and inside battery limit investments (C_{ISBL}). It was evaluated by Eq. (5).

$$FCI = C_{ISBL} \times (1+OS)(1+D\&E+X) \tag{5}$$

Factors for OS, D&E and X were taken as 0.4, 0.25 and 0.1, respectively for solid-fuel processing [45]. C_{ISBL} was multiplied by these factors to give the value of FCI. For C_{ISBL}, purchase cost of major equipment (PEC) required for gasification were taken into account by estimation methods given in the literature [45, 46]. In this gasification plant, PEC included the cost of conveyor belt, dryer, mill, gasifier, scrubber, pumps, compressors and heat exchangers. The additional money, needed to start-up the plant and run it until it starts earning, income is regarded as working capital. It is estimated as 5% of FCI. Both FCI and WC were added up to give total capital requirement. FCOP don't vary with the plant operation rate or output. If the plant cuts back its production, these costs are not reduced like the costs of maintenance,

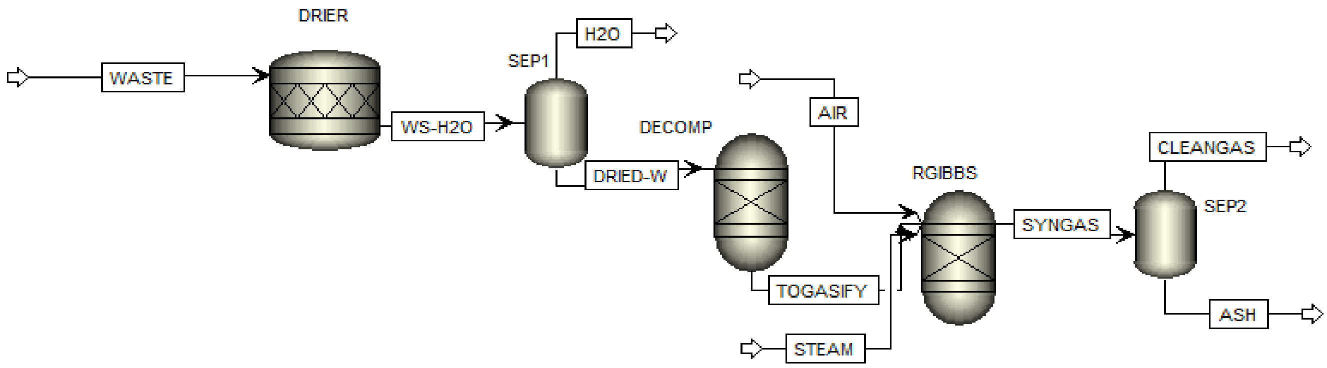

Fig. 3: ASPEN PLUS simulation gasifier model.

supervision, labor tax, property and insurance. VCOP are costs that are proportional to the plant output or operation rate. It comprises of costs of utilities, raw material and miscellaneous. Utilities cost includes cooling water, steam and air, which was found by multiplying the cost of utility in ($/kg) of each with the flow-rate of respective utility in (kg/yr). So, we obtained the cost of utility in ($/yr). MSW cost as raw material was calculated in the same manner as utility cost. Estimation of miscellaneous cost is given in Table 2. FCOP and VCOP were summed up to give annual operating cost. Total cost of production (TCOP) was found by adding annualized capital cost (ACC) and annual operating cost [35]. Eq. (6) is used to estimate the number of operating labors for this plant [34].

$$N_{OL} = (6.29 + 31.7\, P^2 + 0.23 N_{np})^{0.5} \quad (6)$$

Where N_{OL} is the number of operators per shift, P is the number of processing steps involving the handling of particulate solid and N_{np} is the number of non-particulate processing steps.

2.2 *Project's Feasibility Evaluation for Capital Budgeting*

The indicators used for measuring financial characteristics and evaluating the feasibility of the project's investment include: return on investment (ROI), discounted payback period (DPBP), net present value (NPV), profitability index (PI) and internal rate of return (IRR). They are also called profitability projections.

These parameters enable us to check either a particular project is feasible or not, which in turn, assist in making decisions for capital budgeting of a project. The formula given in Eq. (7) is used to calculate ROI [31]. DPBP, NPV and PI were calculated by the formulas available in the literature [46, 47]. IRR has been found from the NPV graph which can be seen in the results section.

$$ROI = \frac{(API - AOC)}{TCR} x\ 100 \quad (7)$$

where API is the annual product income ($/yr), AOC is the

Table 2: Basis of economic assessment

Plant capacity	1.03 MMSCFD of syngas at MSW flow-rate of 2 tons/day or 83.4kg/hr
Location, time, currency	Pakistan, 2020, US$
Plant life (N)	20 years
Annual operating time	7446 hr/year
Cost Items	Equations/Comments
Working capital	5% of FCI
Start-up costs	10% of FCI
No. of operators per shift	17
Operating labor cost	15% of ACC
Supervision cost	25% of operating labor cost
Direct salary overhead Cost	40% of (operating labor cost + supervision cost)
Maintenance of labor and materials cost	3% of C_{ISBL}
Property, taxes and insurance cost	1% of C_{ISBL}
General plant overhead Cost	65% (total labor cost + maintenance cost)
Miscellaneous cost	10% of maintenance cost
Depreciation[a]	D = FCI/N
Annual operating cost	FCOP + VCOP
Annual product income	Revenue = Unit production cost × Annual syngas yield
Interest rate	10%
Feedstock cost	10 US$/ton[b] or 0.01US$/kg
Labor rate	0.14 US$/hr[c]
Electricity cost	0.05-0.11 US$/kWh[d]

a. Source of calculating depreciation [31].

b. MSW cost in Pakistan is approximately 10 US$/ton [48].

c. Minimum Wages for Workers in Pakistan by 2017 is 15000 Rs/month = 20.5 Rs/hr = 0.14 US$/hr [49].

d. Electricity price in Pakistan provided by NEPRA in October 2018 varies between 7.5-15.53 rupees/ unit which is 0.056 US$/kWh and 0.11 US$/kWh respectively.

annual operating costs ($/yr) and TCR is the total capital requirement ($/yr).

3 Results and Discussion

In the present study, techno-economic evaluation of small scale MSW gasification plant has been carried out. Syngas composition, results of equations (1) to (4) and other parameters involved in the technical evaluation of this gasification plant are listed in Table 3.

When cost and flow-rate of MSW were US$ 0.01/kg and 83.4 kg/hr, respectively, syngas yield was found to be 1423 m^3/hr, which was then multiplied by 7446 as operating hours to get annual syngas yield in (m^3/yr). Syngas composition has trace amounts of CH_4 and H_2S. Syngas capacity in Million Standard Cubic Feet Per Day (MMSCFD) increases with MSW capacity (kg/hr). Carbon conversion efficiency to syngas and energy recovery potential of MSW were found to be 80% and 8337 kWh/day, respectively. Power generation potential was 0.175 MW/ton. As feed rate was 83.4 kg/hr or 2 tons/day, this would double the power generation potential, i.e., 0.35 MW. 1 MW has about 2,190,000 kWh; therefore, 0.35 MW has 2,190,000×0.35=766,500 kWh. In Pakistan, household electricity consumption was found to be 240 kWh/capita in 2015 [50]. This consumption (kWh/capita) was then multiplied by average household size, i.e., 6 to get electricity consumption/house, i.e., 1440kWh/house. The total numbers of houses were calculated as 766,500 kWh divided by 1440kWh/house. So, 532 houses can be electrified by this plant or population of about 532×6=3194 inhabitants can be benefitted from 0.35 MW plant. Net energy produced per capita was estimated by taking the product of amount of MSW produced per capita and LHV of MSW, i.e., 0.59×15=8.85 MJ/day. Net energy produced per house was found to be 8.85×6=53 MJ/day by the formula available in the literature [51].

Fig. 4 shows that at higher interest rate, TCOP ($/yr) of syngas increases with increasing MSW cost ($/ton). TCOP was lowest at 5% interest rate at particular MSW cost. MSW consumption rate in tons per day (TPD) has a direct relationship with PGP at constant net calorific value (see Fig. 5). At 10, 20 and 30 TPD of MSW, PGP was found to be 1.7, 3.5 and 5.2 MW, respectively. In economic assessment, it was observed that WC comprises of 4.8% of TCR and rest of it comprises of FCI.

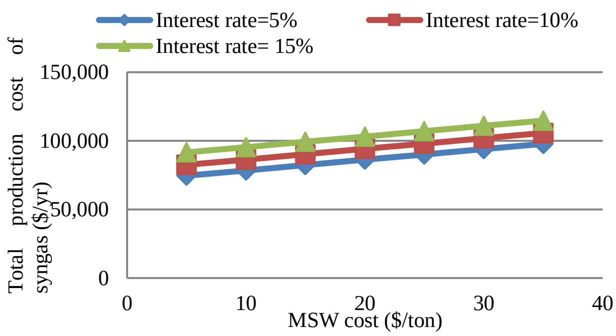

Fig. 4: Effect of MSW cost on TCOP by varying interest rate.

Table 3: Technical assessment of gasification plant.

Biomass type	MSW
MSW calorific value	15 MJ/kg
Particulate processing steps	Trommel screens; Rotary drier; Hammer mill
Mode of feed conveying system	Conveyor belts
MSW consumption rate	2 tons/day or 83.4 kg/hr
Gasifier type	Fixed bed
Gasifier temperature	800°C
Gasifier pressure	1 bar
Oxidizing agent	Air and Steam
Syngas production capacity	1423 m^3/hr
Annual syngas yield	10,595,658 m^3
Syngas calorific value	8-9 MJ/Nm^3
Syngas density	0.16 kg/ m^3
Syngas composition before cleaning	CO: 38.2%, H_2: 7.3%, CH_4: 0.3%, N_2: 38.2%, CO_2: 7.09%, Steam: 1.9%, Ash: 1.7%
Thermal carbon conversion efficiency to syngas	80%
Energy recovery potential of MSW	8337 kWh/day or 347.4 kWh/hr
MSW power generation Potential	0.35 MW
Syngas cleaning treatment Involves	Wet gas scrubber
Specific biomass consumption	0.27 kg/kWh
Specific electric power Production	3.7 kWh/kg_{waste}
Tariff	0.07 $/kWh

We found that the general plant overhead, labour and material's maintenance costs were far more than other costs in FCOP composition (see Table 4). In VCOP, utility costs were higher than raw material cost. MSW is considered as a cheap raw material, i.e., US$10/ton or US$0.01/kg. However, it may be increased if MSW cost varies than US$ 10/ton. Summary of capital and operating costs are listed in Table 4.

Fig. 6 indicates that by increasing the discount rate, DPBP is increasing and hence TCOP is increasing. At higher DPBP, TCOP is highest which isn't favorable as it will take more time to recover the cost of investment in terms of profit. The lower the DPBP, the better the project's profitability. If DPBP is less than the target period, the proposal may be feasible.

Effect of syngas capacity on fixed cost, variable cost, total cost and total revenue can be seen in Fig. 7. Fixed cost remains constant while variable cost and total cost increases but total revenue increases relatively more quickly with the syngas produced (m^3/hr).

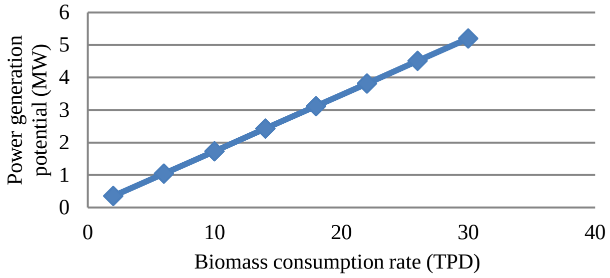

Fig. 5: Effect of biomass consumption rate on power generation potential.

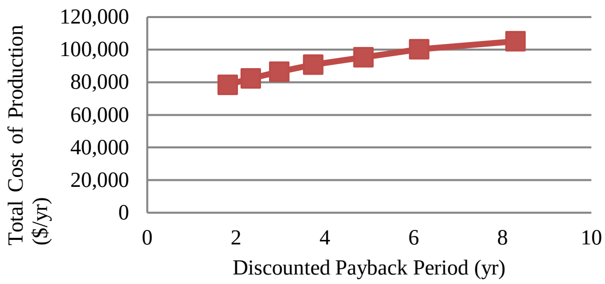

Fig. 6: Effect of DPBP on TCOP by varying discount rate.

Unit production cost (UPC) was calculated as annual product income ($/yr) divided by annual syngas yield (m^3/yr). We got 0.007$/$m^3$ as UPC which was then converted to 0.9$/(MMBTU). Fig. 8 depicts that UPC ($/$m^3$) first decreases and then remains constant with the increasing syngas capacity (m^3/hr). The calculated NPV for this project is positive, which indicates that the project is satisfactory. If NPV is negative, project isn't feasible. If PI is less than one, the project will be rejected and vice versa. The calculated PI is greater than one which ensures its selection criteria for project's feasibility (see Table 5).

Table 4: Summary of capital cost and operating cost for MSW gasification plant.

Capital Costs	US$/ yr	%
Inside battery limits investment (C_{ISBL})	108,617	
Fixed capital investment (FCI)	152,065	95.2
Working capital (WC)	7,603	4.8
Total capital requirement (TCR)[a]	159,668	100
Operating Costs		
General plant overhead	3,489	27.4
Operating labor	2,813	22
Supervision	703	5.5
Direct salary overhead	1,406	11
Labor and material's maintenance cost	3,258	25.5
Property, tax and insurance	1,086	8.5
Fixed cost of production (FCOP)	12,757	100
Raw material costs	7,725	14
Utility costs	46,838	85
Miscellaneous costs	325	0.6
Variable cost of production (VCOP)	54,889	100

Key Financial Indicators	
Annual operating cost (AOC)	67,646
Depreciation	7,603
Annual product income (API)	75,249
Annualized capital cost (ACC)[b]	18,754
Total cost of production (TCOP)	86,400

a. Cost of land isn't included in cost estimation. Other costs accuracy is ±30%.
b. Source of calculating ACC is **[30]**.

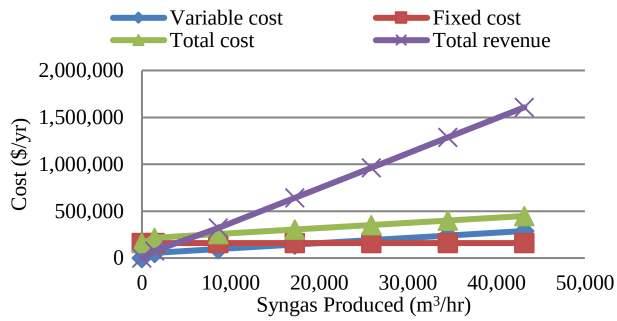

Fig. 7: Effect of syngas produced on various cost.

NPV is decreasing with the increase in plant life, as shown in Fig. 9. At lower discount rate (10%), it is decreasing at a slower rate. While at 15% discount rate, decreasing rate of NPV is bit faster. This indicates that NPV with lower discount rate is preferable. Fig. 10 puts attention towards NPV graph to find the percentage of internal rate of return (discount rate) when NPV becomes zero. Here, ACC is increasing while NPV is decreasing with the increasing discount rate. IRR found to be 17% at NPV is equal to zero. The results of the project's key profitability indicators are summarized in Table 5.

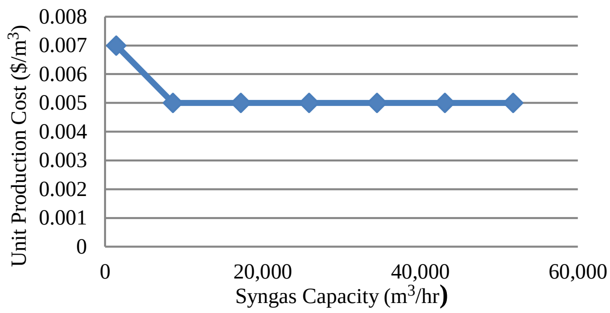

Fig. 8: Effect of syngas capacity on UPC.

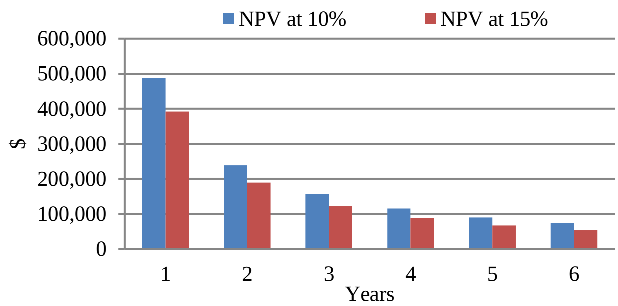

Fig. 9: Effect of Plant life on NPV at different discount rates.

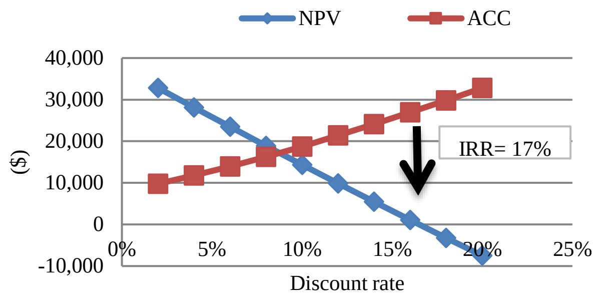

Fig. 10: Effect of discount rate on NPV and ACC.

Table 5: Summary of project's key profitability indicators.

Parameter	Unit	Value
ROI	(%)	4.6
NPV	($)	14,359
IRR	(%)	17
DPBP	(year)	3
PI		1.77

4 Conclusions

Techno-economic study of a small scale biomass gasification plant in Pakistan has been carried out. For this, simulated gasifier model has been established by using commercial software ASPEN PLUS version 8.1, in order to assess the technical aspects of gasification plant like mass and energy balance, thermal carbon conversion efficiency, annual syngas yield, calorific value and density of the syngas. Results indicate that 83.4kg/hr or 2TPD of MSW (having 15 MJ/kg as heating value) generates 1423 m^3/hr or about 1MMSCFD syngas and has 0.35 MW as power generation potential. This 0.35 MW biomass gasification plant has the capability to electrify about 532 houses or beneficiary population would be 3194. This potential increases with biomass generation capacity. The results of economic assessment achieved by using estimation models and rules of thumb available in the literature depict that this small gasification plant has US $ 18,754/yr as ACC and US $ 86,400/yr as TCOP. The obtained results were analyzed to predict the feasibility of the project by estimating profitability projections which indicate that PI is greater than one and NPV is positive with 17% IRR, followed by 4.6% ROI and 3 years as DPBP. These parameters indicate that project is feasible. This assessment can be used as a model to evaluate technical and economic aspects of any gasification plant. Moreover, this study is useful in order to investigate the feasibility of a project.

Abbreviation

ACC	Annualized Capital Cost
API	Annual Product Income
AOC	Annual Operating Cost/ DPC
CGE	Cold Gas Efficiency
C_{ISBL}	Inside Battery Limit Investments
CPEC	China-Pakistan Economic Corridor
D&E	Engineering and Construction Costs
DPC	Direct Production Cost
DPBP	Discounted Payback Period
ERP	Energy Recovery Potential
FCI	Fixed Capital Investment
FCOP	Fixed Cost of Production
GOP	Government of Pakistan
I	Interest Rate
IRR	Internal Rate of Return
LHV	Low Heating Value
MMBTU	Million British Thermal Unit
MMSCFD	Million Standard Cubic Feet per Day
MSW	Municipal Solid Waste
N	Plant life
NEPRA	National Electric Power Regulatory Authority
NPV	Net Present Value
OGRA	Oil and Gas Regulatory Authority
OSBL	Offsite Battery Limits Investment
P_c	Production Capacity
PEC	Purchase Equipment Costs
PGP	Power Generation Potential
PI	Profitability Index
ROI	Return on Investment
SWM	Solid Waste Management
TCOP	Total Cost of Production
TCR	Total Capital Requirement
TPD	Tons per Day
UPC	Unit Production Cost
VCOP	Variable Cost of Production
WC	Working Capital
X	Contingency charges

References

[1] S. Nanda and F. Berruti, "A technical review of bioenergy and resource recovery from municipal solid waste", J. Hazard. Mater., vol. 403, p. 123970, 2020.

[2] "Solid Waste Management", The World Bank, September 2019. [Online].Available:http://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management.

[3] M. Asif, M.S. Malik and Z. Husnain, "Pakistan Economic Survey 2017-18", Islamabad, 2017. [Online]. Available: http://www.finance.gov.pk/survey_1718.html.

[4] R.T. Hassan, "The cost of inefficient solid waste management", The Express Tribune, May 21, 2012. [Online]. Available: https://tribune.com.pk/story/381697/the-cost-of-inefficient-solid-waste-management.

[5] S.M. Hina, "Municipal solid waste collection route optimization using geospatial techniques: A case study of two metropolitan cities of Pakistan", NDSU Repository, February 2016. [Online]. Available: https://library.ndsu.edu/ir/handle/10365/25816.

[6] T. Iqbal, C. Dong, Q. Lu, Z. Ali, I. Khan, Z. Hussain and A. Abbas, "Sketching pakistan's energy dynamics: Prospects of biomass energy", J. Renew. Sustain. Energy, vol. 10, no. 2, p. 023101, 2018.

[7] S. Javied, F. Hanan, S. Munawar and M. Qasim, "Management of municipal solid waste generated in eight cities of Pakistan", Int. J. Sci. Eng. Res., vol. 5, no. 12, pp. 1186-1192, 2014.

[8] "Gas notified prices", Oil & Gas Regulatory Authority. [Online]. Available: https://www.ogra.org.pk/gas-notified-prices.

[9] "Notified petroleum prices", Oil & Gas Regulatory Authority. [Online]. Available: https://www.ogra.org.pk/notified-petroleum-prices.

[10] M.M. Rafique and S. Rehman, "National energy scenario of Pakistan – Current status, future alternatives, and institutional infrastructure: An overview", Renew. Sust. Energ. Rev., vol. 69, pp. 156–167, 2017.

[11] N.H. Mirjat, M.A. Uqaili, K. Harijan, G.D. Walasai, M.A.H. Mondal and H. Sahin, "Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis", Energy, vol. 165, pp. 512–526, 2018.

[12] G.D. Valasai, M.A. Uqaili, H.R. Memon, S.R. Samoo, N.H. Mirjat and K. Harijan, "Overcoming electricity crisis in Pakistan: A review of sustainable electricity options", Renew. Sust. Energ. Rev., vol. 72, pp. 734–745, 2017.

[13] M. Wakeel, B. Chen and S. Jahangir, "Overview of energy portfolio in Pakistan", Energy Procedia, vol. 88, pp. 71–75, 2016.

[14] V. Marcantonio, A. Monforti Ferrario, A. Di Carlo, L. Del Zotto, D. Monarca and E. Bocci, "Biomass steam gasification: A comparison of syngas composition between a 1-D Matlab Kinetic Model and a 0-D Aspen Plus Quasi-Equilibrium Model", Comput., vol. 8, no. 4, p. 86, 2020.

[15] "Biomass explained: Waste-to-Energy (Municipal Solid Waste)", Energy Informmation Administration, 2018. [Online]. Available:https://www.eia.gov/energyexplained/?page=biomass_waste_to_energy.

[16] C. Lin, J. Zhang, P. Zhao, Z. Wang, M. Yang, X. Cui, H. Tian and Q. Guo, "Gasification of real MSW-derived hydrochar under various atmosphere and temperature", Thermochim. Acta, vol. 683, p. 178470, 2020.

[17] M. El-Fadel, A.N. Findikakis and J.O. Leckie, "Environmental impacts of solid waste landfilling", J. Environ. Manage., vol. 50, no. 1, pp. 1–25, 1997.

[18] D.M.Y. Maya, A.L.E. Sarmiento, C.A.V.B. Oliveira, E.E.S. Lora and R. Andrade, "Gasification of municipal solid waste for power generation in Brazil: A review of available technologies and their environmental benefits", J. Chem. Chem. Eng., vol. 10, pp. 249–255, 2016.

[19] A.M. Shakorfow, "Biomass incineration, pyrolysis, combustion and gasification", Int. J. Sci. Res., vol. 5, no. 7, pp. 2319–7064, 2016.

[20] A. AlNouss, P. Parthasarathy, M. Shahbaz, T. Al-Ansari, H. Mackey and G. McKay, "Techno-economic and sensitivity analysis of coconut coir pith-biomass gasification using Aspen Plus", Appl. Energy, vol. 261, p. 114350, 2020.

[21] P. Xu, Y. Jin and Y. Cheng, "Thermodynamic analysis of the gasification of municipal solid waste", Eng., vol. 3, no. 3, pp. 416–422, 2017.

[22] A. AlNouss, G. McKay and T. Al-Ansari, "A comparison of steam and oxygen fed biomass gasification through a techno-economic-environmental study", Energy Convers. Manag., vol. 208, p. 112612, 2020.

[23] Y.A. Situmorang, Z. Zhao, A. Yoshida, A. Abudula and G. Guan, "Small-scale biomass gasification systems for power generation (<200 kW class): A review", Renew. Sust. Energ. Rev., vol. 117, p. 109486, 2020.

[24] U. Arena, "Process and technological aspects of municipal solid waste gasification: A review", Waste Manag., vol. 32, no. 4, pp. 625–639, 2012.

[25] V. Soni and V. Naik, "Gasification: A process for energy recovery and disposal of municipal solid waste", Am. J. Mod. Energy, vol. 2, no. 6, pp. 38-42, 2016.

[26] S. Begum, M.G. Rasul and D. Akbar, "A numerical investigation of municipal solid waste gasification using Aspen Plus", Procedia Eng., vol. 90, pp. 710–717, 2014.

[27] N. Ramzan, A. Ashraf, S. Naveed and A. Malik, "Simulation of hybrid biomass gasification using Aspen plus: A comparative performance analysis for food, municipal solid and poultry waste", Biomass Bioenergy, vol. 35, no. 9, pp. 3962–3969, 2011.

[28] R. Fatoni, S. Gajjar, S. Gupta, S. Handa and A. Elkamel, "Modeling biomass gasification in a fluidized bed reactor", Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management, Bali, Indonesia, January 7-9, 2014, pp. 1047–1056.

[29] C.Z. Wu, H. Huang, S.P. Zheng and X.L. Yin, "An economic analysis of biomass gasification and power generation in China", Bioresour. Technol., vol. 83, pp. 65–70, 2002.

[30] M.N. Islam and F.N. Ani, "Techno-economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel", Bioresour. Technol., vol. 73, no. 1, pp. 67–75, 2000.

[31] P. Hunpinyo, P. Narataruksa, S. Tungkamani, K. Pana-Suppamassadu and N. Chollacoop, "Evaluation of techno-economic feasibility biomass-to-energy by using Aspen Plus: A case study of Thailand", Energy Procedia, vol. 42, pp. 640–649, 2013.

[32] W. Gao, S. Wang, D. Li, J. Liu, M.R. Farahini, Y. Huo, M. Imran and M. Doranehgard, "Techno-economic evaluation of biomass-to-synthesis gas (BtS) based on gasification", Energy Sources Part B Econ. Plann. Policy, vol. 13, no. 2, pp. 83–90, 2018.

[33] R.E. Moshi, Y.A.C. Jande, T.T. Kivevele and W.S. Kim, "Simulation and performance analysis of municipal solid waste gasification in a novel hybrid fixed bed gasifier using Aspen Plus", Energy Sources Part A Recover. Util. Environ. Eff., pp. 1-13, 2020.

[34] B. Burr and L. Lyddon, "A comparison of physical solvents for acid gas removal", Gas Processors's Association Convention, Grapevine, TX, 2008.

[35] R. Bucklin and R. Schendel, "Comparison of fluor solvent and selexol processes", Energy Prog., vol. 4, no. 3, pp. 137–142, 1984.

[36] "Aspen Plus: Leading Process Simulation Software", AspenTech. [Online].Available: https://www.aspentech.com/en/products/engineering/aspen-plus.

[37] O.C. Mutlu and T. Zeng, "Challenges and opportunities of modeling biomass gasification in Aspen Plus: A review", Chem. Eng. Technol., vol. 43, no. 9, pp. 1674–1689, 2020.

[38] M.A. Chawdhury and K. Mahkamov, "Development of a small downdraft biomass gasifier for developing countries", J. Sci. Res., vol. 3, no. 1, pp. 51–64, 2010.

[39] Y. Deng, P.B. Parajuli and H. Kim, "Cost analysis model for catalytic conversion of syngas in to light hydrocarbon gases", Inf. Process. Agric., vol. 2, no. 1, pp. 37–50, 2015.

[40] T. Ramachar, G.C. Rao, M. Umamahesh and D. Nagamouli, "Calculation of energy recovery potential and power generation potential from municipal solid waste of Kurnool city, Andhra Pradesh, India", Int. J. Chem. Sci., vol. 12, no. 4, pp. 1345-1354, 2014.

[41] J. Kahn, "State of municipal solid waste management in Pakistan: A case study of Haripur District", PhD diss., Kingston University, 2016.

[42] M.S. Korai, R.B. Mahar and M.A. Uqaili, "Assessment of power generation potential from municipal solid wastes: A case study of Hyderabad city, Sindh, Pakistan", Pak. J. Anal. Environ. Chem., vol. 15, no. 1, p. 10, 2014.

[43] I.S. Antonopoulos, A. Karagiannidis and E. Kalogirou, "Estimation of municipal solid waste heating value in Greece in the frame of formulating appropriate scenarios on waste treatment", Proceedings of the 3rd International Symposium on Energy from Biomass and Waste, Venice, Italy, November 8-11, 2010.

[44] R.M. Sari and K. Kolmetz, General Process Plant Cost Estimating, Kolmetz Handbook of Process Equipment Design (Engineering Design Guideline), Malaysia: KLM Technology Group, June 2014.

[45] G. Towler and R. Sinnott, Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design, 2nd Ed., California: Elsevier, 2013.

[46] M.S. Peters and K.D. Timmerhaus, Plant Design and Economics for Chemical Engineers, 4th Ed., New York: McGraw-Hill, 1991.

[47] W.J. Stevenson, Operations Management, 12th Ed., New York: McGraw-Hill, 2015.

[48] S.A. Batool and M.N. Ch, "Municipal solid waste management in Lahore city district, Pakistan", Waste Manag., vol. 29, no. 6, pp. 1971–1981, 2009.

[49] "Fair work wages in Pakistan", 2018. [Online]. Available: https://paycheck.pk/labour-laws/wages-work.

[50] "Pakistan household electricity consumption per capita| Statistic", The Statistics Portal, 2015. [Online]. Available: https://www.statista.com/statistics/598318/household-consumption-of-electricity-per-capita-in-pakistan/.

[51] A. Shehzad, M.J.K. Bashir and S. Sethupathi, "System analysis for synthesis gas (syngas) production in Pakistan from municipal solid waste gasification using a circulating fluidized bed gasifier", Renew. Sust. Energ. Rev., vol. 60, pp. 1302–1311, 2016.