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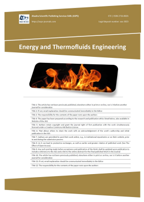

Techno-economic feasibility analysis for gas turbine and reciprocating engine-based power generation using biogas: A case study of Karachi, Pakistan

Syed Saad Ali[1], Asad A. Zaidi[2]✉, Rashid Hussain[1], Abdul Hameed Memon[1], Shujaat Ali[3], Muhammad Asif[4]

1 GSESIT, Faculty of Engineering Science and Technology, Hamdard University, Hakim Muhammad Said Road, Karachi, Pakistan

2 Mechanical Engineering Department, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia

3 School of Electrical and Information Engineering, Tianjin University, Tianjin, China

4 Department of Engineering Science, PN Engineering College, National University of Sciences and Technology, Karachi, Pakistan

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Abstract: The dependency on imported fossil fuels increases cost and environmental issues. Karachi the biggest and most densely populated city of Pakistan is experiencing severe energy shortage issues. This feasibility study evaluates the biogas transformation of Karachi city waste-to-energy utilizing conventional systems with few emissions. An estimation of energy potential was carried out to determine the potential generated in Karachi city for power generation using municipal waste. A modified energy model was used to determine the cooling load for a 100 kW power generation plant. The measurement of mathematical formulations was observed to monitor the affectivity of biogas generation. This study utilizes a biogas digester with anaerobic treatment technology to convert organic waste to energy. Feasibility analysis of this data is conducted in RETScreen Clean Energy Analysis software to compare different clean energy techniques. This feasibility is conducted for a 100 kW Power plant. Two options for power generation using biogas were selected i.e. reciprocating engine and gas turbine. The proposed reciprocating engine-based cooling system initial total cost of the biogas system is US 415,000 $ while gas turbine cost is 120,000 $ with payback period of 15 years. The proposed reciprocating engine produces 305 t CO_2 with 87.1% and gas turbine produces 16,600 t CO_2 with 38.4%. Results showed a cumulative comparative analysis among gas turbine and reciprocating engines that examines that reciprocating engine is recommended for high power efficiency with few emissions. The reciprocating engine has a better predicting ability for power generation with less carbon emissions, which is one of the key findings of the present study.

1. Introduction

Landfills in the United States of America convert organic waste into energy. These landfills use reciprocating engines to transform methane into energy. These engines operate on methane captured at landfill sites. In Canada, Biomass content from waste i.e. industrial, forest, agricultural, and waste calculated between 1.5 Exajoule (EJ) per year to 2.2 Exajoule (EJ) per year. (Peppley, 2006) showed municipal waste-based biogas is produced by anaerobic digestion. The biogas produced in the absence of oxygen is called an anaerobic process. Different reciprocating engines, gas turbines, microturbines, and fuel cells use biogas to produce energy. Generation is another method for efficient clean energy systems. This

✉ Corresponding author. E-mail address: sali@iu.edu.sa

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system uses a combined heat and power system to produce heat with engine heat.

Most reciprocating engines are energized by biogas fuel. Gas turbines are frequently used to energize biogas technology (Niemczewska, 2012).

The optimal size of the renewable scheme was determined by a feasibility study conducted for both electrical and thermal energy with the reduction of carbon dioxide and other gases. RETScreen software was utilized for both electrical and thermal technical analyses (Lee et al., 2012). RETScreen software is innovative for feasibility analysis. This software includes project estimated cost, emission, technical, energy production, and financial analyses. The combined heat and power system increases the electrical efficiency of the system. In comparative analysis for the generation using reciprocating engine efficiency is 81% and gas turbine efficiency is 71 % (Vollaro et al., 2014).

Improper management of waste and energy shortage is one of the biggest challenges in Pakistan. Organic waste-to-energy conversion is a sustainable solution for overcoming this waste treatment and energy shortage. Pakistan is naturally rich in renewable sources such as solar, wind, and biomass. Pakistan separated into four provinces Sindh, Balochistan, Punjab, and KPK with main cities Karachi, Islamabad, Peshawar, Quetta, Rawalpindi, Lahore, Faisalabad, Gujranwala, Sialkot, Multan, and Hyderabad were considered for study purpose. Pakistan's solid waste contains 64% organic matter and 36% inorganic matter (Korai et al., 2015).

Biogas-based energy generation for animal farm feasibility analysis was conducted in Kazakhstan by utilizing RETScreen . A 100 kW reciprocating engine was considered to be energized via farm waste. 87% of Kazakhstan's power is generated via a cogeneration system, and 13% utilizes water-to-power hydropower solutions. The paper focused on anaerobic digester systems. Anaerobic digestion is the process of transforming manure into biogas. The feasibility study was conducted over 15 years.100 kW plant produces 801 MWh of power annually with a decrease of 310 t CO_2 emissions (Rojas-Solórzano et al., 2016).

A fossil fuel-based system with a capacity of 2431 Megawatt system was considered. The major industrial area of the Karachi Pakistan Sindh Industrial Trading Estate (SITE) located in Karachi, with an area spanning over 204,732,000 Sq. ft. with a 7.2 MWh load requirement, was considered for the study (Zahid et al., 2016). Pakistan is naturally rich in livestock resources. Fermentation is a Technique to produce biogas and further utilize it to produce power. Construction of a portable digester was considered which is situated and functional at Nazeer Hussain University with the ability to produce 1.2 to 1.5 cubic meters of biogas. During the experimental analysis of the 100-kg load filled for two days, no leakage was found (Mushtaq et al., 2016).

The RETScreen software analyzes the feasibility of energy production, greenhouse gas emission reduction, and the financial feasibility of biomass. RETScreen was utilized for Project Analysis by performing economic analysis. The RET Screen software was integrated with the National Aeronautics and Space Administration (NASA) to provide annually based climate data parameters. The climate data parameters included wind speed, radiation, and temperature (Asumadu-Sarkodie and Owusu, 2016).

China is a densely populated country with a sustainable energy generation system. The Chinese government initiated renewable contributions to meet energy demand with clean sources. (Pan et al., 2017). Bolivia generates energy using landfill biogas. The 55.2 % of solid waste in Bolivia is organic and can be utilized to produce electricity. The methane gas achieved from the landfill used in reciprocating combustion engines, Santa Cruz, generates energy 265 GW h, La Paz 175 GW h, and Cochabamba 110.4 GW hours utilizing biogas integrated with reciprocating engines. Methane gas is extracted from solid waste via pipes treated in the direction to utilize methane gas as a fuel in a reciprocating combustion engine that generates energy that contributes to meeting grid requirements (Vargas Bautista and Calvimontes 2017).

A feasibility analysis for 5 kW solar power was carried out for Pakistan via RETSCREEN with a payback period of 7 years. Greenhouse emissions of 3.5338 t CO_2 were calculated for the Karachi case study (Bhutto et al., 2018). An economic study of a biomass power plant was conducted in Chittagong district for greenhouse gas reduction using a gas turbine integrated with biogas. This system considers parameters utilizing RETScreen simulation-based software for a 20-year Project life (Chowdhury et al., 2018). Karachi produces more than 15,000 tons of solid waste per day. The city has 18 towns and 178 union councils. Of the total amount of 15000 tons of solid waste, 60% is disposed of at the dumping sites, and the remaining 40% is dumped on the streets of Karachi (Shaikh et al., 2019).

A hybrid solar-biomass-based system was considered for feasibility analysis of the case study of Bangladesh via RETSCREEN. The off-grid system was installed in Ashuganj, Bangladesh. This study considers parameters related to electrical, thermal, cost, and emissions. The study is conducted for 6.9 years to perform financial analysis. The emissions of this project decreased by up to 3.81 tons per year. Both solar and biomass renewable clean energy systems were integrated for feasibility analysis. The annual lifesaving cost is 873.87$ with clean energy production (Chowdhury et al., 2020).

The physical and chemical parameters of waste were analyzed to measure their potential effects on the environment. Potential analysis was performed on the sampled Municipal Solid Waste. 65–70% biogenic matter and 40– 53% moisture. Biogenic waste includes paper, textiles, diapers, fruits/vegetables, wood metal glass, and plastic, which are non-biogenic (28–36%) (Ilmas et al., 2021).

Karachi is a major hub in Pakistan. The waste collected from the city was disposed of in Jam Chakro. This study evaluated waste recycling for power generation (Aslam et al., 2022). The dense populace and mega hub of Pakistan, Karachi, lacks a waste management system. Karachi produces approximately 20k tons of solid waste daily. Fifty percent of waste is officially disposed of at the site and other waste is disposed of in open sites, which causes health issues. This study highlights an alarming system for solid waste in Karachi (Shahid et al., 2022). The Lack of waste sites and mishandling of waste cause pollution and climate change. Sustainable management must meet the aims and goals of considering environmental and health concerns (Sohoo et al., 2022).

Natural gas accounts for approximately 20% of the global power generation. Natural gas decreases carbon emissions compared to other fuels. In this study, biogas was used as an alternative to natural gas. There is an efficient method to produce biogas for energy conversion using organic waste. Purified biogas is the same as natural gas (Rogala et al. 2023).

Cogeneration is a solution to improve the electrical efficiency of power plants and reduce emissions. This system was inspired by a sustainable clean energy solution (Slavica et al., 2023). The increase in environmental pollution and gas emissions need sustainable solution and approach. This study focuses biodiesel extracted from wasted catering oil produced from domestic and corporates. The method considers in this study was transesterification process by employing Methyl alcohol and sodium hydroxide as a catalyst. The sampled collection provides key parameters like kinematic viscosity and density. The viscosity parameters 5.59, 5.46 and 4.91 centistokes and considered biodiesel samples as most innovative selection (Kharshiduzzaman et al., 2025).

2. Materials and Methods

2.1. Study Area

The heavily populated city of Pakistan, Karachi, was considered as the study area. Karachi extends over an area of 3,780 square kilometers per square area. Karachi produces large amounts of organic waste daily. In this case, the six districts chosen were Central, East, South, West, Korangi, and Malir, and the population data of Karachi districts were collected from the 1998 and 2017 censuses. Karachi produces approximately 20,000-ton organic waste daily. The population of Karachi is 14.9 million as per the census 2017.

K-Electric is responsible for Karachi power generation and distribution. The power demand of Karachi is 2900 MW and that of K-Electric. The energy gap is contributed by the National Transmission and Dispatch Company and the independent power plants. The waste management of Karachi is supervised by Karachi Metropolitan Corporation and District Municipal Corporation. The garbage stations of Karachi are Rehri, Ibrahim Hyderi, Sharafi Goth, Murtaza Chowrangi, and Malir River. Karachi includes two main sites named Jam Chakro and Gond Pass with 500 acres of space. Unfortunately, Karachi city is facing a lack of management in waste treatment and there is also a lack of energy conversion technologies Only jam chakro and gond pass waste sites are suitable to produce large amounts of energy (Shown in Figure 1).

The Karachi organic waste includes different compositions including Plastic and Rubber, Metals, Paper, Cardboard, Textiles, Glass, Bones, Food, Animal, Green Waste, Wood, and Fines as shown in Figure 2

The locations for the main landfill sites of Karachi are demonstrated in Table 1.

Fig. 1. Jam Chakro and Gond Pass (Siddiqi et al., 2019)

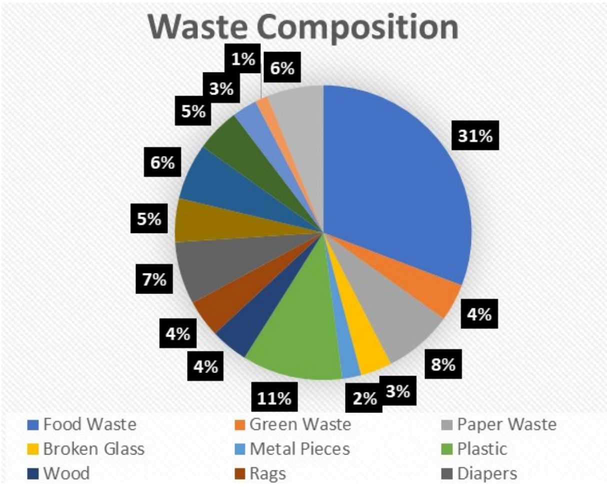

Fig. 1. Karachi solid waste composition in percentage for 2019 to 2020 (Shaikh et al., 2019)

Table 1. Karachi Landfills Coordinates.

Jam Chakro,	25.03006732647229, 67.0303860708082
Gond Pass	25.03017427686776, 67.03036193443089
Mehmoodabad	24.858382864875303, 67.06709678804559

2.2. Feasibility Analysis

The present study uses RETScreen software for energy analysis, Load characteristics, emission analysis, financial analysis, location analysis, Facility analysis and emission analysis. Also RETScreen uses to evaluate the waste-to-energy parameters for the utilization of climate and renewable energy data. This tool analyses the energy production, life cycle cost, and emissions of the system. The emission analysis of RETScreen delivers the emission of Carbon dioxide and nitrogen. Moreover, the present study discovers the potential of organic waste available in Karachi, Pakistan. The daily district-wise production of wastage was calculated for Karachi. Then the feasibility was carried out for the conversion of waste to biogas integrated with a gas turbine & reciprocating engine for power generation. Based on the study, the waste potential of Karachi City contains 24% from the district west, 19% from the district central, 18% from the district East, 16% from the district Korangi, 12% from the district Malir, and 11% waste potential from district South.

2.3 Estimation of organic waste potential

The method applied was referred from previous research. Conversion from the V_{MSW} (m^3) to W_{MSW} (kg) Conversion from the V_{MSW} (m^3) to W_{MSW} (kg) was determined by using the following equation:

$$W_{MSW} = \rho_{MSW} \times V_{MSW} \tag{1}$$

Where ρ_{MSW} is the density of MSW = 240 kg/m^3 (Anshar et al., 2014)

$$VMSW = \frac{WMSW}{\rho\ MSW} \tag{2}$$

Estimation of EP_{MSW} was made based on the W_{MSW} produced and the CV of MSW. EP_{MSW} was calculated by using the Eq.:

$$EP_{MSW} = W_{MSW} \times CV_{MSW} \tag{3}$$

Where EP_{MSW} in Joule or kWh (1 kWh = 3.6106 J), W_{MSW} is the number of MSW, and CV_{MSW} is the calorific value of MSW = 9,240 kJ/kg (Anshar et al., 2014). Based on population data collected from the census 1998 and 2017. In this study the calculation of potential energy, and conversion from organic waste kg to m^3 was calculated using Eq. (1) with density of MSW = 240 kg/m^3 (Anshar et al., 2014).

Figures 3 and 4 show the population and waste data for Karachi districts. The data for comparative analysis of population and waste were collected from censuses 1998 and 2017 for Karachi Pakistan. Further, the feasibility of this collection is carried out for the comparative analysis of the reciprocating engine and gas turbine using biogas. The Cash flow in RETScreen is calculated by considering the project's revenue, operating costs, and savings. The net periodic cash flow formulation can be calculated using:

$$\text{Net Cash Flow} = \text{Revenue} + \text{Savings} - \text{Operating Costs} - \text{Capital Costs}$$

The payback investment period in RETScreen is calculated by the following formulation:

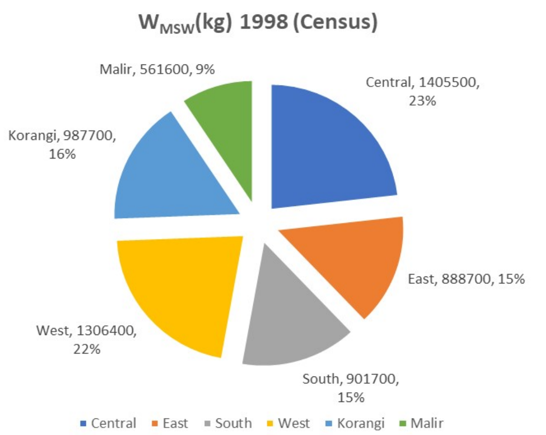

Fig. 3. Distribution of solid waste energy potential in Karachi 1998 (Karaca & Erdoğdu 2017)

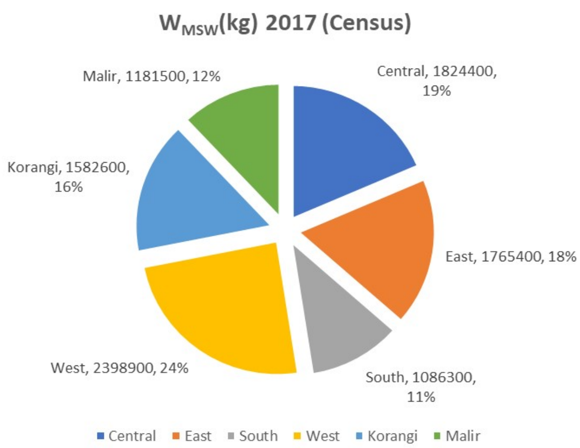

Fig. 4. Distribution of solid waste energy potential in Karachi (2017) (Karaca & Erdoğdu 2017).

The payback investment period in RETScreen is calculated by the following formulation:

$$\text{Payback period} = \frac{\text{Initial investment}}{\text{Annual net cash flow}}$$

The Carbon dioxide (CO_2) savings in RETScreen are calculated based on a reduction in energy consumption and the generation of renewable energy equated to conventional energy sources. It can be calculated using:

CO_2 Savings = Energy Savings × Emissions Factor

3. Results and Discussion

The case study of the Karachi cooling system is considered for feasibility analyses utilizing plant operation on biogas integrated with a gas turbine and reciprocating engine. The official waste sites Jam Chakro & Gond Pass are considered the sites that are able to create huge power potential. The solid waste of Karachi contains biogenic and non-biogenic material.

3.1. Location & Climate Analysis

For this research study, the RETScreen Climate Database is utilized for atmospheric data and satellite data. Figure 5 shows the study location.

3.2. Facility Analysis

To perform the facility analysis for the 100 kW Reciprocating engine system, the data utilized in RETScreen are shown in Table 2 along with the facility data of the Reciprocating Engine, and Table 3 shows the facility data of gas turbine. The feasibility comparative analysis study was conducted individually for reciprocating engines and gas turbines and then comparative analysis were performed to find a sustainable solution.

The organic waste density formulations are as follows:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Table 2. The Facility data utilize for Reciprocating engine

Facility Type	Power | Cooling Load
Description	Reciprocating engine 100 Kw
Manufacturer	Elliott
Model	TA-100
Heat rate	32,562 kJ/kWh
Facility Name	Gas turbine

Table 3. The Facility data utilize for Gas Turbine

Facility Type	Power | Cooling Load
Description	Gas turbine 100 kW
Manufacturer	Elliott
Model	TA-100
Heat rate	32,562 kJ/kWh
Facility Name	Gas turbine

Fig. 5. Study location

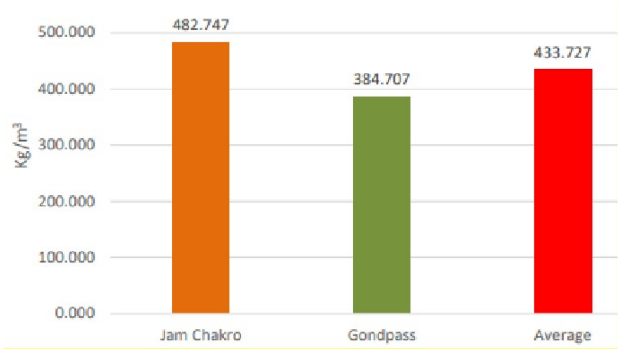

Fig. 6. Density composition of the wastes.

Figure 6 shows the density composition for the organic waste produced from the Karachi. The above formulation was utilized to calculate the density for the two official sites of Karachi.

3.3. Energy Analysis

The particular input parameters utilize in this analysis using RETScreen for gas turbine and reciprocating engine. This study considers biogas produced by anaerobic fermentation technology utilizing a biogas digester. The anaerobic digestion is divided into four gas compositions i.e. hydrolysis, fermentation, acetogenesis, and methane occur in the same reactor. This process temperature effect depends on the amount of fuel consumed. The pressure of 870 Kilopascal with normal temperature and density of 0.75 kg/m^3 were considered in this study. The microorganism's temperature was considered 48-55°C for this study for active formation of biogas. The study with the same parameters was conducted for comparative analysis with different options of reciprocating engine & gas turbine. Figure 7 shows the cooling load energy facility.

3.3.1. Load Characteristics

Figure 8 indications the energy requirements of 2017 to 2018 and 2018 to 2019. The ultimate energy requirement is observed in July & August, and fewer requirements are observed in November & December.

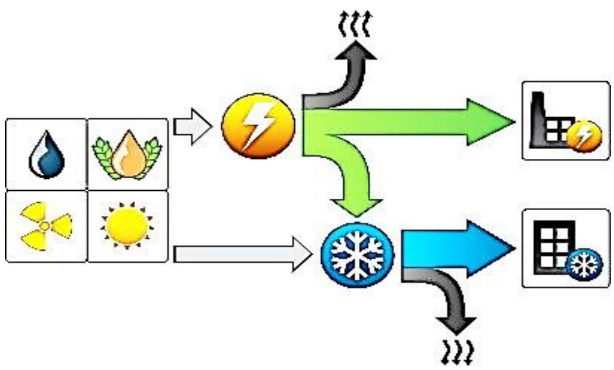

Fig. 7. Energy model for Facility Analysis.

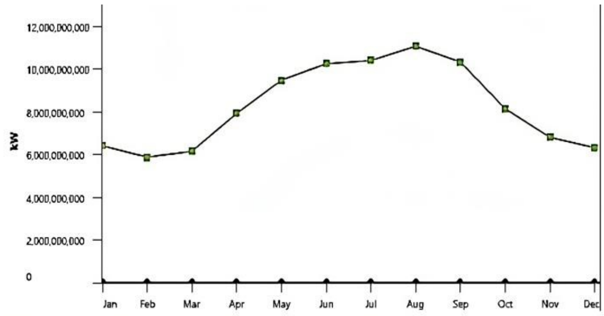

Fig. 8. Power demand comparison Krishan (Khatri et al. 2021).

3.3.2. Emission Analysis

The reciprocating engine attains an 87.1% reduction in greenhouse gas emissions, although the gas turbine attains a 38.4% reduction. For the case of the reciprocating engine, the excluding transmission and distribution the 0.392 t CO_2/Megawatt hour was calculated while 0.421 t CO_2/Megawatt hour was calculated including transmission and distribution. The 7% transmission and distribution losses were calculated with 832 Megawatt hours with grid export. The greenhouse gas for the base case was calculated 351 t CO_2 and the proposed case is 45.1 t CO_2.

The bar graph in Figure 9 shows the reciprocating engine significant reduction in greenhouse emissions in the proposed case compared with the base case.

For the case of gas turbine, excluding transmission and distribution the 0.392 t CO_2/Megawatt hour was calculated while 0.421 t CO_2/Megawatt hour was calculated including transmission and distribution. The 7% transmission and distribution losses were calculated. The greenhouse gas for the base case was calculated at 43,284t CO_2 and the proposed case is 26,684t CO_2.

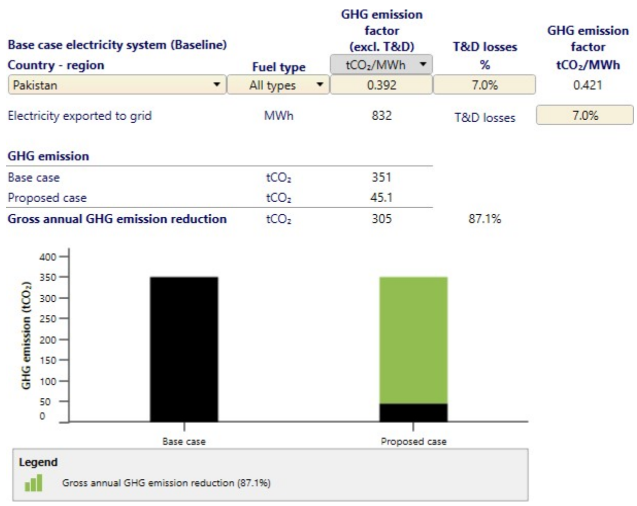

Fig. 9. Emission Analysis for reciprocating engine

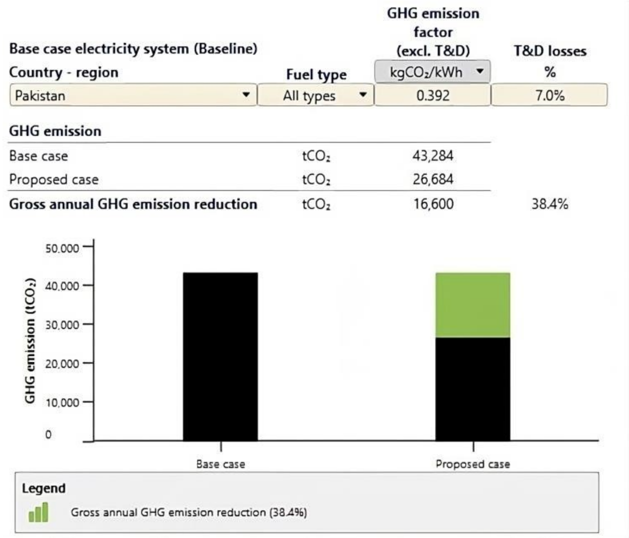

Fig. 10. Emission Analysis for gas turbine.

The bar graph in Figure 10 shows the gas turbine's significant reduction in the greenhouse emissions in the proposed case compared with the base case.

Both figures for the reciprocating engine and gas turbine use the same transmission and distribution greenhouse gas emission factors 0.392 excluding and 0.421 including. The unit representation is different for reciprocating engines CO_2 megawatt hour and CO_2 kilowatt hour for gas turbines.

3.4. Cost Analysis

The cost analysis is utilized to calculate initial operation and maintenance costs. Tables 5 and 6 demonstrate the cost analysis of reciprocating engines and gas turbines respectively.

Table 5. Cost analysis for reciprocating engine.

Description	Reciprocating Engine 100 kW
Manufacturer	Daimler Chrysler
Model	OM 904 LA
Initial cost	415,000 $
O&M costs	12,583 $

Table 6. Cost analysis for gas turbine.

Description	Gas turbine 100 kW
Manufacturer	Elliott
Model	TA-100
Initial cost	120,000 $
O&M costs	5,620 $

3.5. Financial Analysis

The financial parameters containing the inflation rate of Pakistan at 31.5% and the project life is 15 years (2023-2037). The debt ratio 50% with debt interest rate of 16% was also considered Figures 11 and 12 represent the cash flow over time for a reciprocating engine-based power generation system. The cumulative cash flow is a financial analysis that demonstrates the net amount of cash in the form of revenues and expenses. The cash flows are influenced by the operative efficacy of the reciprocating engine including maintenance costs, fuel costs, and power generation capacity.

Figures 13 and 14 same cash flows for the case of the gas turbine. For Comparative analysis, the same parameters with reciprocating engine & gas turbine were considered. These cash flows jointly support in evaluating the techno-economic feasibility and comparing the periodic financial aspects of reciprocating engines and gas turbines integrated with biogas for power generation in Karachi.

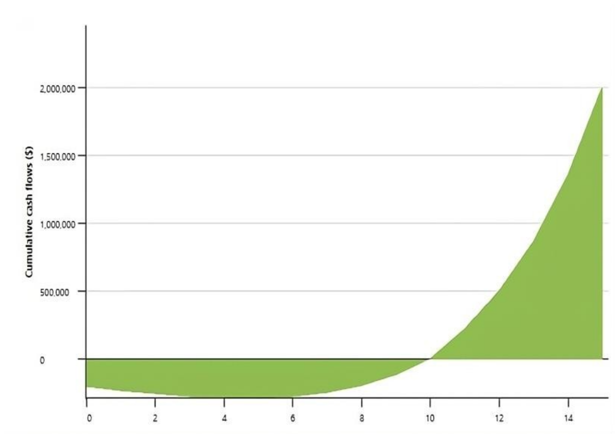

Fig. 11. Cumulative cash flow for reciprocating engine

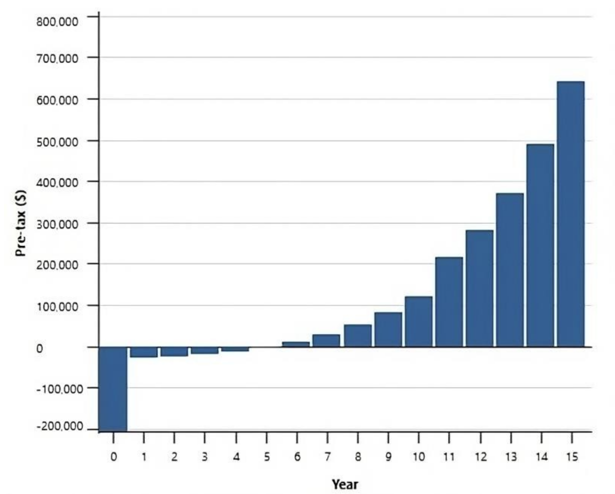

Fig. 12. Cash flow for reciprocating engine.

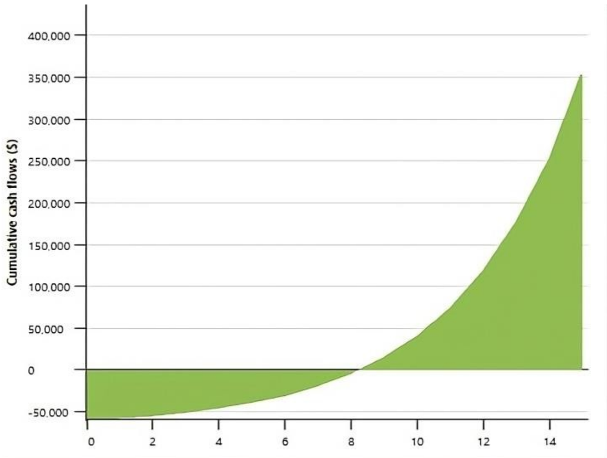

Fig. 13. Cumulative cash flow for gas turbine.

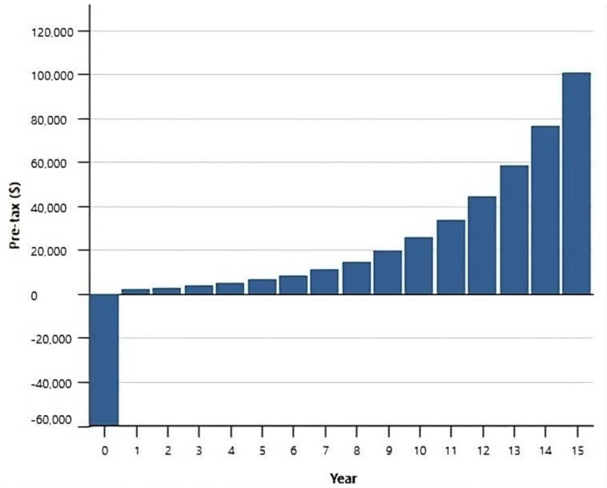

Fig. 14. Cash flow for gas turbine.

These cash flows analyses the total cost for the reciprocating system US 415,000 $ for the initial and the US 12,583 $ for the operating and maintenance as compared to the gas turbine cost 120,000 $ for the initial stage and the 5,620 $ for operating and maintenance. Cash flow study delivers understandings periodic flow where the system might face financial up and down. This figure demonstrates the periodic cash flow, on a annually basis, for the energy generation utilizing a reciprocating engine or gas turbine.

8. Conclusion

The cumulative increase in power shortage, a techno-economic feasibility analysis for the case study city Karachi has been conducted. Karachi has great potential in feeding biogas to the reciprocating engine or gas turbine. The RETScreen Clean Energy software is utilized for the purpose of feasibility analysis. A modified energy model was used to determine the cooling load for a 100 kW power generation plant. This system meets the demands of Pakistan as well as Karachi with sustainable development and reduction of emissions. The RETScreen software shows a simple payback of 15 years with CO_2 Emissions. This study estimates the financial parameters for investors for cost analysis.This system uses biodigester reactor with anaerobic technology treatment for the organic waste this technology achieves 96-98% methane content to utilize. The pressure of 870 Kilopascal was considered with a carbon dioxide composition of 22,847 tons of CO_2 yearly.

The key findings from the present study are as follows:

- The proposed cooling load-based system Installation of 100 KW Power Generation plant for Karachi is a model for local empowerment of the Karachi power sector.
- The waste potential of Karachi was estimated equivalent to about 24% from the district west, 19% from the district central, 18% from the district East, 16% from the district Korangi, 12% from the district Malir and 11% waste potential from district South.
- The comparative emission analysis indicates the result with a lower reduction percentage for the gas turbine at 38.4% while reciprocating with a higher reduction percentage at 87.1%. This recommends the reciprocating system produces less emissions while the gas turbine produces much higher emissions.
- The initial cost for the reciprocating system is US 415,000 $ and the operating and maintenance is US 12,583 $ while the initial cost for the gas turbine is 120,000 $ and the operating and maintenance is 5,620 $ which includes a feasibility study, the cost of the cooling load.
- In this study comparative analysis was carried out between gas turbine and reciprocating engine that shows the results that the reciprocating engine is suggested due to high power efficiency with less emissions. The Less emissions is produce due to biogas utilization without ash and Sulphur Oxides content as compare to oil and coal based generations.

In this Study six districts considered are Central, East, South, West, Korangi and Malir the population data of Karachi districts collected from 1998 and 2017 census. This study estimates that district west produces large amount of waste potential. The census data is utilized for the mathematical formation for Conversion from the VMSW (m^3) to W_{MSW} (kg)

Acknowledgments

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Nomenclature

a	Volume municipal solid waste mole cube, V_{MSW} (m^3)
b	Weight municipal solid waste Kilogram, W_{MSW} (kg)
c	Energy potential municipal solid waste, EP_{MSW}
d	Calorific Value municipal solid waste, CV_{MSW}
e	Carbon dioxide, CO_2

Greek symbols

ρ	Density

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