Araştırma / Research

WASTE TO ENERGY: EXPLOITATION OF LANDFILL GAS IN MICRO-TURBINES

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ABSTRACT

The energy consumption has been increasing due to social and economic development, risen up of people's living standard and also population growth in the world. In addition, solid wastes occurring as result of these driven causes have emerging as a significant pressure on environment. Solid waste is the most visible and pernicious by-product of consumer-based economic lifestyle. The Municipal Solid Waste (MSW) is the principal volume of residues produced worldwide. Landfill gas which is generated by means of MSW due to considerable methane content can be used as fuel in the energy generation machines for sustainable energy production. In this study, a technical and economic study using micro-turbine of the 30 kW power for utilization in small size landfill areas is presented. Annual electricity generation of micro-turbine considered is 210,240 kWh when capacity factor is 0.80. Economical evaluation for micro-turbine was made using the Levelized Cost of Electricity method. The electricity cost is predicted to be US$0.079 for 8% discount rate and the considered turbine-specific cost. The results show that electricity production based on biogas with micro-turbine of 30 kW power is realistic in terms of techno-economic for the small size landfill area.

Keywords: Landfill gas, micro-turbine, energy cost

ATIKTAN ENERJİ: MİKRO-TÜRBİNLERDE DEPONİ GAZLARININ KULLANIMI

ÖZ

Sosyal ve ekonomik kalkınma, nüfus ve yaşam standartlarındaki artışın sonucu olarak enerji tüketimi tüm dünyada sürekli artmakta ve bu etkilerin sonucu olarak ortaya çıkan katı atıklarda çevre üzerinde önemli etkilere sebep olmaktadır. Katı atıklar tüketici temelli ekonomik yaşam tarzının önemli ve zararlı bir sonucudur. Sürdürülebilir enerji için kentsel katı atık depolama sahalarında oluşan deponi gazları yüksek metan içeriği nedeniyle enerji üretim sistemlerinde yakıt olarak kullanılabilmektedirler. Bu çalışmada, küçük ölçekli bir katı atık depolama sahasında 30 kW gücünde mikro-türbin kullanarak elektrik enerjisi üretimi teknik ve ekonomik olarak incelenmiştir. Mikro-türbinin yıllık elektrik enerjisi, üretimi kapasite faktörü 0,8 olduğunda, 210.240 kWh olarak hesaplanmıştır. Türbin özgül maliyetine göre hesaplanan elektrik enerjisinin bir değere getirilmiş maliyeti % 8 indirim oranı için 0.079 $ olarak belirlenmiştir. Çalışmadan elde edilen sonuçlar, küçük ölçekli katı atık depolama sahasında 30 kW gücünde mikro-türbin kullanılarak elektrik enerjisi üretiminin teknik ve ekonomik olarak uygun olduğunu göstermiştir.

Anahtar Kelimeler: Deponi Gazı, mikro-türbin, enerji maliyeti

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1. INTRODUCTION

The energy requirement has been growing because of social and economic progress, risen up of people's living standard and also population growth in the whole world [1, 2]. The Municipal Solid Waste (MSW) is the principal volume of residues produced worldwide. The landfilled MSW causes numerous environmental problems such as waste leaching liquid, detonation and fire, suffocation, flora destruction, and greenhouse gas (GHG) emissions [3]. The MSW according to Intergovernmental Panel on Climate Change (IPCC) consist of food waste, garden and park waste, paper and cardboard, wood, textiles, nappies (disposable diapers), rubber and leather, plastics, metal, glass, and other (e.g., ash, dirt, dust, soil, electronic waste) [4].

The management of solid waste using proper methods is critical to the health and comfort of urban residents [5]. The Solid Waste Management includes numerous solutions such as the reduction of waste production, the materials recovery, the recycling, and the energy recovery and as a last option, the landfilling to reaching minor environmental and social effects [6]. Landfill gas (LFG) after landfilling process of solid waste in a site is formed via anaerobic decomposition of organic waste. Landfill gas mainly composed of methane (40-60%) and carbon dioxide (40-60%). In addition, it includes, in trace amounts, nitrogen compounds, hydrogen sulphide and non-methane organic compounds [3, 5-7]. Methane warms the earth 20 times more than carbon dioxide because of catching in the atmosphere [8]. In the landfill areas, flaring process is the principal way to reduce methane emissions. Despite the fact flaring becomes effective control method for mitigation of methane emission, landfill gas is sustainable source owing to its considerable methane content and it can be used as renewable energy source [7, 9]. Waste-to-Energy is defined as process of recovering energy, in the form of electricity and/or heat, from waste [10]. The use of solid waste as an energy source shifts fossil fuels and reduces the emissions from extraction and processing. The biogas, is produced by biological process, can be used in combined heat and power generators such as internal combustion engines, micro-turbines and fuel cells for electricity and heat generation [11] and also direct use, and fuel for vehicles [12]. Production capacity in these power plants varies from a few kilowatts (kW) to several megawatts (MW). The electricity generated from the biogas power plants can then either be used directly or sold to the grid. Although the cost for micro-turbines are higher than for internal combustion engine, they have various advantages such as lower gas flow in landfill, operation of lower percent methane, low nitrogen oxide emission, relatively easy interconnection. Thus, the micro-turbines can be used in landfill projects instead of internal combustion engine technologies. Estimations of landfill emissions in disposal site and analysis of energy recovery potential have been studied by several researchers. Broun and Sattler [9] compared landfill biogas management in a conventional landfill with bioreactor landfill by considering greenhouse gases emissions and electricity production potential. In the study, electricity was produced by means of the reciprocating internal combustion engines. Kumar and Sharma [13] carried out a study the estimation of GHG emission potential using software LandGEM and electricity production potential for three landfill sites in Delhi, India. The results of the study show that the LCOE values for sites considered are between 0.12 and 0.17 USD/kWh. Aguilar-Virgen et al. [14] determined the model constants used in biogas models and estimated the biogas generation for the final disposal sites in Baja California, Mexico. In the study, results show that over the period 2013-2030 the considered sites have a power generation potential of 760492.8 MW/h. Zuberi and Ali [15] estimated the methane emissions by applying first order decay model to landfills in Pakistan. A methodological approach for techno-economic assessment of energy derived municipal solid waste proposed by Bidart et al. [16]. Landfill gas-to-energy and direct waste-to-energy alternatives was used for electricity generation. Due to energy supply and environmental pollution concerns in future, waste-to-energy projects should be studied further for clean and economic electricity production, disposal of air pollution and the more efficient management of waste. Therefore, exploitation of biogas in landfill in electricity production as renewable energy source and economic analysis of electricity production in terms of various economic parameters are the main motivations for this study.

In this study, the electricity energy production and energy cost using landfill gas in the micro-turbines of 30 kW power is evaluated. An economic evaluation is studied using the Levelised Cost of Electricity Method.

2. MATERIAL AND METHODS

The extractable gas amount in landfill areas varies with time and compositional difference of landfill wastes. Characteristically, extraction rates in the landfill areas is varied from 25 to 100 m^3/h for small sites of 100,000 m^3 municipal solid waste capacity up to 250 to 10,000 m^3/h or more for large sites with capacities of 1–10 million m^3 [17]. The formation of landfill gas occurs with chain mechanisms that include physical, chemical, and microbial processes. The most important process for gas formation is anaerobic decomposition in organic waste. The formation process occurs over the course of 10 to 80+ years. However, considerable volumes of LFG are

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produced within 1–3 years of waste settlement, peaking at 5-7 years after. LFG formed in a landfill site is most related to the amount of organic matter in the landfills. In addition, higher temperatures and appropriate moisture content affect microbial activity in the waste and increase the gas production [12]. In this study, micro-turbine was used as electricity production device. Figure 1 shows diagram of a micro-turbine operation.

In the analysis, the gas flow in landfill area was assumed 100 m³/h and a 30 kW micro-turbine was used due to the convenience of biogas flow on the site. The performance ratings of the investigated micro-turbine are listed in Table 1 [18]. It is assumed that unused gas in energy generation is flared.
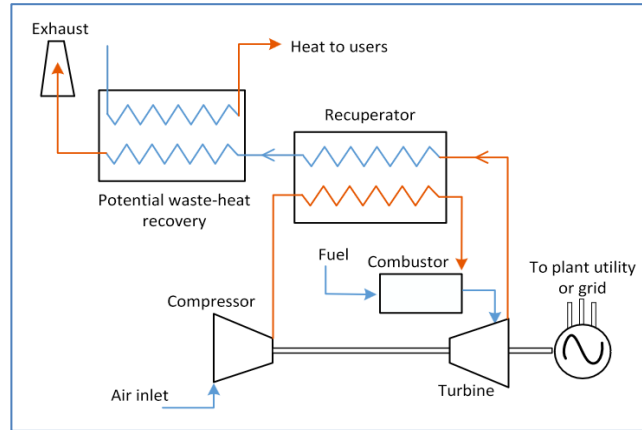

Figure 1. Diagram of micro-turbine operation

Annual Capacity Factor (ACF) is defined as the ratio of the amount of net energy generated per year to the amount of energy that can be produced in case of rated capacity operation for a year. The characteristic annual capacity factors for power plants that use landfill gas depending on generator outage rates (4% to 10% of annual hours), landfill gas availability, and plant design range between 80% and 95%. Annual electricity generation (AEP) is the amount of electricity generated per year, taking into account likely energy recovery equipment downtime [17].

Table 1. Performance ratings of the investigated micro-turbine

Characteristic	Capstone C330
Net Power Output	30 kW
Electrical Efficiency (LHV)	26 %
Nominal Net Heat Rate (LHV)	13,800 kJ/kWh
Nominal Steady State Fuel Flow (HHV)	457,000 kJ/hr

$$\mathrm{AEP} = 8760 \cdot \mathrm{P_{mt}} \cdot \mathrm{ACF} \, [\mathrm{kWh}] \tag{1}$$

where $\mathrm{P_{mt}}$ is the net power of micro-turbine, ACF is the annual capacity factor and its value was selected between 0.80 and 0.90.

All expenditures made for the establishment and operating of a power plant such as capital, land, construction, fuel and operating and maintenance must be known for the calculation of electrical energy cost. However, in the cost calculations, time value of money during the period considered must be taken into account. The levelised cost of electricity (LCOE) is one of the most important factors in predicting the economic performance of renewable power plants, such as biogas power systems. The levelised electricity cost for a biogas power plant is calculated by dividing the total annualized cost of the biogas energy system to the amount of annual electrical energy produced by the system. It can be described by the following equation [19].

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \dfrac{\mathrm{I_t + OM_t + F_t}}{(1+r)^t}}{\sum_{t=1}^{n} \dfrac{\mathrm{AEP_t}}{(1+r)^t}} \, [\mathrm{US\$/kWh}] \tag{2}$$

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where I_t is investment costs in the year t, OM_t is operating and maintenance costs in the year t, F_t is fuel costs in the year t, AEP_t is electrical energy production in the year t, r is discount rate, and n is lifetime of the system.
   The investment cost for a micro-turbine can be determined from Equation 3.

$$I_t = I_{sc}P_{mt} \text{ [US\$]} \tag{3}$$

where I_{sc} is the specific cost. The specific cost of micro-turbine for the suggested system is US\$2,800/kW [20]. The useful lifetime of the power plants was taken as 15 years. It is assumed that the micro-turbine produces the same amount of energy every year during its useful lifetime. Present worth of the annual operating-maintenance cost throughout the lifetime of turbine is given by Equation (4).

$$OM_{t,esc} = \left[\frac{OM_t}{r-e}\right]\left[1-\left(\frac{1+e}{1+r}\right)^n\right] \tag{4}$$

where OM_t is the operating and maintenance cost for the first year, e is escalation of the operating-maintenance.

3. RESULTS AND DISCUSSION

   For exploitation of biogas potential in a prospective landfill area, various adoptions of energy production technologies such as reciprocating internal combustion engine, gas turbine, fuel cell can be used. In this paper, a micro-turbine of 30 kW power is used to convert landfill biogas to electricity. Nominal Steady State Fuel Flow (HHV) of micro turbine is 440,000 kJ/h and it is assumed that micro-turbine is operated at full load in all time. The factors manipulating the electricity produced by the biogas power plant at the prospective site over the related period can be listed as the gas availability in site, and operation of energy production device. Due to operation and maintenance and generator outage, energy production in micro-turbine can be stopped. Thus, Annual Capacity Factor (ACF) is evaluated in this study. Figure 2 shows annual energy production of micro-turbine for various capacities. Annual electricity generation of micro-turbine considered is 210,240 kWh when capacity factor is 0.80.
   The levelised cost of electricity in biogas power plants based on landfill gas is determined by the specific cost of energy production device, landfill gas quality of prospective (methane amount in biogas), the technical specifications of the energy production device, operating and maintenance costs, power plant lifetime, and other economic parameters such as interest rate and discount rate. The specific cost of the micro-turbine considered in this study is selected as US\$2,800/kW. A typical annual operation and maintenance cost of the micro-turbine is considered as US\$230/kW [20]. The discount rate converts the stream of future costs and electrical output to their present values has a significant effect on the unit energy cost [21]. The electricity production cost is sensitive to changes in the discount rate [22]. Table 2 summaries the effect of discount rate on the levelised cost of electricity for micro-turbine considered in this study. The levelised costs of electricity are calculated between US\$0.079 and US\$0.091/kWh as lower and upper values for discount rates that are 8% and 12% when capacity factor is 0.80. LCOE values predicted in this study are between the ranges given in the literature.
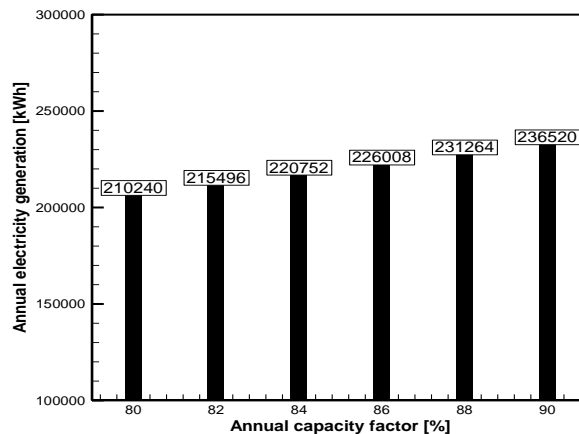

Figure 2. Annual electricity energy production of micro-turbine

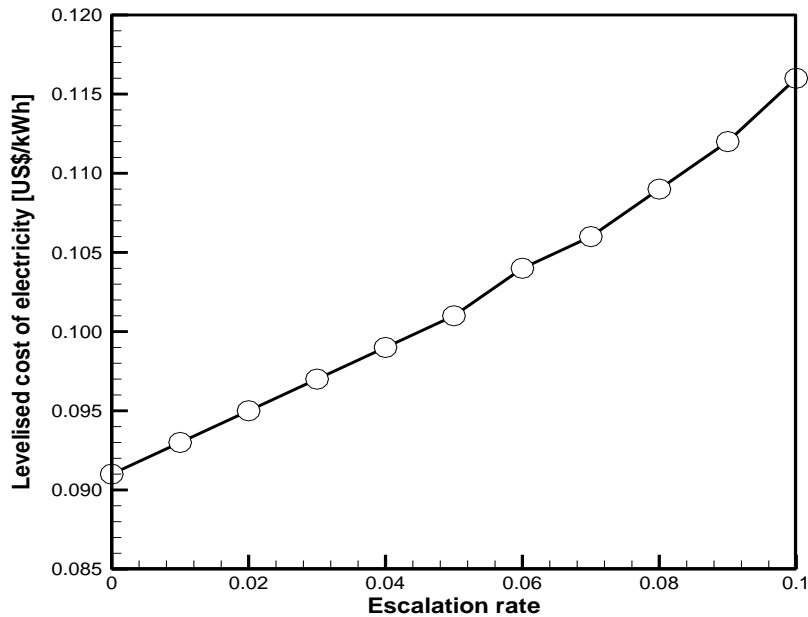**Table 2.** Levelised cost of energy for different discount rates

r (%)	Energy Cost for Capstone C330 Micro-Turbine (US$/kWh)
8	0.079
9	0.082
10	0.085
11	0.088
12	0.091

The levelised costs of electricity with regard to different annual capacity values are listed in Table 3. When discount rate is 12%, the levelised costs of electricity varies between US$0.081 and US$/kWh 0.091 for different annual capacity factors. The costs of operation and maintenance for newer energy production devices are low. However, these costs increase as the useful lifetime of this device decreases. The energy costs calculated are nearly related to the life of energy production devices. Thus, for calculating of unit electricity cost, an escalation range is considered. The escalation ratio of operation and maintenance is assumed varying between 0% and 10%.

Table 3. Levelised cost of energy for different annual capacity values (US$/kWh)

ACF (%)	Energy Cost for Capstone C330 Micro-Turbine (US$/kWh)
80	0.091
82	0.089
84	0.087
86	0.085
88	0.083
90	0.081

Figure 3 depicts the effect of operating and maintenance escalation ratio on cost of unit energy based on levelised cost method. As seen from these figure, cost of unit energy with escalation for micro-turbine considered varies between US$0.091 and US$0.116/kWh. An increment from 0 to 0.1 escalation ratio of operation and maintenance in the case of the micro-turbine increases the estimated cost of unit energy about 27%.

Figure 3. Levelised cost of electricity for different operation and maintenance escalation rates

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4. CONCLUSIONS

This study investigated energy production and energy cost with the micro-turbines of 30 kW nominal power using biogas for the small size landfill areas. An economic evaluation presented by using Levelised Cost Method Electricity (LCOE). Annual electricity generation was 210,240 kWh when capacity factor is 0.80 for the considered micro-turbine. The levelised costs of electricity are predicted to be US$0.079 for an 8% discount rate using a 30-kW micro-turbine based on the turbine-specific cost. Levelised cost of electricity with escalation for micro-turbine considered was between US$0.091 and US$0.116/kWh. The results show that electricity production based on biogas with micro-turbine of 30 kW power is economically and technically reasonable for the small size landfill area.

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