The reduction of greenhouse gas emissions using various thermal systems in a landfill site

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Abstract: In this paper, the Greenhouse Gas (GHG) emissions from an uncontrolled landfill site filled with Municipal Solid Waste (MSW) are compared with those from controlled sites in which collected Landfill Gases (LFG) are utilised by various technologies. These technologies include flaring, conventional electricity generation technologies such as Internal Combustion Engine (ICE) and Gas Turbine (GT) and an emerging technology, Solid Oxide Fuel Cell (SOFC). The results show that SOFC is the best option for reducing the GHG emissions among the studied technologies. In the case when SOFC is used, GHG emissions from the controlled site are reduced by 63% compared to the uncontrolled site. This case has a specific lifetime GHG emission of 2.38 tonnes CO₂-eq/MWh when only electricity is produced and 1.12 tonnes CO₂-eq/MWh for a cogeneration application.

Keywords: greenhouse gas; GHG; global warming; landfill gas; LFG; municipal solid waste; MSW; solid oxide fuel cell; SOFC.


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1 Introduction

Global warming, which is a specific case of global climate change, refers to the increase in the average temperature of the atmosphere and oceans in recent decades, and the projected continuation of this increase. The drivers of climate change are seen as: changes in the atmospheric concentrations of Greenhouse Gases (GHGs) and aerosols, land cover, and solar radiation (IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), most of the increase in global average temperatures since the mid-20th century is linked to the observed increase in the anthropogenic GHG concentrations.

The four long-lived GHGs, which are released due to human activity, are: CO₂, CH₄, N₂O and halocarbons. The effect of these gases on global warming is assessed using an index called ‘Global Warming Potential’ (GWP), which is a measure of how much a given mass of GHG contributes to global warming relative to a reference gas (usually CO₂) for which the GWP is set to 1. For a 100-year time horizon, GWPs of CO₂, CH₄, and N₂O are reported to be: 1, 25 and 298, respectively (IPCC, 2007). Using this index, one can calculate the equivalent CO₂ emission by multiplying the emission of a GHG by its GWP.

Municipal solid waste may have significant effects on the production of GHG as well as other environmental problems and human health if it is disposed in landfills where there are no treatments and processes. There are several steps in the production of GHG from waste. Waste is first decomposed by aerobic bacteria until all the oxygen is
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consumed. Then, organic acids are produced in the absence of oxygen, which is followed by methanogenic state in which organic materials are decomposed into CH₄ and CO₂. The leachate is also produced, which may contaminate the groundwater. There are also explosion risks due to the release of flammable gases, e.g., CH₄. To prevent the health and environmental effects of landfills, these sites should be properly designed and operated. For example, while the groundwater may be protected by using liners and leachate collection systems; gas collection, treatment and processing systems must be used to reduce the GHG effect.

Energy may be produced from Municipal Solid Waste (MSW) through technologies such as: incineration, gasification, and generation of biogas and its utilisation. Murphy and McKeogh (2004) investigated these technologies and concluded that generation of biogas and its conversion to transport fuel requires the least gate fee. Landfill Gas (LFG) can be converted into fuel and energy forms by direct combustion, chemical energy storage, introducing it into the natural gas grid, and electricity generation. Qin et al. (2001) analysed LFG combustion through experimental and numerical studies. Their experiments include the determination of laminar flame speeds, extinction strain rates, stable species and NOx concentrations, and flame structures. Electricity generation from landfill gas can be accomplished by technologies such as the internal combustion engine, gas turbine, the Stirling engine and fuel cells. Bove and Lunghi (2006) compared several technologies used to generate electricity from landfill gases, and showed that the internal combustion engine, which is the most widely used technology due to economical reasons, presents the poorest environmental performance. On the contrary, fuel cells are shown to be the cleanest electricity generating systems; however they are not yet economically advantageous. There are different types of fuel cells and most of them may be fueled by LFG. However, low temperature fuel cells need a reformer to convert the fuel into hydrogen. Additionally, in all fuel cell types, LFG should be cleaned according to the impurity tolerance levels of the fuel cell. Lombardi et al. (2006) compared conventional treatments with the following alternatives: the direct LFG feeding to a fuel cell; the production of a hydrogen-rich gas, by means of steam reforming and CO₂ capture, to feed a stationary FC; and the production of a hydrogen-rich gas, by means of steam reforming and CO₂ capture, to feed a vehicle FC. Their study reveals that LFG reforming to a vehicle FC has the lowest specific greenhouse effect emission. Spiegel et al. (1999) demonstrated the operation of a commercial Phosphoric Acid Fuel Cell (PAFC) with LFG. Their system produces up to 137 kW power, 37.1% efficiency at 120 kW, and exceptionally low secondary emissions. Lunghi et al. (2004) conducted life cycle assessment analysis of a Molten Carbonate Fuel Cell (MCFC) system for LFG recovery for an evaluation of environmental consequences, and to provide a guide for further environmental impact reduction. Duerr et al. (2007) analysed a biogas fueled Alkaline Fuel Cell (AFC). They chose the AFC because of its very low freezing point of the potassium hydroxide electrolyte (~ –50°C).

The Solid Oxide Fuel Cell (SOFC) has the highest operating temperature level among the fuel cell types. According to the manufacturing type, i.e., electrolyte, electrode or interconnect supported, the SOFC may operate between 500°C and 1000°C, which enables successful integration with other systems. Currently, there is more research on intermediate and low temperature SOFCs since they have better structural integrity and a lower startup time. Another important advantage of SOFCs over other fuel cell types is that gas mixtures including hydrocarbons may be reformed inside the fuel cell, which is
called direct reforming. This feature together with the other advantages of SOFCs makes this fuel cell type very appropriate for production of electricity in landfill sites. A review of the SOFC and its modeling may be found in the paper by Colpan et al. (2008).

In this study, GHG emissions from an uncontrolled landfill site are compared with those from controlled landfill sites in which flaring, conventional electricity generation technologies such as internal combustion engine and gas turbine, and an emerging technology, the SOFC, are utilised. For this comparison, GHG emission from each technology is first found for each year of its lifetime for a selected case study using the method developed by the authors. Then, the GHG reduction ratio and specific lifetime GHG emission are calculated for each case. Consequently, the most effective technology is determined. It should be noted that GHG emissions are calculated using on site direct emissions (from flaring, Internal Combustion Engine (ICE), Gas Turbine (GT) or SOFC), without taking into consideration the life-cycle emissions occurring during manufacture of the infrastructure (engines, flares, cells, pipes), production and delivery of auxiliary materials, auxiliary energy consumption, gas cleaning treatment and so on.

2 Landfill processes

In a landfill site, LFG, which is composed of methane, carbon dioxide and Non-Methane Organic Compound (NMOC), i.e., ethane, butane, hexane, hydrogen sulfide, etc., is generated due to a series of biological processes. Over time, the amount of gas generated increases until such time the site reaches its capacity. Subsequently, the amount of gas generated begins to decrease due to the reduction in the organic material components. Because of the adverse environmental effects of the LFG, this gas should be collected and properly utilised by flaring or electricity generation technologies. In the following subsections, LFG generation and collection processes are discussed.

2.1 Calculation of landfill gas generation

Landfill gas generation from MSW can be calculated using the software called LandGEM (2008), which was developed by the US Environmental Protection Agency (EPA). This software is based on a 1st order decomposition rate equation for quantifying emissions from the decomposition of landfilled waste in MSW landfills, which is shown in Equation (1) (Alexander et al., 2005).

\[ Q_{ch4} = \sum_{i=1}^{e} \sum_{j=0}^{1} kL_o \left( \frac{M}{10} \right) e^{-k_j} \]  

From Equation (1), annual methane generation in a year can be calculated. Generally, it is assumed that landfill gas has a composition of 50% CH₄ and 50% CO₂. Hence, total landfill gas generation may be found by doubling the result from Equation (1). Methane generation rate, k, is a function of factors such as moisture content, availability of nutrients for methane-generating bacteria, pH, and temperature of the waste mass. The potential methane generation capacity, L_o, depends on the type and composition of the waste placed in the landfill. The Clean Air Act (CAA) default values, which are based on federal regulations for MSW landfills laid out by the CAA for k and L_o, are, 0.05 year⁻¹ and 170 m³/tonnes, respectively (Alexander et al., 2005).
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2.2 Landfill gas collection

Landfill gas generated by the decomposition of organic materials should be collected in a well designed and managed site due to environmental, health and energetic considerations. The quantity of gas collected is estimated by multiplying the generated landfill gas by collection efficiency. According to the EPA (1998), collection efficiencies at well designed landfills typically range from 60% to 85%, with an average of 75%. A very well designed collection system, i.e., 85% efficiency, should have the following features: a composite bottom liner consisting of a synthetic (plastic) layer over 2 feet (0.6 m) of clay or similar material; soil cover applied over newly deposited refuse on a daily basis; no significant off-site lateral migration of landfill gas; a comprehensive landfill gas collection system with vertical wells and/or horizontal collectors providing 100% collection system coverage of all areas with waste within a few years after the waste is deposited; a gas collection system which is operating effectively so that all wells are fully functioning (i.e., relatively free of liquids and drawing landfill gas under vacuum) (Stege, 2003).

The GHG emission routes in a well-designed landfill site with a collection system are shown in Figure 1. These routes will be discussed in detail in the following sections.

**Figure 1**  Greenhouse gas emission routes in a landfill site with LFG collection system

3 Thermal systems considered

Flaring (direct combustion) is the traditional approach to utilise the collected LFG for reducing the GHGs in a landfill site. The flaring of LFG is an economical approach, and also it reduces the risk of explosion of uncontrolled LFG emissions. The operation principle of landfill gas flare is simple; LFG is ignited by bringing it into contact with a supply of air. Different configurations of conduit and chambers can be used for this purpose. In today’s market, open and closed flare types are available. Open flares burn landfill gas as open flames, whereas closed flares burn landfill gas in a vertical,
cylindrical or rectilinear enclosure. Details of these flare types may be found in the report by Environment Agency and Scottish Environment Protection Agency (2002). On the other hand, since the collected gas has a considerable amount of heating value, it may be utilised to produce electricity and/or heat. The most commonly used technology for utilising LFG is internal combustion engines, followed by gas turbines. Additionally, SOFCs are very promising candidates to be used in landfill sites in the future due to their advantages discussed in the previous and following sections. These technologies are discussed in detail in the following subsections.

3.1 Internal combustion engine (ICE)

The internal combustion engine is the most widely used technology for electricity generation from LFG, mainly because of its economical feasibility. These engines are attractive because they are compact and easy to transport. The main disadvantage is the high amounts of NO\textsubscript{x} and CO emissions produced by these engines as compared with other technologies, which contribute to the air pollution. Lean-burn spark ignition engines are the most common type of ICE used in landfill sites. When these engines are operated using LFG, engine power ratings are commonly reduced by 5% to 10% (SCS Engineers, 1994) compared to operation using natural gas. It should be noted that before the LFG is fed to the ICE, moisture and particulates must be removed according to the tolerance limits of the engine, so as not to reduce the engine efficiency and reliability and increase the necessity for more regular maintenance.

The power output of these engines varies between 300 kW and 3.6 MW for an individual unit (Environment Agency and Scottish Environment Protection Agency, 2004). Generally, many ICEs operate together according to the LFG generated to produce more power. A typical landfill site operating with this type of engine should also include a gas flare to burn any LFG collected in excess of maximum requirements of the engine, to burn LFG when the generated gases are low enough to justify the operation of the engine, and to operate during the maintenance.

3.2 Gas turbine (GT)

Gas turbines are the second most popular technologies that utilise LFG. The majority of gas turbines presently operating at landfills are the simple cycle, single shaft type. They are very similar to natural gas turbines except that, because of the low heating value, the number of fuel regulating valves and injectors are doubled (SCS Engineers, 1997). During its operation, large quantities of air enter the compressor. After the air is compressed, it mixes with fuel in the combustor, and the combusted gas expands in the turbine where power is produced. Some amount of this power is used to drive the compressor.

Compared to ICEs, gas turbines have lower NO\textsubscript{x} and CO emissions, and also fewer moving parts. Their exhaust can also be utilised in a cogeneration application. However, if electricity generation is more important in an application, the gas turbine is disadvantageous since it has a lower electrical efficiency than the ICE. Other disadvantages are having a high capital cost, being sensitive to LFG supply loads and ambient air temperature variations, and not being suitable for moderate size landfills. For small size landfills, microturbines are generally selected instead of gas turbines.
3.3 Solid oxide fuel cell (SOFC)

The SOFC is an emerging technology that is expected to replace conventional energy systems like ICEs and gas turbines once it has become economically competitive. The SOFC has higher electrical efficiency, lower emissions, a higher exhaust gas temperature that makes it possible to be used in cogeneration applications, quieter operation and fewer moving parts compared to conventional systems.

There have been demonstrations of SOFC operation using biogas (News, 2005; 2007). These demonstrations include biogas production from wastewater in a sewage treatment plant and animal waste. It has been recently reported that a planar SOFC unit in Finland, which will produce 20 kW of electric power and 14–17 kW of thermal output, is believed to be the first SOFC in the world that is fueled by LFG (News, 2008).

The SOFC is a very attractive option for LFG application since it can use hydrogen and carbon monoxide as fuel, which are reformed from methane. In high temperature SOFCs, this reformation occurs inside the fuel cell; this is called direct reforming. The reforming mechanism is controlled by water-gas shift and steam reforming reactions, which are shown by Equations (2–3). In some cases, it is preferable to use a dry reformer before the LFG enters the SOFC to prevent the carbon deposition at the anode catalyst. The dry reforming reaction is shown in Equation (4).

$$\begin{align*}
2\text{CO} + \text{H}_2\text{O} & \rightleftharpoons \text{H}_2 + \text{CO}_2 \\
\text{CH}_4 + \text{H}_2\text{O} & \rightleftharpoons 3\text{H}_2 + \text{CO} \\
\text{CH}_4 + \text{CO}_2 & \rightleftharpoons 2\text{H}_2 + 2\text{CO}.
\end{align*}$$

It should be noted that the collected LFG must be subjected to an extensive gas cleanup process before it enters to SOFC due to high levels of contaminants in the gas. The tolerance limits of SOFCs to these contaminants may be found in the literature (Xenergy, 2002; Sime et al., 2002).

4 Analysis of greenhouse gas emissions

In this section, a method for calculating GHG emission from a landfill site without an active collection system is first described. Then, methods for calculating GHG emissions from landfill sites in which the collected LFG is utilised by flaring, conventional electricity generation technologies such as ICE and GT, and SOFC, are discussed. Finally, some parameters for comparing these technologies are introduced.

4.1 Landfill site without an active collection system

In a landfill site without an active collection system, not all of the methane generated is emitted to the atmosphere. A portion of the methane generated is oxidised while passing through soil and landfill covers. The fraction of methane that is oxidised is generally taken as 10% (Climate Leaders, 2004). The oxidation of methane reaction is given as Equation (5).

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}.$$
If we neglect the NMOC portion of the LFG, total GHG emissions from this kind of a site may be expressed as shown in Equation (6). It should be noted that the equations in this paper are derived for a LFG composition of 50% CH\textsubscript{4} and 50% CO\textsubscript{2}. However, similar equations may be derived with simple modifications to these equations for different ratios of CH\textsubscript{4} and CO\textsubscript{2}.

\[
m_{\text{GHG,burn}} = \sum_{j=1}^{t_{\text{down}}} \left( m_{\text{CH}_4,\text{gas}} \times (1 - \eta_{\text{col}}) \times (m_{\text{GHG,burn}}^j) \right) + \eta_{\text{col}} \times \left( m_{\text{GHG,flare}}^j \right)
\] (6)

4.2 Landfill site with an active collection system

In a landfill site with an active collection system, LFG is recovered by vertical wells or horizontal collectors. The recovered gas can be flared, or utilised to generate electricity by technologies such as gas turbines, ICEs or fuel cells. In the following subsections, the methodologies for calculating the GHG emissions, when flaring and these electricity generating technologies are used in a landfill site, are discussed.

4.2.1 Flaring

The combustion of methane may also be represented by Equation (5). If we assume that all the collected gas is flared, and a small portion of the collected gas is vented during the routine and unscheduled maintenance, total GHG emissions from the site can be found by using Equation (7).

\[
m_{\text{GHG,flare}} = m_{\text{CH}_4,\text{gas}} \times \text{vent} \times \text{GWP}_{\text{CH}_4} + \left( m_{\text{CO}_2,\text{gas}} + (1 - \text{vent}) \times m_{\text{CH}_4,\text{gas}} \times \frac{\rho_{\text{CO}_2}}{\rho_{\text{CH}_4}} \right).
\] (8)

4.2.2 Electricity generation technologies from LFG

Internal combustion engine

GHG emissions per energy output of ICEs suitable for LFG operation are given in the literature (Lombardi et al., 2006). Using this emission data, amount of collected LFG, electrical efficiency of the ICE, days of operation of the engine per year and higher heating value of the fuel, one may calculate the total GHG emissions from such a landfill site using Equation (9). In this equation, it is assumed that after year, t\text{down}, engines stop operating and collected LFG is burned. There is also enough number of ICEs that can utilise LFG even at the year when its generation is at maximum level.

\[
m_{\text{GHG,cell}} = \sum_{j=1}^{t_{\text{down}}} \left( (1 - \eta_{\text{col}}) \times (m_{\text{GHG,cell}}^j) \right) + \eta_{\text{col}} \times \left( m_{\text{GHG,ICE}}^j \right)
\] (9)
where GHG generated from ICE can be calculated as:

$$m_{GHG,ICE} = \left( \frac{\tau}{365} \right) \times \left( \frac{m_{LFG,gen} \times hHV \times \eta_{ICE} \times \epsilon_{ICE}}{3600} \right) + \left( \frac{1 - \tau}{365} \right) \times m_{GHG,flare}. \quad (10)$$

**Gas turbine**

Since there is insufficient data in the literature regarding GHG emissions from LFG fueled gas turbines, a simple model is developed by the authors. In this model, it is assumed that air gas composition is: 77.48% N$_2$, 20.59% O$_2$, 0.03% CO$_2$ and 1.9% H$_2$O. For the fuel-air ratio, $\lambda$, the combustion equation may be written as shown in Equation (11).

$$\lambda(0.5CH_4 + 0.5CO) + 0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O \rightarrow (1 + \lambda)(x_{N_2} + x_{O_2} + x_{CO_2} + x_{H_2O}H_2O). \quad (11)$$

Exit gas composition of the combustor may be shown using Equations (12–15).

$$x_{N_2} = \frac{0.7748}{1 + \lambda} \quad (12)$$

$$x_{O_2} = \frac{0.2059 - \lambda}{1 + \lambda} \quad (13)$$

$$x_{CO_2} = \frac{\lambda + 0.0003}{1 + \lambda} \quad (14)$$

$$x_{H_2O} = \frac{0.019 + \lambda}{1 + \lambda}. \quad (15)$$

Applying an energy balance around the control volume enclosing the combustor, as shown in Equation (16), $\lambda$, hence exit gas composition may be calculated.

$$0 = -0.02 \cdot \dot{n}_f \cdot LHV + \dot{n}_f \cdot \bar{h}_f + \dot{n}_{c,i} \cdot \bar{h}_{c,i} - \dot{n}_{c,o} \cdot \bar{h}_{c,o}. \quad (16)$$

The first term in the right hand side of Equation (16) denotes the assumed heat loss from the combustor.

The total GHG emissions from a landfill site, where a gas turbine is used for electricity production, may be calculated using Equation (9), if the $m_{GHG,ICE}$ is replaced with $m_{GHG,GT}$ which is shown in Equation (17).

$$m_{GHG,GT} = \left( \frac{\tau}{365} \right) \times \left( \frac{m_{LFG,gen} \times \lambda + 0.0003 \times \frac{M_{CO}}{M_{LFG}}}{\lambda} \right) + \left( \frac{1 - \tau}{365} \right) \times m_{GHG,flare}. \quad (17)$$

**SOFC**

GHG emissions per LFG entering the system may be found using the model developed by the authors (Colpan et al., 2007). This SOFC model may be described as follows: The gas composition of the fuel channel exit can be found using chemical equilibrium
equations and the relation between the electric current and the molar flow rate of hydrogen that is utilised. Then, the air utilisation ratio, which measures the amount of excess air that should be sent to the air channel to carry away the unutilised heat in the fuel cell, is calculated. Hence, cell voltage, work output of the cell and electrical efficiency of the cell are found. After finding the GHG emissions from the SOFC, the total GHG emissions from the landfill site may be calculated in a similar method as conducted with ICEs and gas turbines.

4.3 Comparison of LFG utilisation technologies

The authors propose two parameters for comparing the usefulness of technologies in reducing the global warming in landfill sites. The first parameter is called ‘GHG reduction ratio’, as shown in Equation (18). This ratio quantifies the GHG emission reduction when an active collection system is used. If there is no emission from the landfill site when an active system is used, this ratio is equal to 100%. If this ratio is equal to one, it also means there is no contribution to global warming from this landfill site.

\[
\Gamma = \frac{m_{\text{GHGuncoll}} - m_{\text{GHGcoll}}}{m_{\text{GHGuncoll}}} \quad (18)
\]

The second parameter is called ‘specific lifetime GHG emission’ which may be defined as the ratio of the total GHG emission from the landfill site in its lifetime to the total amount of useful energy produced from LFG. This ratio is shown in Equation (19) and is useful to compare GHG emissions for the same amount of power produced from different technologies. From the point of view of global warming and energy, the lower the ratio is, the more effective the technology is:

\[
\sigma = \frac{m_{\text{GHGcoll}}}{(m_{\text{CH}_4, \text{gen}} + m_{\text{CO}_2, \text{gen}}) \times \eta_{\text{cell}} \times \frac{x}{365} \times \frac{h_{\text{hy}}}{3.6} \times \eta_{\text{i}}} 
\]

5 Case study

For our case study, we considered that the landfill site, which is filled with municipal solid waste, opened in 2008 and it will accept waste for 20 years. The annual waste acceptance rate is taken as 200 000 tonne/year. CAA default values, which are based on federal regulations for MSW landfills laid out by the Clean Air Act, are considered for the methane generation rate and the potential methane generation capacity. The LFG composition is considered as 50% CH₄ and 50% CO₂. Other input data is given in Table 1. The results obtained using the data in Table 1 are presented in the following section.
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6 Results and discussion

Generated and collected LFG, and GHG emissions for each scenario were calculated using the methodology described in Sections 4 and 5. Then, to find the most effective technology, a comparison of the different scenarios was carried out.

Annual gas generation rates for all components of the LFG, i.e., methane, carbon dioxide and NMOC, were calculated by LandGEM software. The results are shown in Figure 2. As can be seen from this figure, LFG generation increases until the final year it accepts the waste. Then it decreases exponentially. For this landfill site, which has a 20 year lifetime, the site continues releasing GHGs for 120 years more after it stops accepting waste as can be seen from this figure.

Taking an average collection efficiency of 75%, collected and uncollected LFG and its components were calculated for each year and shown in Figure 3.

For a landfill site without an active collection system, some amount of methane will be oxidised and converted into carbon dioxide. Remaining gases will be released into the atmosphere. Given that high amounts of methane, which is 25 times more contributing to global warming than carbon dioxide, are released in this case, this gas should be collected and utilised since it has a considerable amount of heating value and high global warming potential. In this study, different technologies for utilising the collected gas were considered. These include flaring, and electricity generation technologies such as ICE, gas turbine and SOFC. Annual GHG emission from the landfill site for each technology is shown in Figure 4. For example, in the final year that the site will accept waste,
i.e., 2028; 366 831 tonnes-CO$_2$-eq could be released to the atmosphere from a site without an active collection system. Using the most economical solution, which is flaring, GHG emissions would be much lower, 153 456 tonnes-CO$_2$-eq. However, there is no electricity production when flaring is used. In the case where a gas turbine is used to utilise the LFG, GHG emissions would be slightly lower than the case of flaring, which is found to be 151 404 tonnes-CO$_2$-eq. The most effective technologies for reducing GHG emissions are ICE and SOFC. For the peak year, when ICE and SOFC are utilised, the site produces GHG emissions of 127 430 and 134 208 tonnes-CO$_2$-eq, respectively. It should be noted that, for all technologies, it is considered in the calculations that many power generators of the same type operate together, and they may be replaced with new ones if necessary. Additionally, after the year 2088, due to the low methane generation, it is assumed that collected gas will be sent to gas flare instead of the power generator.

**Figure 2** Annual gas generation of LFG and its components (see online version for colours)

**Figure 3** Collected and uncollected amount of LFG and its components (see online version for colours)
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Figure 4  Total GHG emissions for various LFG utilisation methods (see online version for colours)

As previously mentioned, the results obtained by using the methodology discussed in Section 4 were used in constructing Figure 4. When modeling an ICE, the specific GHG emission ratio of the ICE, which has unit of tonnes.eq.CO₂/MWh of an existing engine, was taken from literature (Lombardi et al., 2006) and used in Equation (10). In the case of the gas turbine, a simple model was developed by the authors as discussed in Section 4.2.2. Using input data given in Table 1, the fuel/air ratio on a molar basis was calculated to be 0.070935. According to this ratio, exit gas composition of the gas turbine was found to be 72.3% N₂, 12.6% O₂, 6.7% CO₂ and 8.4% H₂O. Finally, in the case of the SOFC, the model is discussed in Section 4.2.2. Using input data given in Table 1, performance of a single cell can be found and is shown in Figure 5. For the type of fuel used in this study, it is reasonable to assume a 0.65 V cell voltage. At this voltage, the corresponding current density and electrical efficiency is 0.28 A/cm² and 40.3%, respectively. It is also found that for 1 tonne of LFG entering a SOFC system, 0.98595 tonne CO₂.eq GHG is emitted to the atmosphere.

Figure 6 shows the comparison between different technologies operating at controlled landfill sites in terms of their effect on production of GHGs. As shown in Figure 6, the simplest solution, which is flaring, will reduce the GHGs by 58%. Hence, this result reveals the fact that an active collection system together with a gas flare would be very effective in reducing the GHG emission if an economical solution is desired and there is no consideration of getting benefit from this gas to convert it into electricity. This figure also shows that using an ICE results in the highest GHG reduction ratio, which is slightly higher than the ratio when SOFC is used. The gas turbine has the least global warming reduction potential of the electricity production technologies studied in this paper.
Since each technology has different electrical efficiency and global warming potential, a more meaningful comparison between the controlled landfill sites studied may be conducted calculating the total GHG emissions in the lifetime per total amount of energy produced for each technology. The results of this comparison are shown in Figure 7. It may be seen from Figure 7 that the SOFC has the lowest specific lifetime GHG emission among the technologies studied, which is 2.3836 tonnes CO$_2$.eq/MWh, when the SOFC is only used for electricity generation. Since the SOFC has a high exhaust temperature, useful heat may be produced which would increase the fuel utilisation efficiency of the system. Producing work and heat at the same time, which is called cogeneration, the specific lifetime GHG emission may be further reduced to 1.1217 tonnes CO$_2$.eq/MWh, as shown in Figure 7.
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7 Conclusions

In this paper, GHG emissions from an uncontrolled landfill site are compared with those from controlled landfill sites in which flaring, conventional electricity generation technologies such as ICE and GT, and SOFC are utilised. It is shown that even with the simplest solution, which is flaring, total GHG emissions in the lifetime of the site can be reduced by 58% compared to the uncontrolled case. Among the different technologies, the SOFC seems to be the best option, as it reduces the GHG emissions by 63%, and has a specific lifetime GHG emission of 2.38 tonnes CO$_2$-eq/MWh when it only produces electricity and 1.12 tonnes CO$_2$-eq/MWh when it is used in a cogeneration application. Hence, this study has shown that SOFC is very effective in combating global warming in landfill sites in addition to its other advantages like low emissions and noise, and high efficiency. A future study will include an optimisation of a SOFC in a landfill site. In this study, operating variables will be optimised to maximise the energetic performance and minimise the GHG effect.

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Nomenclature

GWP \hspace{1em} \text{global warming potential}

\bar{h} \hspace{1em} \text{specific enthalpy, } J/mol

hhv \hspace{1em} \text{higher heating value of landfill gas, MJ/tonnes}

k \hspace{1em} \text{methane generation rate, year}^{-1}

L_{ox} \hspace{1em} \text{potential methane generation capacity, m}^3/\text{tonnes}

LHV \hspace{1em} \text{lower heating value, J/mol}

m \hspace{1em} \text{mass, tonnes-CO}_2\text{-eq}

\dot{n} \hspace{1em} \text{molar flow rate, mol/s}

M_i \hspace{1em} \text{mass of waste accepted in the } i\text{-th year, tonnes}

OX \hspace{1em} \text{fraction of methane oxidised in the soil}

Q_{CH_4} \hspace{1em} \text{annual methane generation, m}^3/\text{year}

t_{ij} \hspace{1em} \text{age of the } j\text{-th section of waste mass } M_i \text{ accepted in the } i\text{-th year, years}

x \hspace{1em} \text{molar concentration}

vent \hspace{1em} \text{fraction of vented gas in flare}

Greek letters

\epsilon_{ICE} \hspace{1em} \text{specific GHG emission ratio of internal combustion engine,}
\hspace{1em} \text{tonnes.eq.CO}_2/\text{MWh}

\rho \hspace{1em} \text{density, g/cm}^3

\sigma \hspace{1em} \text{specific lifetime GHG emission, tonnes.eq.CO}_2/\text{MWh}

\eta_{el} \hspace{1em} \text{electrical efficiency}

\eta_{coll} \hspace{1em} \text{collection efficiency}

\eta_{ICE} \hspace{1em} \text{electrical efficiency of internal combustion engine}

\Gamma \hspace{1em} \text{greenhouse gas reduction ratio}

\tau \hspace{1em} \text{Number of days that electricity producing technology operates per year, days}

\lambda \hspace{1em} \text{fuel-air ratio on molar basis}

Subscripts

c,i \hspace{1em} \text{combustor inlet}

c,o \hspace{1em} \text{combustor outlet}

f \hspace{1em} \text{fuel}
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References