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Streamlined life cycle analysis for assessing energy and exergy performance as well as impact on the climate for landfill gas utilization technologies

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HIGHLIGHTS

- Different biogas energy utilization technologies are assessed.
- Energy and exergy efficiencies and GWP are used as criteria.
- In situ fuel cell systems are advantageous if all heat can be used.
- Upgrading by amine scrubbing is advantageous if no heat can be used in situ.
- The advantage of fuel cell systems is supposed to rise in future.

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ABSTRACT

Three landfill gas (LFG) valorization technologies were compared using energy and exergy efficiency and a streamlined Life-Cycle Assessment (LCA) method. The technologies were (i) steam reforming and hydrogen utilization in an in situ cogeneration fuel cell (SR-IS-FCC), (ii) biogas utilization in an in situ gas engine cogeneration plant (IS-GEC), and (iii) amine scrubbing and biomethane utilization in an ex situ gas engine cogeneration plant (AS-ES-GEC). The SR-IS-FCC alternative recorded the highest exergy efficiency and savings in cumulative energy demand (CED), and the lowest global warming potential (GWP) when all the heat is utilized in situ; otherwise, the highest exergy efficiency and the lowest GWP and CED were associated with the AS-ES-GEC alternative. The results indicate that AS-ES-GEC is the preferential choice when heat cannot be utilized in situ. Otherwise, SR-IS-FCC records the best values for the three criteria, and the AS-ES-GEC technology is the least interesting alternative.

1. Introduction

Landfills are the world's oldest and still most widely used way of disposing of municipal waste, but they involve the problem of greenhouse gas (GHG) emissions due to the fermentation of organic material and the subsequent production of CO_2 and CH_4. At the same time, advantage may be taken of the high heating value of the methane generated, transforming or valorizing it through different technologies. Thus, upgrading landfill gas (LFG) has a significant impact on both climate change and resource consumption, which are often considered the greatest challenges of our time. There are different alternative technologies for valorizing LFG, and the best one needs to be selected under well-defined conditions and conducting rigorous analyses, considering both energy saving and climate effects.

The most common utilization of LFG is the production of electricity and heat in a cogeneration engine by in situ combustion. Another possibility is the upgrading of biogas to biomethane by CO_2-separation, which also enables the resulting biomethane to be transported over long distances. This last technology shows the advantage of using the biogas at the place of demand under high efficiency conditions, whereas the in situ gas engine cogeneration plant may lack customers for the heat, as landfills are often far away from other facilities. The LFG technologies of open dump, flaring, cogeneration engine, and upgrading to biomethane for use in buses have been compared by Life-Cycle Assessment (LCA), investigating emissions, but not resource consumption, by Beylot

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Nomenclature

AS	amine scrubbing
BG	biogas
BM	biomethane
CED	cumulative energy demand
ES	ex situ
FCC	fuel cell cogeneration
GAC	granular activated carbon
GWP	global warming potential (kg CO_2 equivalents/kg_LFG)
GHG	greenhouse gas
HHV	Higher Heating Value (kJ/kg_LFG)
IS	in situ
LCA	Life-Cycle Assessment
LCIA	life-cycle impact assessment
LFG	landfill gas
LHV	Lower Heating Value (kJ/kg_LFG)
LHV_{LFG}	lower heating value of LFG (kJ/kg_LFG)
MCFC	molten-carbonate fuel cells
PAFC	phosphoric acid fuel cell
SA	sensitivity analysis
SR	steam reforming
WWTP	waste water treatment plant

Notation

$\dot{m}_{LFG}$	mass flow rate of the LFG leaving the extraction well (kg/h)
$\dot{W}_{el,in}$	electricity demand (kJ/h)
$\dot{W}_{el,P}$	produced electricity (kJ/h)
$\dot{Q}_P$	product heat (kJ/h)
$\dot{Q}_{in}$	heat input (kJ/h)
$\dot{B}_{\dot{Q}_P}$	exergy of the hot district heating water (kJ/h)
T_0	ambient temperature (288.15 K)
$T_{\dot{Q}_P}$	temperature of the product heat (348.15 K)
$T_{\dot{Q}_{in}}$	temperature of the steam (417.15 K)

Greek letters

η	energy efficiency (%)
Ψ	exergy efficiency (%)

et al. [1]. Manfredi et al. [2] also used LCA to compare the LFG management system based on flaring and the use of the collected biogas for heat generation. Different upgrading technologies have been investigated by Starr et al. [3–5] in LCA models and by Xu et al. [6], using the green degree method. Biogas co- and trigeneration (electricity, heat and chilled water supply) have been investigated by LCA by Chevalier and Meunier [7]. More recently, Gazda and Stanek [8] also suggest a biogas trigeneration system supported by a photovoltaic one in order to reduce the greenhouse gas emissions into the environment. Evangelisti et al. [9] have examined a biogas solid oxide fuel cell micro CPH system with biogas utilization in a boiler, with a reference scenario based on natural gas in a LCA focussing on emissions, reaching the conclusion that fuel cell systems have the best GHG-balance.

Another very promising technology, which is not yet fully established, is hydrogen production by reforming, and its utilization in a fuel cell. This device allows converting hydrogen chemical energy into electricity with high electrical efficiencies, which are expected to rise in the future. Some experiments are already being carried out using fuel cell pilot plants of around 0.3–1 kW, which shows that this technology should also be taken into account [10,11]. A study by Ochs and Ahrer [12] has compared hydrogen production by steam reforming from natural gas with the non-thermal production of hydrogen from biomass by bacteria (Hyvolution) and hydrogen production from biogas by steam reforming, discovering that hydrogen production from biogas steam reforming has the lowest environmental impact. Patterson et al. [13] have compared biohydrogen production by dark fermentation and biomethane production for use in vehicle fuels. Assefa [14] has compared hydrogen production using biogas steam reforming and the thermal gasification of the entire waste with the direct use of biogas for fueling vehicles, finding that both biogas conversion to hydrogen by steam reforming and thermal gasification for use in fuel cell vehicles have promising environmental prospects. One interesting result of this work is that the primary energy consumption for biogas conversion to hydrogen by steam reforming is the lowest among the technologies compared. Lunghi et al. [15] have carried out a LCA of molten-carbonate fuel cells (MCFC) using LFG, and compared them to MCFC fueled by steam reformed natural gas with lower GHG emissions in the first case.

No previous publication has been found in the open literature discussing the main alternatives for LFG utilization as an energy source. Recently, in the editorial article of the 7th International Conference on Applied Energy (ICAE2015) published as a special issue of Applied Energy [16], a thorough review about clean, efficient and affordable energy is carried out and not any reference about the discussion of different landfill gas treatment technologies appears. Thus, trying to fill in this gap, this article will use LCA and energy and exergy analyses to evaluate the three most used or promising technologies for LFG valorization, which have hitherto not been compared:

(i) In situ gas engine cogeneration (IS-GEC).
(ii) Biogas upgrading to biomethane removing CO_2 by means of amine scrubbing (AS-ES-GEC). Considerable amounts of biomethane are already being produced in Sweden, Germany, the Netherlands, and Spain [17]. The amine scrubbing technology was selected for biomethane production because it is the most widespread in Germany [18], and it is suitable when the biogas contains relatively high siloxanes, mercaptans and sulfur compounds.
(iii) Biogas steam reforming and its in situ utilization in a phosphoric acid cogeneration fuel cell (SR-IS-FCC). The phosphoric acid fuel cell (PAFC) [19] and the proton exchange membrane fuel cell [20] are the only types of fuel cell on the market. In this study, the PAFC was selected because it produces heat at a higher temperature, and is therefore less sensitive to fuel impurities and better suited to cogeneration applications.

This study will rate these technological alternatives in terms of their corresponding resource efficiencies and climate impacts. The goal here is to compare energetic and exergetic performance, as well as GHG) emissions and the climate impact of these three different LFG technologies. As hydrogen production from biogas has hitherto hardly been investigated as a possible alternative for LFG valorization, the evaluation of this alternative technology in terms of its future viability is also an important objective of this work.

2. Technologies

This section describes the three alternative technologies to be evaluated for LFG valorization. The three corresponding process