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Bioreactor Landfilling: Operations, Benefits and Prospects

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Abstract

The amount of waste being discarded at the landfill and without tapped its associated landfill gas (LFG) is alarming. Almost five million tons of MSW is produced in Abu Dhabi annually and almost all waste produced is land filled. Nearly 30% of the 240 million tons generated waste in the US is recycled while the rest is primarily destined to land filling. Landfill gas (LFG), which is mainly composed of carbon dioxide and methane, is widely recognized as one of the largest sources of methane emission to the atmosphere and a central contributor to GHG. Methane, however, is 21 folds more potent than carbon dioxide by weight and is second most abundant GHG after carbon dioxide. The estimate of global methane emission from solid waste disposal sites ranges from 20- 70 Tg/yr, or about 5 to 20% of the total estimated methane emission of 375Tg/yr from anthropogenic sources. Therefore, LFG recovery presents an opportunity to reduce global warming and fossil fuel consumption. In this work the concept of Bioreactor landfill and its estimated gas production compared to dry tomb is presented. A review of their operation and their biodegradation steps and their intermediate that lead to stable compost is presented. The distribution of MSW of community in USA and Abu Dhabi are considered. The amount of biogas is calculated based on 1,000,000 residential metropolitan communities. The gas power production and the anthropogenic CO_2 reduction are calculated through the use of conventional combined cycle. The bioreactor landfill yielded a carbon offset of 26,409.5 tons of CO_2 as compared to a coal power plant with utilization of dry tomb.

Keywords: *Dry tombs, Landfilling, LFG, GHG, MSW, Bioreactor, Combined Cycles*

1. Introduction

Recent advancements in the understanding of the behavior of landfills have created a shift from the conventional landfilling (dry tomb) to bioreactor landfilling. Bioreactor landfilling is the state-of-the-art technique of landfilling that quickens the degradation of solid wastes by controlling the moisture content via leachate recirculation and water addition [1]. Although early development of the bioreactor was not well applauded due to the concerns of leachate contamination in unlined landfills, composite liners has been designed to lower this contamination to insignificant amount. Amongst the other benefits are that it enhances stabilization of landfills in shorter time into usable compost [2], prevents liner failure and leachate contamination, increase methane production and reduces cost of monitoring and leachate treatment [3]. The produced methane from the landfill can, thus, be used for energy recovery process via power production-contributing in finding solution to the combined problem of energy demand and global warming simultaneously. The conventional landfill (dry tomb) on the other hand works by reducing the moisture content of the landfill in order to lower its leachate and LFG emissions albeit it still persist at low rates. Another major problem with dry tombs is the slowness in the degradation of wastes which prompts for a long term management and monitoring, thereby adding a high maintenance cost to the landfill and their wastes tend to occupy more space compared to bioreactor landfills.

This work seeks to establish the advantages of bioreactor landfills over dry tomb while also presenting a review of its operations and stages involved. The objective is to estimate the landfill gas production rate of easily degradable and slowly degradable components of wastes using the Scholl Canyon model, utilization of the produced gas in an energy recovery system with anthropogenic CO_2 and to provide the economics of bioreactor landfills.

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2. Review of Bioreactor Landfills

2.1. Operations

The operation of a bioreactor landfill is similar to modern municipal wastewater treatment plants because it biodegrades organic waste in a controlled way. However, the bioreactor landfill's mode of operation is different from traditional landfills (dry tomb) which has slow rate of degradation.

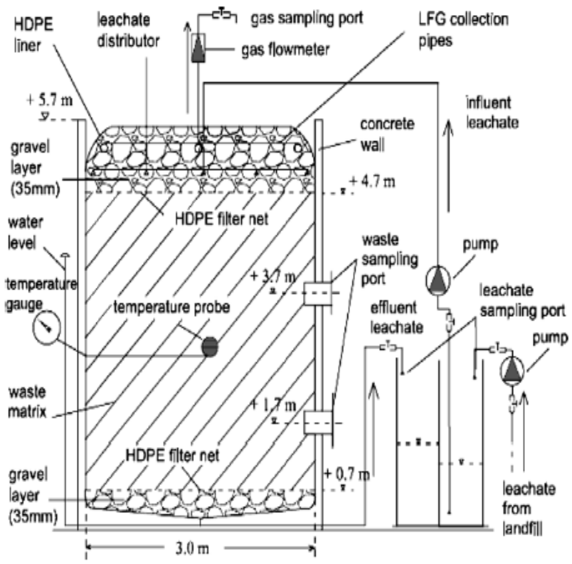

Figure 1: Schematic of a bioreactor landfill [4]

As against dry tombs, in bioreactor landfills, rather than keep the waste dry, water is added to the waste and a system of piping and conveyance infrastructure is built in for recirculating the leachate. The water accelerates the biodegradation process and allows more complete decomposition. The waste in a bioreactor landfill fully degrades in approximately 10 years rather than several decades like a typical dry tomb landfill, thereby generates faster LFG for use as fuel.

A typical bioreactor landfill shown in figure 1 consists of waste compartments/lifts, liners, gravel layers (35mm), leachate recirculation pumps, LFG collection pipes, gas and waste sampling ports and temperature gauge. The waste compartment houses the solid waste to be degraded to the LFG and leachate. The waste is constantly monitored through the sampling ports to ensure that the moisture content is within the stipulated range. The produced leachate is subjected to buffering to adjust its pH before recirculation. The liners prevent the leachate seepage and contamination of the groundwater by while the LFG collection pipes send the produced gas to stations for cleaning and power production.

2.2. Biodegradation steps

The biodegradation of MSW in the landfill takes place in two steps: aerobic and anaerobic digestions. The aerobic digestion stage takes place in a short period of time, its duration being determined by the amount of oxygen that is present in the waste. In turn, the amount of oxygen present in the waste is dependent on the permeability of the soil cover and waste compaction. In this stage, the organic waste reacts with oxygen in the presence of aerobic bacteria to produce carbon dioxide, water, biomass and heat [5]. After a short time, the activity of the aerobic bacteria declines due to depletion in oxygen concentration, causing the landfill to shift to the anaerobic stage.

The anaerobic digestion stage follows three sequenced biochemical reactions involving three different groups of anaerobic bacteria. In the anaerobic stage, bacteria groups convert waste into biogas (CH_4, CO_2) as end products, and organic acids as intermediate products. There are four steps involved in the anaerobic biodegradation of MSW to biogas (CH_4 and CO_2): Hydrolysis, acidogenesis, acetogenesis and methanogenesis. Figure 2 shows the stages involved in biodegradation of MSW and their gas composition against biodegradation time.

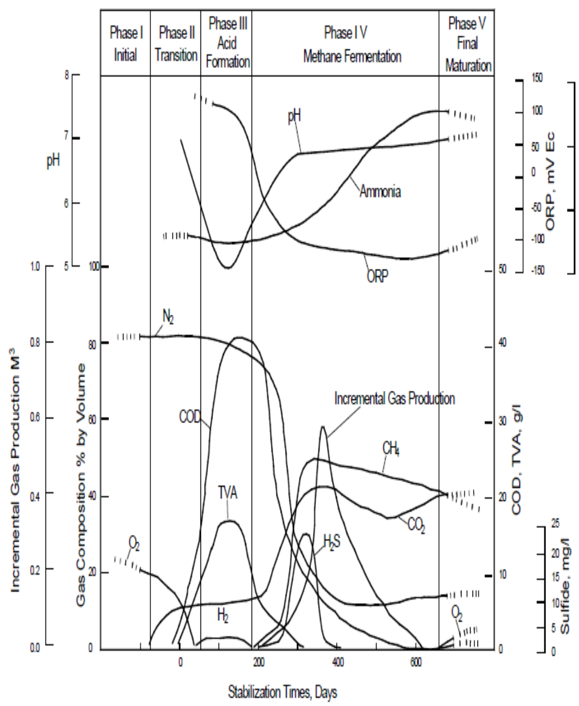

Figure 2: Phases of biodegradation [6]

The first stage of the anaerobic biodegradation is hydrolysis. The hydrolysis process is a very important step in the biodegradation of solid waste in the landfill. In the hydrolysis step, the complex organic compounds are solubilized and converted into smaller sized organic compounds by extracellular enzymes. This step is important because microorganisms cannot deal with large molecules. Only smaller organic molecules can pass through the membrane cell of bacteria [7]. The carbohydrate, fats and proteins are reduced to lower molecules as described by the following reactions [8]:

$$(C_6H_{10}O_5)_n + n\ H_2O \rightarrow n\ C_6H_{12}O_6 \quad (1)$$

The end results of hydrolysis are solubilization of waste to sugars, alcohols, fatty acids and amino acids.

After hydrolysis, the acidogenic process begins. In this stage, the end products of hydrolysis are oxidized to organic acids. The organic acids are then broken into acetic acid, as shown in the following reactions [8]:

$$C_6H_{12}O_6 \rightarrow CH_3(CH_2)_2COOH + 2H_2 + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (3)$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + CO_2 \quad (4)$$

The formation of acetic acid in the acidogenic process marks the beginning of the acetogenesis stage. In this stage, conversion of propionic and butyric acids into acetic acid occurs as described in the following reactions [9]:

$$CH_3(CH_2)_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \quad (5)$$

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2 + CO_2 \quad (6)$$

The final stage, methanogenesis, involves the formation of methane either from acetate or carbon dioxide reduction with hydrogen, as shown in the following reactions [8]:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (7)$$

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O_2 \quad (8)$$

3. Landfill Gas Estimation

To estimate the rate of production of methane, the Scholl Canyon model is used:

$$Q_{CH4} = kL_oM_ie^{(-kt)} \quad (9)$$

In order to estimate the mass of biodegradable volatile solids (BVS) waste disposed in the i-th year (M_i), the yearly waste disposal was analyzed for four equally divided periods; spring, summer, fall and winter. This division is due to the seasonal different waste generation. The total solid waste generated (biodegradable and non-biodegradable) in tons by the 1,000,000 residential metropolitan community was then derived as presented in tables 1and 2 based on a generation rate of 2kg/day/capita and 1.76kg/day/capita for the US and Abu Dhabi, respectively.

Table 1: Total solid waste for US at 2kg.day-1 capita-1

Year	Season	Population	Total solid waste(tons)
1	Spring	1,000,000	73,600
	Summer	1,000,000	73,600
	Fall	1,000,000	72,800
	Winter	1,000,000	72,000
2	Spring	1,015,000	74,704
	Summer	1,015,000	74,704
	Fall	1,015,000	73,892
	Winter	1,015,000	73,080

Table 2: Total solid waste for Abu Dhabi at 2kg.day-1 capita-1

Year	Season	Population	Total solid waste(tons)
1	Spring	1,000,000	61,529.6
	Summer	1,000,000	61,529.6
	Fall	1,000,000	60,860.8
	Winter	1,000,000	60,192.0
2	Spring	1,015,000	62,452.54
	Summer	1,015,000	62,452.54
	Fall	1,015,000	61,773.71
	Winter	1,015,000	61,094.88

The individual components' weights in the slowly and easily BVS were then obtained from their percentage of the total solid waste based on the literature in figure 3 and tables 3 and 4. The components vary from region to region even within the same country with organics and paper forming the major component in UAE and US, respectively. The total BVS (M_i) was then obtained from the sum of the total easily and slowly biodegradable volatile solids.

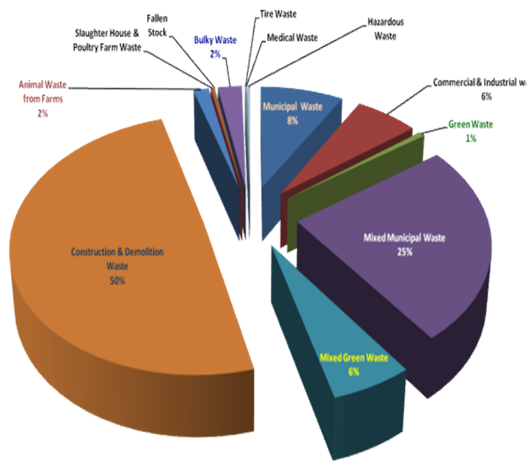

Figure 3: Total Waste Composition in Abu Dhabi [12]

Table 3: Composition of MSW in UAE [11]

Fraction (2010)	Abu Dhabi (%)	Dubai (%)
Organics	49	28
Paper	6	22
Metals	8	6
Plastics	12	20
Glass	9	7
Wood	-	4
Textiles	-	5
Inert	-	3
Others	16	5

Table 4: Composition of MSW in US [13]

Fraction/year	1970	1998	2010
Paper	36.6	38.2	36.9
Plastics	2.4	10.2	12.0
Rubber & Leather	2.5	3.1	2.8
Textile	1.7	3.9	4.5
Wood	3.1	5.4	5.3
Food (garbage)	10.6	10.0	11.3
Yard Wastes	19.2	12.6	11.5
Non-Combustible	24.1	16.6	15.7
Total	100.0	100.0	100.0
Total Weight (Mtons)	121	158.1	171.6

3.1 Selection Criteria for Methane Production Parameters

Methane Generation Rate (k): It is a first-order biodegradation rate at which methane is generated after waste placement. Although the k value is usually influenced by many factors like moisture content, the availability of nutrients, pH, and temperature, the moisture content within a landfill has a high impact on the gas generation rate. Moisture serves as a medium for transporting nutrients and bacteria. The moisture content within a landfill is influenced primarily by the infiltration of precipitation through the landfill cover. The precipitation in Abu Dhabi is usually very low at annual average of 100 mm and reaching as low as 10 mm in some seasons (Figure 4). On the other hand, the annual precipitation in the US is comparably high ranging from 106mm in Las Vegas, Nevada to as high as 1592mm in New Orleans, Louisiana [13]. The selection of the k values is based on the variation due to degradability and annual precipitation as presented in table 5. Typical k values range from 0.02 for dry sites to 0.07 for wet sites [10].

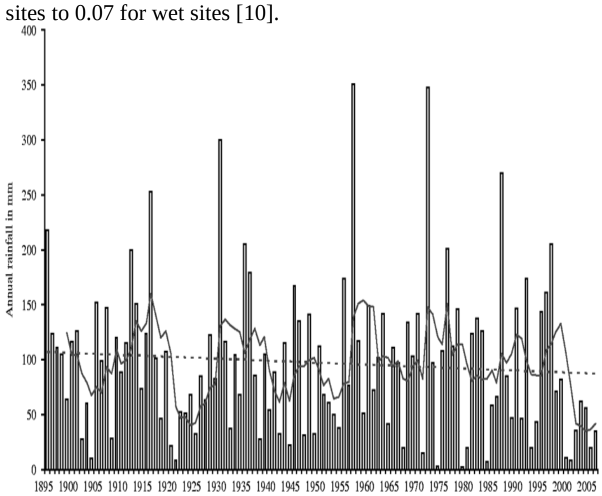

Figure 4: Annual rainfall in the Arab region [14]

Table 5: Variation of k values with annual precipitation and degradability [10]

Annual Precipitation	Range of k Values		
	Relatively Inert	Moderately Decomposable	Highly Decomposable
<250 mm	0.01	0.02	0.03
>250 to <500 mm	0.01	0.03	0.05
>500 to <1000 mm	0.02	0.05	0.08
>1000 mm	0.02	0.06	0.09

Other factors that affect the moisture content in the waste and the rate of gas generation include the initial moisture content of the waste; the amount and type of daily cover used at the site; the permeability and time of placement of final cover; the type of base liner; the leachate collection system; and the depth of waste in the site.

Potential methane generation capacity: Another parameter of importance is the potential methane generation capacity. The methane generation potential (L_o) represents the total yield of methane, expressed in m3 of methane per ton of waste. The Lo value is dependent on the composition of the waste, and in particular, the fraction of organic matter present. The Lo value is estimated based on the carbon content of the waste, the biodegradable carbon fraction, and a stoichiometric conversion factor. Typical values for this parameter range from 125 m^3 of methane/ton of waste to 310 m3 of methane/ton of waste [10]. Increased compaction of the waste has no direct effect on the Lo parameter.

Table 6: Variation of Lo values [10]

Waste Categorization	Minimum Lo Value	Maximum Lo Value
Relatively Inert Waste	5	25
Moderately Decomposable Waste	140	200
Highly Decomposable Waste	225	300

3.2 Summary of results

Figures 5 and 6 shows the rate of production per year of methane in dry sites and under bioreactor landfilling conditions both in the US and Abu Dhabi by a municipality of 1,000,000 people from 2013. The generation rate of methane in bioreactor landfills has been shown to be greater than for the dry tombs for both US and Abu Dhabi. The methane generation was found to be higher in the US than Abu Dhabi under both conditions owing majorly to the high annual precipitation and waste generation rate. In 2013 alone, the bioreactor landfills produced around 1.67 and 1.84 million cubic meters per year in Abu Dhabi and US respectively as compared to 0.44 and 0.53 million cubic meters per year in dry tombs.

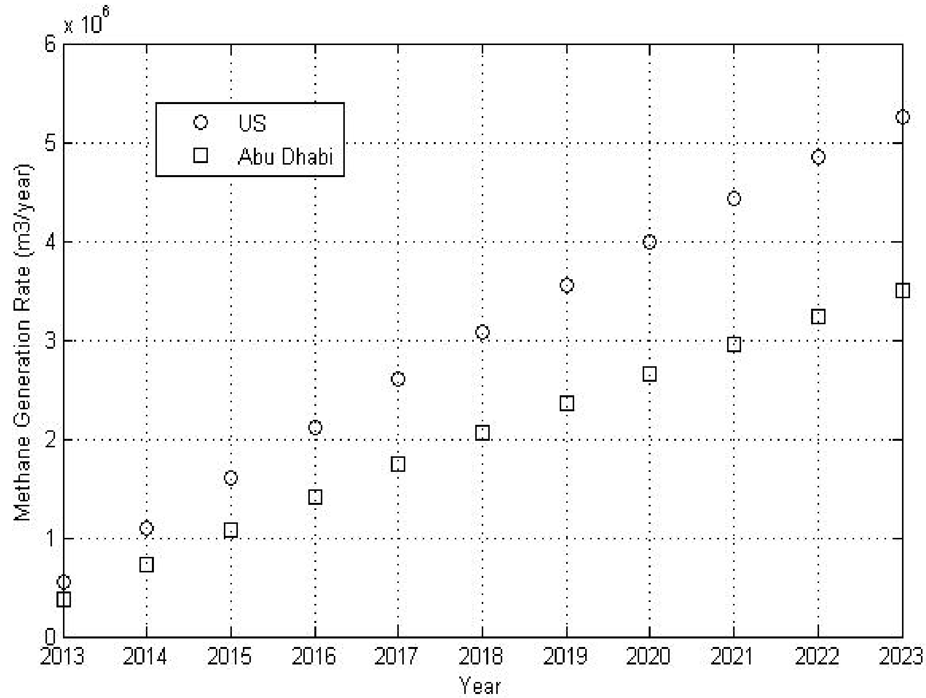

Figure 5: Landfill gas estimation for a dry tomb

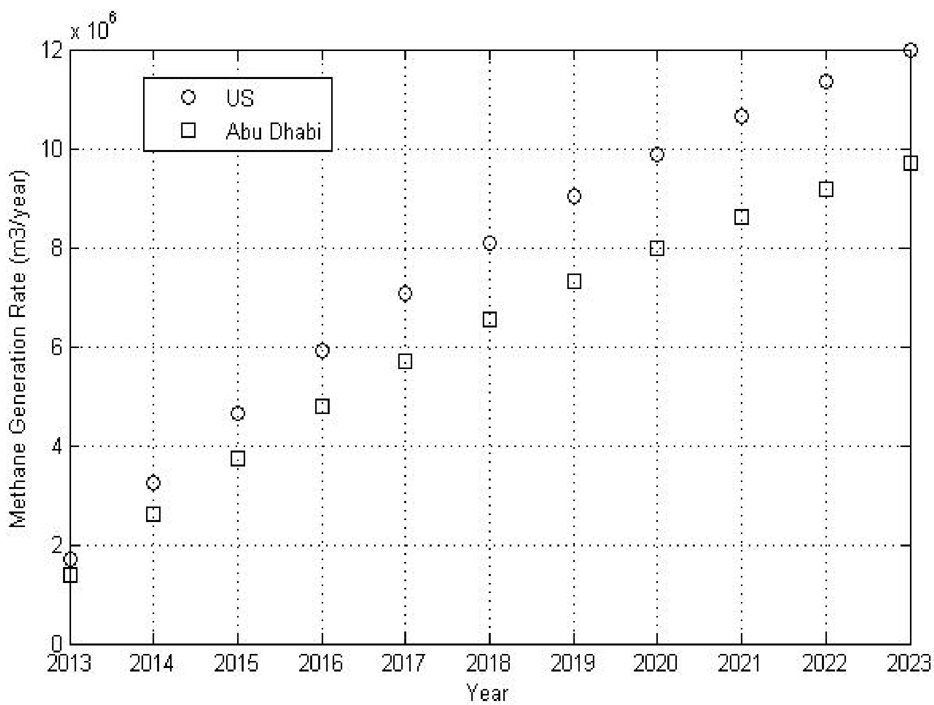

Figure 6: Landfill gas estimation for a bioreactor landfill

The ability of the bioreactor landfill over dry tombs for CO_2 reduction has also been exploited as carbon offset. This resulted in offsetting 26,409.5 tons/year in US and Abu Dhabi when compared with a 2MW and 32% efficiency (η) coal power plant with an average heating value of 33.3MJ/kg (HV). This calculation based on the coal combustion ($C_{coal}+O_2=>CO_2$) can be summarized in Appendix 1.

4. Utilization of the Landfill Gas

The produced LFG can be utilized either for electricity generation or heating and other applications. After the LFG is produced, it is collected through the LFG collection pipes where it is channeled to the fuel processing unit for upgrading. The fuel produced after processing usually ranges from low grade to high grade fuels. The low grade fuels have been found useful as fuel for steam turbines, space heating and process heating. Medium grade fuels can be used in gas turbines in a combined cycle, reciprocating engines, micro-turbines, and process heating, while high grades is used in fuel cells and in production of pipeline quality gas and other applications (Figure 7). Electricity generated using LFG has proven to be economical in a large number of landfills in Canada, USA and Europe. The bioreactor landfills will be more cost effective in the generation of electricity than other traditional landfills, although the initial/capital investment may appear to be higher.

5. Conclusion

An over view of the bioreactor landfill concept, its operation and benefits over dry tomb have been studied. The potentiality of a bioreactor landfill to produce higher landfill gas as compared to dry tomb has been established both in US and Abu Dhabi. In 2013 alone, the bioreactor landfills produced around 1.67 and 1.84 million cubic meters per year in Abu Dhabi and US respectively as compared to 0.44 and 0.53 million cubic meters per year in dry tombs. The ability of the bioreactor landfill over dry tombs for CO_2 reduction has also been exhibited with carbon offset of 26,409.5 tons/year in US and Abu Dhabi when compared with a 2MW coal power plant with utilization of the gas emission from the dry tomb.

A shift to using bioreactor landfills creates an opportunity to successfully generate energy in an environmentally responsible manner that reduces the potential for future pollution, offsets the use of fossil fuel , marked as contributing sources to greenhouse gas, and creates economic incentive for industries to locate plants and jobs adjacent to bioreactor landfills.

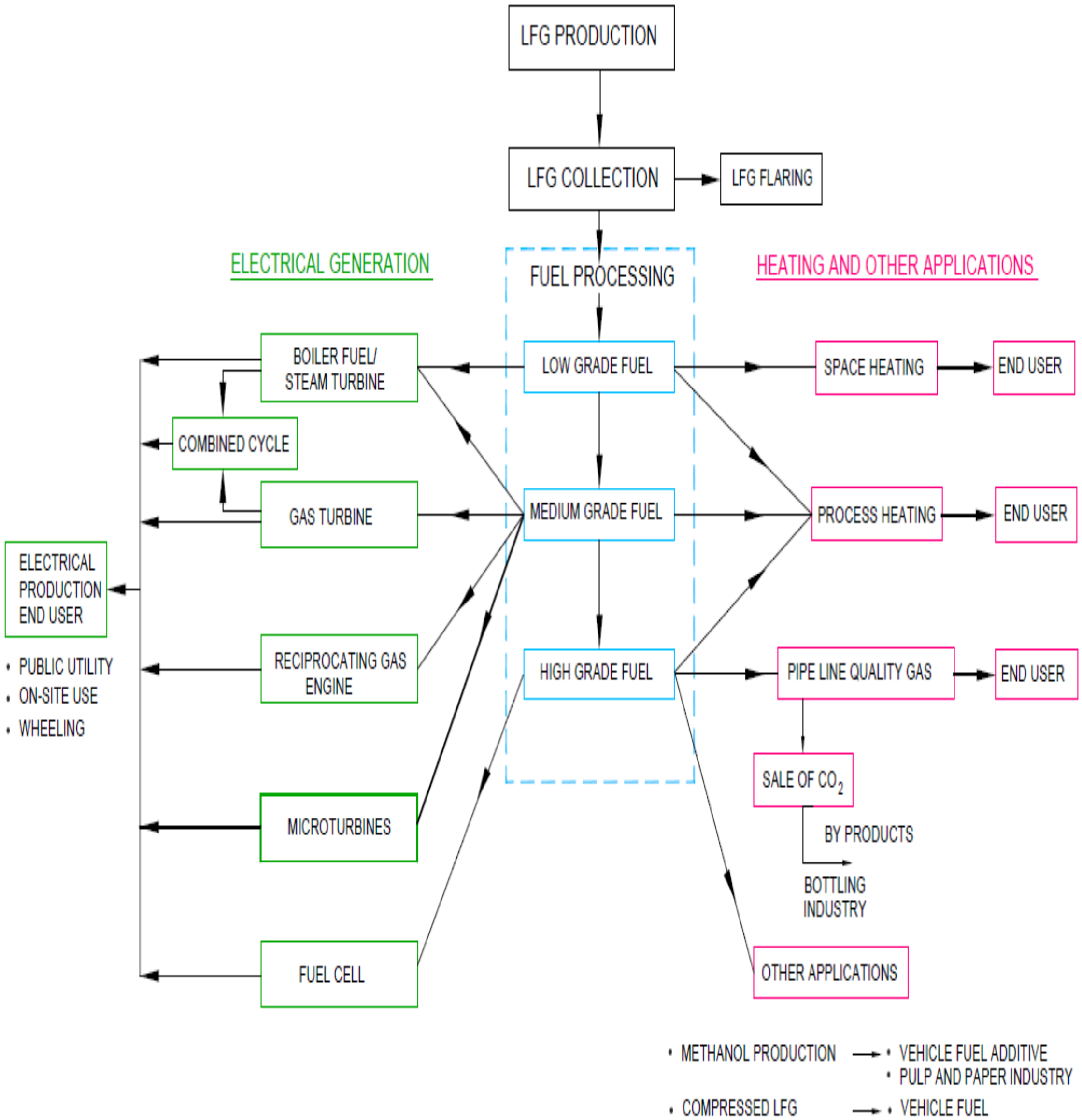

Figure 7: Applications of LFG [10]

Nomenclature

Q_{CH4} = Estimated methane generation flow rate (in cubic meters [m3] per year or average cubic feet per minute [cfm])

i = 1 to n year time increment

K = Methane generation rate (year-1)

L_o = Potential methane generation capacity (m3 per megagram [Mg] or cubic feet per ton)

M_i = Mass of solid waste disposed in the ith year (in Mg)

T = Time increment

ρ = Density

GWP =Global Warming Potential

HV = Heating Value

Appendix 1: Evaluation of CO_2 Offset

Annual Energy input = 2MW*year/hpower plant

= 197,100,000 MJ

Annual CO2Emissions from coal power plant

= (197,100,000 /HV_{coal})*(3.66 kg of CO2/kg of Coal)

= 21,406,112.76 kg of CO_2/yr

The volume of methane required to generate 2MW at typical combined power cycle efficiency is equal to 2,829,731.5 m3/year. Therefore, using the same time and reading the value form the dry tomb emission one can obtain 826,000 m3 of methane per year. This corresponds to the following emissions:

Emission from dry tombs = 826000*(GWP* ρ_{CH4}+ ρ_{CO2})

= 15,586,620kg of CO2

Total emission from coal plant and dry tomb

= 36,992,732.76 kg

Total emission from bioreactor

= 2829731.5 *(ρ_{CH4}+ ρ_{CO2})

=10,583,196.04 kg/yr

Therefore,

Carbon offset = 36,992,732.76 - 10,583,196.04

= 26,409,536.72 kg of CO_2/yr

Acknowledgement

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