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Case Study of Viability of Bioenergy Production from Landfill Gas (LFG)

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Abstract

The landfill gas (LFG) produced from the existing landfill site in Heraklion city, Crete island, Greece, is not currently exploited to its full potential. It could however be exploited for power generation and/or combined heat and power (CHP) production in near future by fully unlocking its energy production potential of the gas generated from the landfill site. This gas (LFG) could feed a 1.6 MW_{el} power plant corresponding to the 0.42% of the annually consumed electricity in Crete. The LFG utilization for power generation and CHP production has been studied, and the economics of three energy production scenarios have been calculated. An initial capital investment of 2.4 to 3.2 M €, with payback times (PBT) of approximately 3.5 to 6 years and Net Present Values (NPV) ranging between 2 to 6 M € have been calculated. These values prove the profitability of the attempt of bioenergy production from the biogas produced from the existing landfill site in Heraklion city, Crete. Based on the current economic situation of the country, any similar initiative could positively contribute to strengthening the economy of local community and as a result the country, offering several other socioeconomic benefits like e.g. waste minimization, creation of new job positions etc. by increasing, at the same time, the Renewable Energy Sources (RES) share in energy production sector etc. Apart from the favorable economics of the proposed waste to energy production scheme, all the additional environmental and social benefits make the attempt of a near future exploitation of the landfill gas produced in Heraklion, an attractive short term alternative for waste to bio-energy production.

Keywords: economics, electricity, heat, municipal solid waste, Greece

1. Introduction

1.1 Background

The disposal of municipal solid waste (MSW) in landfills is a common waste handling practice in a worldwide level. As nowadays there are numerous of not only controlled, but also uncontrolled landfill sites—either closed or still under operation—EU has set a sustainable strategy towards waste minimization. Municipal solid waste handling move towards recycling, reuse of waste sources and if possible prevention of waste production (Figure 1). When the waste used as a bioenergy feedstock helps to reduce the amount of waste send to landfilling and offers positive environmental and socio-economic results. In EU a number of ~150-500.000 active and closed landfill sites contain approx. 30-50 billion m^3 of waste (Damigos et al., 2016), while total prevention of waste production seems to be an utopia for the modern societies. Along with the sustainable exploitation of all available waste in order to prevent environmental pollution and at the same time lower the Green House Gas (GHG) emissions release to the atmosphere, the EU prioritize waste minimization routes as shown in Figure 1. Nowadays there interest focus in integration of MSW management techniques with innovative energy production technologies. This trend is increasing due to concerns such as environmental pollution, global warming, sustainability of energy production and increase of energy security.Such concerns led to stringent environmental regulations for more efficient handling of waste and energy production. According to the Landfill Directive (99/31/EC) (Council Directive 1999/31/EC, 1999), the amount of waste sent to landfilling should be cut down to

35% of the1995 level, by the year 2016. Consequently, the amount of MSW deposited in landfills should be reduced or processed through the best suited, and efficient, way of waste volume reduction route.

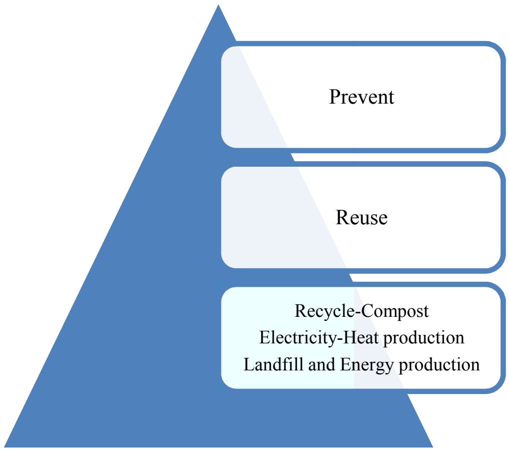

Figure 1. Waste exploitation strategy according to landfill directive (Council Directive 1999/31/EC, 1999)

In Greece the waste volumes send for landfilling in 2010 reached 4.2 million tones, representing the 81% of the total produced waste in the country (Damigos et al., 2016). These numbers alone indicate the fact that shifting from the practice of landfilling to waste-to-bioenergy production will pass first from the valorization route of the full potential of the waste.However, any waste disposal facility, and especially a landfill site,is very often associated with health and safety concerns, as well as matters of aesthetic pollution and social acceptance. In some extreme cases a landfill consist a social nuisance which influence not only the quality of life, but also the image of the neighboring areas. As a result reduction of the waste volumes in source,optimization of the waste logistics and application of technologies of waste upgrading to a biogas, landfill gas (LFG) according to European Council Directive 1999/31/EC, and exploitation of its full energy production potential gain to day much interest.

Anaerobic digestion achieves to reduce the waste volume and also unlock the 'hidden' energy stored in the chemical bonds of waste by converting the solid and difficult to handle waste to a value added biogas, namely the landfill gas (LFG). Anaerobic digestion achieves degradation of the organic components and successfully converts around 90% of the available chemical energy in the waste into methane (CH_4) gas. The LFG, specifically, consists of almost equal volumes of CH_4 (50-60% vol) and CO_2 (40-50% vol) (Amini & Reinhart, 2011) while its heating value is approx. 5,000 kcal N m^{-3} (Council Directive 1999/31/EC, 1999). Such gas due to the fact that is rich in methane (CH_4) and carbon dioxide (CO_2), if released in atmosphere has a high harmful potential towards global warming.

In terms of economics, savings can result from the displacement of a percentage of conventional fuels with the biodegradable part of municipal solid waste being of low or zero cost. Some wastes are low cost because some of them are undesirable waste material. Additionally, the long-term environmental benefit of avoiding landfilling of such part of the waste but move towards a biogas rich in methane production (a 20 times more harmful gas than CO_2 in terms of ozone depletion and a more powerful greenhouse gas) are some of the important factors that are driving the interest in utilizing such kind of biomass. The attractiveness of the in situ exploitation of the locally produced biogas is a desired alternative, instead of such gas to remain unexploitedor even worse released in atmosphere. The later, exploitation of LFG's calorific value can result in economic, environmental and social benefits ensuring the sustainability of the attempt, able to shift the Greek economy under crisis towards a less depended on fossil fuels bio-economy in near future. Such an attempt could also offer an escape from a problem which appeared some years ago and related to the exploitation of dedicated crop seeds for energy production (biofuels), a practice which raised issues concerning utilization of crops for food versus energy production.

1.2 Literature Review: Best Practices around the World

The bioenergy production scenarios discussed within this study concern the unavoidable, biodegradable part of the MSW upgrading to a value added renewable source of energy. The later along with the viability of developing the appropriate scale of power generation plant(s) integrated in the cycle of the waste-to-bioenergy through the existing landfill sites, could be considered as a sustainable solution for the South and East European countries. Therefore, dedicated bioenergy production facilities which will operate and produce supplementary energy in-situ, where the MSW are either produced or centrally gathered, might consist a viable solution of near future, as long as will be proven that the waste elimination is not utopic idea for the future generations. Such waste based bioenergy production plants could exploit not only the locally available waste, but also other biomass waste streams e.g. manure and nonedible agricultural biomass, with the aim to provide a solution in both waste minimization and energy production from cheap and underestimated resources (Skoulou & Zabaniotou, 2007).

Power generation from LFG both in traditional and innovative downstream technologies has been studied by Bove and Lunghi (2006) who indicated that the Internal Combustion Engine technology is still the most widespread used, even though presents the poorest environmental impact compared to other technologies. Integration of LFG with Fuel Cells (FC), on the other hand, seem to be an expensive technological approach, while emerges mainly as one of the innovative and cleanest energy conversion technologies with the highest energy conversion efficiency, but with high economic values (Bove & Lunghi, 2006).

A technical, economic and environmental analysis of the landfill gas utilization has been presented by Murphy et al. (2004a) investigated the utilization of the LFG biogas for CHP and the production of transport fuel concluding that the latter is more economic than the CHP, provided that the waste fuel taxes are not very high. Recently Lantz (2012) also investigated the economic performance of the combined heat and electricity generation from biogas produced from manure in Sweden, comparing different downstream CHP technologies. The researcher concluded, among else, that the process is not profitable under the current conditions. It seems that the profitability of such an attempt is influenced by the scale of production and the small scale CHP plants at individual farms are not yet an attractive alternative. Therefore it is necessary for the farmers (producers of the unavoidable waste feedstock) to cooperate in order to increase the production of biogas and as a result impact the profitability of the combined heat and electricity production attempt from their own waste sources. Comparing, in addition, the different CHP technologies, he found that the compression ignition engine is in many cases the most profitable choice. Lombardi et al. (2006) investigated the energy recovery from a landfill site under three innovative integration strategies including the direct feeding of LFG to a fuel cell and hydrogen (H_2) rich gas production which was fed to a stationary fuel cell and a vehicle fuel cell. They concluded that direct feeding of the LFG to a fuel cell has the highest overall energy efficiency.

Another technical, economic and environmental analysis of energy production from MSW has been presented by Murphy et al. (2004b). The authors studied four (4) different technologies which, among others in use, lead to the production of energy from municipal solid wastes by processes (some as shown in Figure 2): a) incineration of waste (high temperature combustion), b) gasification, c) production of biogas through the biochemical route and d) utilization in a CHP plant and the production of biogas and its conversion to transport fuel. They concluded that biogas production technologies require significantly lower investment costs compared with thermal conversion technologies like e.g. gasification and producer gas production. Among the four abovementioned technologies, transport fuel production requires the lower gate fee. CH_4 generation in landfills has been investigated by Themelis and Ulloa (2007) and they found that 70% of the biogas captured in landfills in the USA is further exploited to produce heat and/or electricity. The rest 30% is flared. According to the US Environmental Protection Agency (EPA) over 700 landfills across the USA could install economically viable energy recovery systems taking advantage of the energy content of the produced LFG, however only 380 of the energy recovery facilities were in place in 2004. Currently, 295 of these facilities generate electricity; the rest use LFG for heating, assisting the reduction of the volume of leachates etc. Fundamental and environmental aspects of LFG utilization for power generation have been also investigated by Qin et al. (2001). The authors found that NO emissions in exhaust gases are increased and the optimum solution in terms of efficient energy utilization and lower emissions is the combined use of LFG with natural gas.

In the Mediterranean area Energy production from LFG in Italy has been also reported by Caresana et al. (2011) with reference to the landfill site in Marche region which receives about 100,000 ton yr^{-1} of urban and industrial waste. They investigated the use of an internal combustion engine, a CHP plant as well as micro-turbines for energy generation. Their results proved that electricity generation from LFG is profitable, while the co-generation plant offers the highest profitability provided that the heat produced is sold. However, it seems that the higher initial investment cost and its complexity hinders the adoption of such an approach. The authors concluded that for the time being the best solution in Italy seems to be the exploitation of the landfill gas in an internal combustion engine. Additionally a similar study of the energy potential of the biogas produced by an urban waste landfill in Granada, southern Spain has been reported by Zamorano et al. (2007). According to the economic viability study of the landfill, operating with an overall LFG flow rate of 250-550 Nm^3 hr^{-1} and achieving an electricity generation of approx. 4,500 MW_h y^{-1}, the internal recovery rate of the investment was 20% for an exploitation period of seven (7) years. In Greece, the viability of waste heat recovery from the large power plant fired with LFG in Ano Liosia, Athens with installed capacity of 23.5 MW and equipped with 15 internal combustion engines has been investigated by Gewalt et al. (2012). The authors concluded that the plant efficiency would be significantly improved when a water/steam cycle was added aiming at converting the original plant to a combined cycle power plant. The energy production potential of two other landfill sites in Greece has been reported by Tsave and Karapidakis (2008). The authors investigated the biogas production potential over a period of many years of two different landfill sites in the proximity of Volos and Heraklion cities, respectively. They used a mathematical model in order to estimate quantities and concluded also that LFG is not broadly used in Greece for power generation. According to Zafiris (2007), the LFG power stations in A. Liosia, Attiki have a nominal power of 3.5 MW and in Tagarades, Macedonia - Greece is 5 MW. Analysis of private and social benefits of LFG to energy projects has been presented by Jaramilo and Matthews (2005), too. The authors estimated that in the USA the private breakeven price of electricity is lower than \$0.04 KW h^{-1} and the optimum social subsidy less than \$0.0085 KW h^{-1}. Cost analysis of various biomass conversion technologies for energy generation has been presented by IRENA (2012) and was estimated that the fixed operation and maintenance cost of electricity generation from LFG varies from 11-20% of the total investment cost.

The technical and economic evaluation of the biogas produced by anaerobic digestion utilization for energy generation in Heraklio, Crete island, Greece has been presented by Tsagarakis and Papadogiannis (2006). In the existing sewage treatment plant in Heraklion, the cost of electricity generation from biogas was estimated at 0.072 € K Wh^{-1}. The estimation of greenhouse gas emissions (GHG) from the landfill located at Akrotiri, Crete island, Greece has been presented by Chalvatzaki and Lazaridis (2010) using mathematical models and they estimated the quantities of various gas emissions from the existing landfill site. The possibilities of using LFG produced by the landfill in Heraklion, Crete for heating greenhouses have been reported also by Vourdoubas (2016). The author estimated the amount of electricity which could be generated and the greenhouse area which could be heated by the operation of a CHP plant using the LFG produced in the existing landfill.

A Life Cycle Assessment of landfills and their greenhouse gas emissions (GHG) in Thailand has been reported by Wanichpongpan and Gheewala (2007) who tried holistically to evaluate the consequences of waste landfilling. The authors concluded that in terms of GHG emissions as well as of economics, it is more advantageous to have large centralized landfills which produce electricity from LFG, than to operate several small localized landfills without energy production. A technical and economic analysis of the Saveh, Iran LFG power plant has been reported by Taleghani and Shabani Kia (2005), who concluded that the biogas power plant has positive environmental, economic and social benefits like e.g. waste upgrading in a feedstock for energy production, waste volumes reduction, emmisions' control, energy production etc. The optimal size for biogas plants has been investigated by Walla and Schneeberger (2008) who concluded that plants with capacities of 575 and 1150 KW_{el} have an attractive economic performance, although such a plant profitability depends on political decisions concerning feed-in tariffs and investment capital subsidies. They reported also that most of the biogas plants established in Austria during 2003-2004 have capacities of 250 KW_{el}. The experience from biogas plants in Denmark has been reported also by Raven et al. (2007). The authors claim that three (3) factors were important for the current status of biogas plants in Denmark: firstly, the Danish government applied a bottom-up approach for their promotion; secondly, a social network and long-term stimulation has enabled a continuous development of the biogas plants; and thirdly, circumstances specific to Denmark have been beneficial for the promotion of biogas plants in the country.

2. Current Status of Biogas Production in Crete Island, Greece

The biggest island of Greece, Crete, attracts annually more than 20% of the Greek tourist activity, is traditionally one of the worldwide touristic destinations and where more than 50% of the renewable energy sources (RES) initiatives take place (Michalena & Angeon, 2009).

In general the biogas in Crete is mainly produced from the MSW treatment and/or theWaste Water Treatment Plants (WWTP). In addition to the sewage treatment plant in Heraklion and Chania cities of the island, there are also landfills in the sub-urbans of both cities where nowadays LFG is produced in situ. The biogas, rich in methane generated from the sewage sludge treatment plants is utilized for the co-generation of heat and power. Heat is consumed in-situ in order to cover part of the energy needs of the WWTPs while the generated power is sold to the grid at a price depending on current feed-in tariffs. However, the energy content of the LFG biogas produced in Chania and Heraklion is not currently exploited at its full potential for energy production although the process could be profitable, based also the successful stories indicated by theliterature review, shown above.

In addition neither the agricultural biomass, nor manure has been utilized for biogas production in Crete, yet. An opportunity in Greece however appeared for biogas exploitation due to the attractive feed-in tariffs given for electricity production over the last five years; thus the investment interest is nowadays focused in establishing LFG-running power plants of capacity ranging from 0.5 to 3 MW_{el} in the biggest island of Greece, Crete.

LFG is currently produced in Crete from two landfills located in the prefectures of Chania and Heraklion. The landfill site in Chania is located in the rural area of Akrotiri and serves the MSW disposal demand of a current population of 100,000 in the metropolitan area of Chania. The landfill site consists of two cells of capacity of 440,000 and 660,000 m^3 with a MSW acceptance rate ranging between 80,000-85,000 ton/yr. The Heraklion city landfill site is located in the region of Fodele, 20 km west of the city occupying a total surface area of 0.08 km^2. Fodele landfill site capacity is 165,000 tons/yr of MSW and has the ability to serve a population of 192,000 citizens. The LFG production from both the above mentioned landfill sites are estimated being 2.9×10^6 Nm^3 yr^{-1} and 14.3×10^6 Nm^3 yr^{-1} from Akrotiri and Fodele sites, respectively. The impressive notice is the Fodele's LFG production is also almost five times higher than the annual production of LFG from the Akrotiri landfill site. The owners of these landfill sites are the municipal cooperative companies in Crete island Greece. Even though the LFG produced is not currently utilized for heat or power generation, the fact that both landfills are located in remote areas without many established urban or industrial activities, the exploitation of LFG only for heat generation is not advisable. However, power generation or co-generation of heat and power under specific circumstances are the most preferable options for the exploitation of the LFG produced in Crete, especially during the current situation of economics in the country; thus any achievement of a positive balance between socio-economics and environmental benefits are of crucial importance not only for local communities, but also the country.

3. Aspects of the LFG Exploitation Opportunity of the Heraklion Landfill Site

Even though the biogas currently produced in Crete from the existing landfill site in Heraklion city suburban area has to offer socioeconomic benefits of its high energy content are lost as it currently remains unexploited. Due to its high global warming potential, LFG must be burnt instead of being released into the atmosphere (Council Directive 1999/31/EC, 1999). According to existing studies the average biogas production from the landfill site in Heraklion during the period of 2006-2026 is estimated to reach an equivalent of 1,637 Nm^3/hr. Assuming also, based on the above mentioned information, that 75% of the biogas produced can be recovered and exploited for energy production, its inherent energy content exploitation is able to produced 55.95 GW_h yr^{-1}. If the power efficiency of the carefully selected downstream electricity production technology is of 25%, then the electricity generation is estimated to reach 13.99 GW_h yr^{-1} and the capacity of the plant the 1.6 MW_{el}. In the case of a co-generation plant with a power efficiency of 25% and a heat efficiency of 50%, the co-generated heat is estimated to reach 28GW_h yr^{-1}. The Heraklion landfill is located in an agricultural area with an intensive agriculture activity, away from any urban or industrial activities. The LFG produced there could be utilized for power generation or combined heat and power production part of which could be recycled to support the agricultural activities e.g. drying of products, cover part of the energy demands of small farms, lighting etc. If only power was generated, it could be sold to the grid the price being in accordance with the current feed-in tariffs. If heat and power are co-generated from LFG, then the power could be sold to the grid and the co-produced heat could be sold to heat consumers. Since at the moment there is no heat consumers in the area surrounding the landfill site, greenhouses could be established on the agricultural land nearby to utilize the heat for their space heating and or used to dry wet feedstock. The heat produced from the LFG exploitation could be offered at a low price, as being renewable, compared with heat generated from fossil fuels, creating a competitive advantage to greenhouse farmers in order to promote those investments near the landfill. The exploitation of MSW for such a biogas production and the use of the LFG produced for energy generation promote the wider circular bioeconomy perception of the future societies in a sustainable way, which is one of the pillars of E.U. development during not only the current but also the decades to come. The whole process then upgrades an 'unwanted' renewable source of energy, the organic fraction of the MSW, to a valuable fuel source for the production of a biogas with a high energy content.

4. Technologies for Power Generation from LFG

Some of the common waste-to-bioenergy production routes from the biodegradable part of the MSW are shown in Figure 2. Establishment of such processes should be done with an environmental safe, of low economic risk and in a socially acceptable way which at the same time offer investment opportunities with increased profit margins.

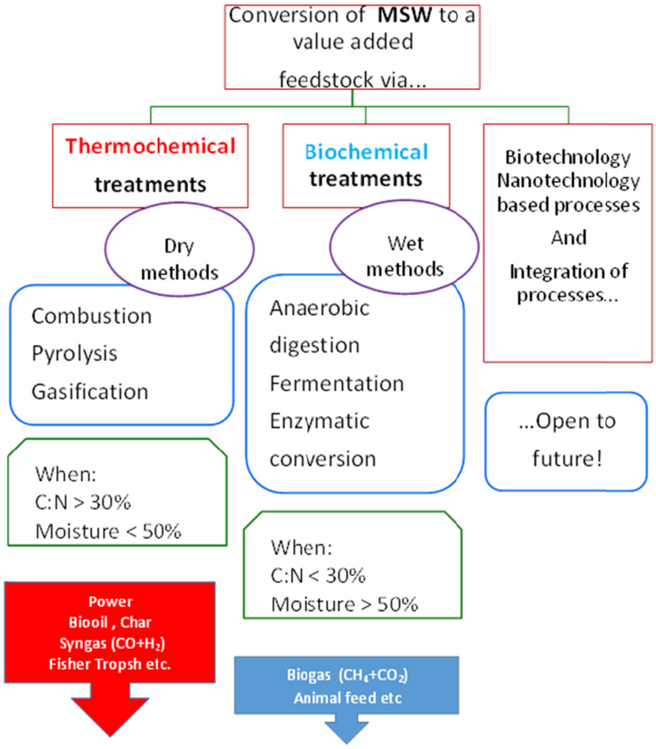

Figure 2. MSW valorization routes and future perspectives

The thermochemical treatments of pyrolysis and gasification for syngas and biofuels/bioenergy/biomaterials production (Skoulou & Zabaniotou, 2012), when the biodegradable part of the waste has the appropriate physicochemical characteristics (moisture content less than 50% wt and carbon-to-nitrogen ratio more than 30%) is a viable route for syngas and biooil production, or even other chemicals through the Fisher Tropsh processes.

When however thebiodegradable part of the MSW are such of high moisture content (> 50% wt) and low carbon- to -nitrogen content (< 30%), the feedstock is usually better to be treated through the biochemical route, as shown in Figure 2. Among others (enzymatic conversion and fermedetion) the anaerobic digestion (AD) seems to be vastly applied for the biodegradable waste volumes reduction. In longer term the future is open to the development of innovative waste exploitationprocesses and integration of the thermochemical with the biochemical processes for increasing the efficiency of bioenergy production.Some examples of such integrated approaches of processes is heat production by waste combustion and exploitation of such heat for drying the wet feedstock, torrefaction of carbonaceous sources and even provide energy to gasifiers etc.

A great share of interest should however focuse in the formation, problems as well as sequestration of CO_2, NO_X, SO_X, dioxins and other harmful emission emerging during waste exploitation for energy production. Cleaning the produced gas from particulates and gaseous pollutants greatly affect the capital and maintenance costs in a power production plants however it is crucial for preventing the public health and environment. Basu (2010) refers that even if the solid feed in combustion is not of a biogenic origin the emissions from gasification is 3% lower than combustion of pulverised coal; thus sequestration of CO_2 is important for integrated gasification combined cycle (IGCC) plants where, however the concentration of CO_2 is higher in the producer gas and thus it can be separated easier from the main stream. NOx pollutants are also closely related to environmental problems and can be produced during combustion of waste, as well as during pyrolysis and gasification. Pollutants, such as NH_3, HCN, and HNCO can be formed during pyrolysis, while during gasification of waste such chemicals may even affect the continuous operation of the gasification systems (Yuan et al., 2011).

Various technologies are in useor under research and development stages for energy recovery from the LFG including reciprocating internal combustion engines (ICE), gas turbines (GT), steam turbines (ST) and Organic Rankine Cycle (ORC) systems. Among all the most widely used technology for power generation is the internal combustion engine technology. ICEs with capacities of between 1 and 3 MW_{el} offer the advantage of a low investment cost, and thus result in good economic revenues. Another advantage of the specific technology is its compact, small size. However, the main disadvantage of ICE is its poor environmental performance as during operation pollutants like NOx and CO are released in atmosphere. Gas turbines (GT) have also been used for LFG burning and energy production. Their efficiency of small-sized ones is low, but the pollutants emitted are also low compared with the ICE. The organic Rankine cycle (ORC) systems are currently used for energy generation from geothermal fluids. However, it seems that when LFG is used instead of a geothermal working fluid the same engines can also be used successfully. Fuel cells are high efficiency conversion systems but their high initial cost does not favor their use with LFG as well as their sensitivity in poisoning of their working surfaces. Biogas conversion to transport fuel could be used in the future presenting various advantages. An overview of the various availability of energy production technologies from LFG is presented in Table 1.

Table 1. Advantages and disadvantages of various energy generation technologies using LFG as fuel (Adapted from Bove & Lunghi, 2006)

Type of Technology	Internal Combustion Engine (ICE)	Gas turbines (GT)	Organic Rankine Cycle systems (ORC)	Cogeneration of Heat and Power (CHP)systems	Integration with Fuel Cells (FC)
Advantages	Relatively high efficiency Low fuel consumption Reasonable cost for 1-3 MW system Low economic risk Compact, easy to transport	Low emission (NO_X, CO)	Relatively low efficiency	Higher efficiencies	Highest efficiency High operating temperatures
Disadvantages	High Emissions (NO_X, CO)	Energetic losses comparable to ICE Low performance (for low work load)	Moderate emissions High fuel consumption		Minimum emission

In a long term perspective it seems that integration of LFG with fuels cells would be an attractive energy production solution offering high energy production efficiencies. Such case necessitates also the application of efficient biogas conditioning methods as fuels cells are sensitive to gaseous pollutants and deactivate very quickly. Since internal combustion engine is the most widespread and suitable technology for energy generation from LFG, it is assumed that this technology will be selected for the landfill site serving the waste management necessity of the Heraklion city. The design characteristics of an internal combustion engine system generating electricity from LFG in Heraklion, Crete are presented in Table 2.

Table 2. The design characteristics of an internal combustion engine generating electricity from LFG in Heraklion, Crete island Greece

Design characteristics of an internal combustion engine	
Plant capacity	1.6 MW_{el}
Plant availability	85% (7,446 hr yr^{-1})
Power efficiency	25%
Electricity generation	11,914 MW_h yr^{-1}
Initial capital investment[1]	2.4 mil. €
Fixed operation and maintenance cost	30.2 €/MWh_{el}
Variable operation and maintenance cost	13.5 €/MWh_{el}
Total operation and maintenance cost	43.7 €/MWh_{el}
Feed-in tariff	120 €/MWh

Note. [1]: Capital cost of theinternal combustion engine: 1,500 €/KW_{el}.

In order to assess the profitability of the energy generating internal combustion engine, estimates of payback times (PBT) and net present values (NPV) of the plant have been made in three different scenarios, as shown in Table 3. *Scenario 1* (S_1) is the base scenario which data are tabulated. *Scenario 2* (S_2) is similar to S_1 but the feed-in tariff as low as 100 €/MW_h, and lower than the assumption made in S_1. *Scenario 3* (S_3) is similar to S_1 but the total operating and maintenance cost is 20% higher reaching the value of 0,0524 €/KW_h. The Net Present Values (NPV) have been estimated for a 10-year period with a 2% interest rate. An important factor contributing to the plant profitability is the attractive feed-in tariff which is guaranteed for a long period of time.

Table 3. Payback periods and net present values for electricity generation from LFG in Heraklion, Crete for three (3) different scenarios (S_1 to S_3)

Characteristics	Scenario		
	S_1(base case)	**S_2**	**S_3**
Electricity generation (MW_h/yr)	11,914	11,914	11,914
Feed-in tariff (€/MW_h)	120	100	120
Total operating cost per power unit (€/MW_{hel})	43.7	43.7	52.4
Total Revenues (€/yr)	1,429,680	1,191,400	1,429,680
Total Operating Cost, TOC (€/yr)	520,642	520,642	624,294
Net Income (€/yr)	909,038	670,758	805,386

A comparison between the payback periods (PBP) and net present values (NPV) of the three different scenarios calculated for electricity generation from LFG in Heraklion city, in Crete, Greece are depicted in Figure 3.

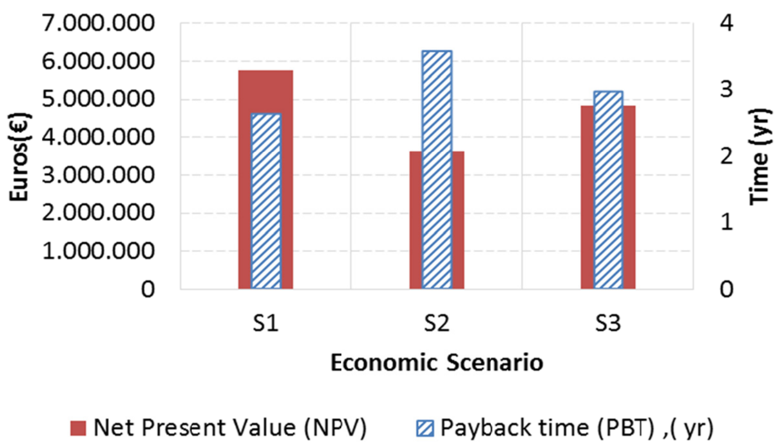

Figure 3. The payback periods (PBP) and net present values (NPV) for electricity generation fromLFG in Heraklion, Crete for three different scenarios, S_1-S_3

As can be also seen from Table 3 the results from the three scenarios, S_1 to S_3, prove the profitability of the attempt since the PBT and NTV values are very attractive. Changes in the total operational costs and in feed-in tariffs do not alter significantly the attractiveness of the attempt. In all scenarios the payback times are less than four years (PBT < 4 yrs) and the net present values are higher than 3,000,000 € (NPVs > 3×10^6 €). Assuming that the operation of the LFG based power plant will be longer than 10 years and the plant will receive an initial investment capital subsidy from the government, its profitability will be even more attractive than the values presented in Table 2. The possibility of using the rejected heat for additional power generation should also be studied. Organic Rankine Cycle (ORC) and water/steam cycle systems could be used changing the internal combustion engine to a combined cycle plant. Taking into account the fact that the total annual electricity consumption in Crete is 2,837.8 GWh the power which can be generated from the Heraklion LFG corresponds to 0.42% of the current annual electricity consumption on the island.

5. Use of LFG for the Co-Generation of Heat and Power

The LFG could be used for the co-generation of heat and power if the co-produced heat could be used locally. Since there are no heat consumers near the landfill itself which could utilize the heat in situ, it has been assumed that greenhouses could be established near the LFG production site. These would utilize the heat for their space heating (Vourdoubas, 2016b). Greenhouses would utilize the co-produced heat for approx. six months during a year due to the mild climate of Crete and the price of the heat would be approx. half the price of the heat generated from fuel oil which is currently used in greenhouses. The low price of the heat would be an incentive to farmers to create greenhouses in this area. Investment and operational costs of the co-generation plant would be higher than power generation only if the cost of heat transportation for short distance was included. However the plant would have additional income due to revenues from the heat sold. The design characteristics of a co-generation plant using LFG in Heraklion, Crete are presented in Table 4.

Table 4. The design characteristics of a co-generation plant, using the LFG produced from the landfill in Heraklion city, Crete

Characteristics	
Plant capacity	1.6 MW_{el}
Plant availability	85% (7,446 hours/yr)
Power efficiency	25%
Heat efficiency	50%
Electricity generation	11,914 MWh yr^{-1}
Heat production	23,828 MWh yr^{-1}
Initial capital investment[1]	3.2 mil. €
Fixed operation and maintenance cost	40.3 €/MWh_{el}
Variable operation and maintenance cost	27.0 €/MWh_{el}
Total operation and maintenance cost	67.3 €/MWh_{el}
Feed-in tariff	120 €/MW_h
Heat selling price	16 €/MWh_{th}

Note. [1]: Capital cost of the co-generation: with internal combustion engine 2,000 €/KW_{el}.

In order to assess the profitability of the co-generation plant four different scenarios have been examined. Scenario 1 (S_1) is the base scenario with data as in Table 4 while scenario 2 (S_2) differs from the first only in the feed-in tariff offered which is lower at 100 €/MW_h. Scenario 3 (S_3) differs from the basic scenario only in the total operating cost which is 20% higher while Scenario 4 (S_4) differs from the basic scenario only in the heat selling price which is 20% higher. Results of the estimates are presented in Table 5.

Table 5. The payback periods and net present values for the co-generation of heat and power from LFG in Heraklion city, Crete island, Greece for four (4) different scenarios

Characteristics	Scenario			
	S1(base case)	S2	S3	S4
Electricity generation (MWh/yr)	11,914	11,914	11,914	11,914
Heat generation (MWh/yr)	23,828	23,828	23,828	23,828
Heat sold to greenhouses (MWh/yr)	11,914	11,914	11,914	11,914
Feed-in tariff (€/MWh_{el})	120	100	120	120
Heat selling price (€/MWh_{th})	16	16	16	19.2
Total operating cost (€/MWh_{el})	67.3	67.3	80.8	67.3
Total revenues (€/yr)	1,620,304	1,382,024	1,620,304	1,658,429
Total operating cost (€/yr)	801,812	801,812	962,651	801,812
Net income (€/yr)	818,492	580,212	657,653	856,617

The payback times and net present values for four different scenarios for electricity generation from LFG in Heraklion, Crete are presented in Figure 4.

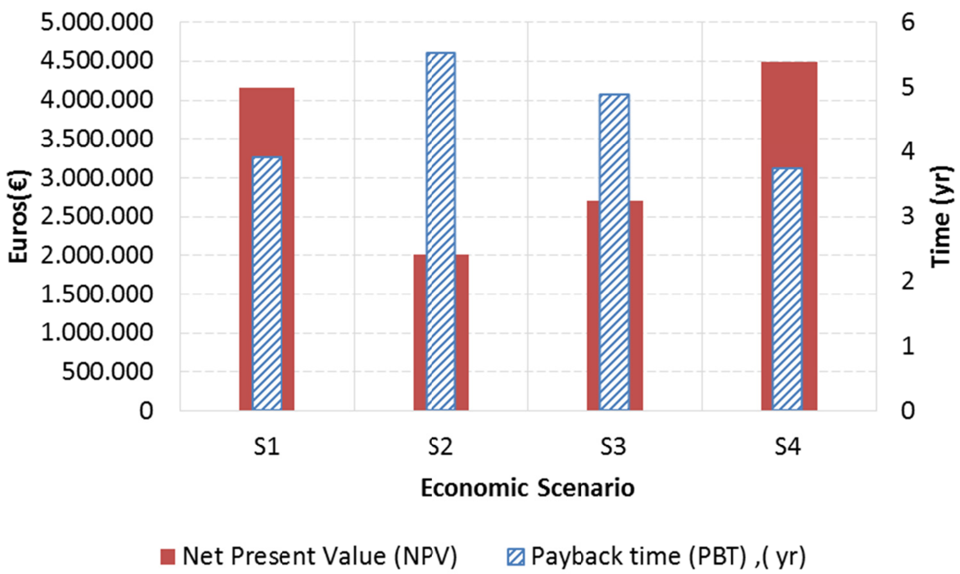

Figure 4. The payback time (PBT) and net present values (NPV) for co-generation from the LFG produced in Heraklion, Crete for three different scenarios, S_1-S_3

The profitability of the co-generation plant is proved by the attractive payback periods and the high net present values in all scenarios. The economic viability of the CHP plant depends largely on the price of electricity since its price is significantly higher than the price of heat. A reduction of feed-in tariffs and an increase in total operating costs would negatively influence the plant profitability. This negative impact is less if heat selling prices are higher. However comparison between the power generating plant and the co-generation plant proves that the power-only generating plant is more profitable. This is due to various factors including the higher investment cost of the co-generation plant, its higher operational costs and the difficulty of selling the co-produced heat for long periods at attractive prices in order to increase the plant revenues.

6. Conclusions

The existing landfill site in Heraklion city, Crete island of Greece generates large quantities of landfill gas which remains unexploited, even though it could feed a 1.6 MW_{el}power production plant, generating an amount of energy which corresponds to 0.42% of the current total annual electricity consumption in Crete. Such a biogas could also be exploited in a CHP plant provided that there is a local market which will take advantage of the co-produced heat. Two different options for the exploitation of LFG have been studied: a) the power-only generation based on an Internal Combustion Engine (ICE), the most widely used attractive technology for biogas conversion to power and, b) the co-generation of heat and power. An initial capital investment of 2.4-3.2 M € depending on the plant option is required and the payback times fluctuate between 3.5 and 6 years, with NPV values ranging between 2-6 M € have been estimated in both cases of different scenarios proving the profitability of this investment.

Taking into account the higher initial investment cost of the CHP plant, its lower profitability and its technological complexity compared to the power only generating plant, it is clear that the use of latter is preferable for the generation of energy from the landfill in Heraklion city, Crete island. The profitability of power generation from LFG the positive environmental and social impact make this investment desirable while reducing the use of fossil fuels in the energy mix of Crete at the same time. While still there is a lack of confidence and a gap of knowledge in biomass exploitation for energy production, the vast majority of the biomass used today in the EU for heat and power are considered to provide significant GHG savings compared to fossil fuels.

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