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Technical and economical assessment of power generation technologies firing syngas obtained from biosolid gasification*

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Evaluación técnica y económica de tecnologías de generación de potencia a partir de gas de síntesis obtenido de la gasificación de biosólidos

Avaliação técnica e econômica de tecnologias de geração de potência a partir de gás de síntese obtido da gasificação de biosólidos

ABSTRACT

Introduction. The wastewater treatment process generates two byproducts biogas and biosolid. Biosolid is sewage sludge which has a high moisture content and low organic material. Currently, the biosolid is utilized as fertilizer to sustainably improve and maintain productive soils and stimulate plant growth, however there are some studies that show high heavy metal and pathogens content that turn the use of biosolid into a hazard for other species and the humankind. **Objective**. This paper shows another way for using this residual byproduct; The paper shows a technical and economical assessment about two power generation technologies as Dual-fuel Engines [DE] and Gas Engines [GE], using the syngas obtained from biosolid gasification as fuel. **Materials and methods**. In this study the scale-up factor method and the correlation method were used by determination of generation plants and gasification process cost, respectively. The variables studied were: investment cost, Syngas cost, M&O cost and generated energy cost, and the economical assessment was made with the financial factors Net Present Value [NPV] and Internal Rate of Return [IRR] with a project lifetime of 15 years. **Result.** The main result of this study drew that a generation over 545 kWe with GE technology brings a best profit-earning capacity for the project. **Conclusion**. The total capital investment

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of gasification plant and diesel cost must be effectively addressed in order to increase their potential viability of this kind of projects.

Keywords: biomass gasification, Dual-fuel Engine, Gas Engine, Syngas.

RESUMEN

Introducción. Los procesos de tratamiento de aguas residuales generan dos subproductos, biogás y biosólidos. Los biosólidos son lodos, los cuales tienen un alto contenido de humedad y bajo contenido de material orgánico. Por lo general, los biosólidos son utilizados como fertilizantes para mantener los suelos productivos; Sin embargo, algunos estudios revelan que los biosolidos contienen gran cantidad de metales pesados y patógenos lo cual representa un peligro para los seres vivos. **Objetivo.** Realizar evaluación económica a dos tipos de tecnologías de generación de potencia, motores duales y motores a gas, usando gas de síntesis obtenido de la gasificación de biosólidos como combustible. **Materiales y métodos.** En este estudio se utilizó el método de factor de escalado y el método de correlación para determinar los costos de las plantas de generación y los costos de los proceso de gasificación respectivamente. Las variables estudiadas son: costo de inversión, costo del gas de síntesis, costo de la energía generada y costo de operación y mantenimiento. La evaluación tuvo en cuenta factores financieros como valor presente neto y tasa de retorno con un tiempo de vida del proyecto de 15 años. **Resultados.** El principal resultado de este trabajo es la viabilidad económica cuando se genera sobre una capacidad de 545 KWe con la tecnología de motores a gas. **Conclusión.** Para incrementar la viabilidad de este tipo de proyectos se debe atacar el costo de generación de gas de síntesis a partir de biosólidos y el costo del diesel cuando hablamos de motores duales.

Palabras clave: gasificación de biomasa, motor dual, motor a gasolina, gas de síntesis.

RESUMO

Introdução. Os processos de tratamento de águas residuais geram duas subprodutos, biogás e biosólidos. Os biosólidos são lodos, os quais têm um alto conteúdo de umidade e sob conteúdo de material orgânico. Pelo geral, os biosólidos são utilizados como fertilizantes para manter os solos produtivos; No entanto, alguns estudos revelam que os biosólidos contêm grande quantidade de metais pesados e patogênicos o qual representa um perigo para os seres vivos. **Objetivo.** Realizar avaliação econômica a dois tipos de tecnologias de geração de potência, motores duais e motores a gás, usando gás de síntese obtido da gasificação de biosólidos como combustível. **Materiais e métodos.** Neste estudo se utilizou o método de fator de escalado e o método de correlação para determinar os custos das plantas de geração e os custos dos processo de gasificação respectivamente. As variáveis estudadas são: custo de investimento, custo do gás de síntese, custo da energia gerada e custo de operação e manutenção. A avaliação teve em conta fatores financeiros como valor presente neto e taxa de volta com um tempo de vida do projeto de 15 anos. **Resultados.** O principal resultado deste trabalho é a viabilidade econômica quando se gera sobre uma capacidade de 545 KWe com a tecnologia de motores a gás. Conclusão. Para incrementar a viabilidade deste tipo de projetos se deve estabelecer o custo de geração de gás de síntese a partir de biosólidos e o custo do diesel quando falamos de DE.

Palavras importantes: gestão gasificação de biomassa, motor dual, motor a gasolina, gás de síntese, estudo econômico.

INTRODUCTION

In Colombia, protection of hydric resource has been studied for a long time, but just in 1984 a law about water use and liquid residuals was implemented. In 1994, the building of the first Wastewater Treatment Plant (*WWTP*) located in Bogotá was approved; this *WWTP,* named Salitre, was brought into operation in 2000, motivating the creation of others *WWTP* around the country. *WWTP* are able to successfully manage and control the hydric contamination, also generate byproducts like biosolids and biogas. Biosolid is a sludge generated by an anaerobic process which has been defined by the Environmental Protection Agency (EPA) as a solid derived from wasted water treatment and biologically stabilized, with enough nutrient concentration, low pathogenic microorganisms content and permissible concentration of heavy metal. In the last 30 years, research studies about biosolid utilization has emerged (Daguer, 2003). The studies show that biosolids can become an environmental problem due to its rapid production increase. Initially, studies about biosolid utilization have been focused on agricultural activities like compost and soil recovery (Baldwin, et al, 1983; Petersen & Ahring, 1990; Couillard & Mercier, 1990; Brown, et al, 1990). According to the norms *NOM-004-SEMARNAT-2002 (Mexico)* y *EPA 40CFR- 503 PC –EQ QUALITY (USA)* there are three type of biosolids (A, B and C) depending on its pathogen and heavy metal content, hence not all type of biosolids can be used for agricultural activities, risks to human and environmental health, impose an active monitoring of all processes, use and disposal (Vélez Zuluaga, 2007; Macías Mazo, 2005; Torres, 2009). This is why, new alternatives for biosolid utilization are considered. In 1989, Kamisky & Kummer (1989) carried out a research about pyrolysis of biosolids, in this work, as a result the characterization of syngas from pyrolysis process was obtained, where syngas had a calorific value of 23 MJ/m^3, and was composted by hydrogen, methane, ethane, propane, carbon monoxide and carbon dioxide. *The company KALOGEO* (2006) Anlagenbau GmbH patented an optimal and unique system for the sludge utilization, this system is composed by four processes: solar drying, gasification, post-combustion, and energy recovery. The result of this research showed an energy efficiency of 86 %. Mexico has also conducted studies for energy recovery from biosolids. In 2007, *Enerkem Technologies Inc*. developed a project named "*Valorización de los biosólidos vía gasificación*" (Chornet, 2007), in this project the principal processes for biosolids assessement are also implemented (drying, gasification, fumes treatment and energy recovery). Another project about biosolids utilization was presented by *Politécnica of Catalunya University* in conjuction with the *company SGT S.A*. (Catalunya project, 2005), where gasification process was used and the main aim was to design the gasification plant. State of the art has shown that most of the mentioned projects only make a biosolid assessment until gasification process but they do not analyze the power generation process.

Gasification is a process of thermochemical conversion which transforms the biomass to produce a gaseous fuel, called syngas, its composition depends of aspects such as: organic matter characteristics, gasifying agent, temperature and pressure (De Andrés, 2010). Gasification offers advantages compared with incineration because syngas combustion shows better properties compared from solid fuel combustion, also syngas is a relatively free of impurities gas (control CO_2, NO_x, SO_x emission), less emission of particulate matter, and the gas produced has several applications, can be burned to produce heat and steam, and then generate mechanical and electrical energy, can be burned in turbines or internal combustion engines, or as a precursor chemical reagents (Bodo, 2007). Experts predict that gasification will be the process used in new power plants (Fytilli, 2008).

Colombia has no large-scale applications of energetic recovery of biosolid. Medellin, Bogotá y Cali have a60 to 130 Ton/day output; biosolid has a moisture content of 66-68 %, the balance corresponds to organic matter and inert material (Vélez, 2007); but many studies have been developed about biosolid characterization and possible uses (Vélez, 2007; Macías, 2005; Torres, 2009). In 2012, German researchers presented the results of syngas from a gasification plant in Balingen and the demonstration plant in Mannheim (Burgbacher, Gaiffi, Judex, 2012), due the scale of process, the composition of syngas was taken as the basis for the calculations of this work.

Technologies of power generation

Spark Ignition Engine (SI engine) – Gas Engine (GE)

In recent years the interest toward the use of syngas in SI engines has been growing significantly. Engine in small scale can be used in CHP systems (Combined Heat and Power) obtaining high efficiencies with low costs, providing a high competence (Günter, 2003). The principal difficulties with syngas into an internal combustion engine are its low calorific value and its quality. Tar is one of the present components that cause damages in the internal parts of the engine. The variation of the syngas composition is another problem that has a direct impact in the deflagration velocity, ignition timing delay and its propagation. The change of burning velocity in a SI engine could produce unburnt fuel, auto-ignition effects (Przybyla et al, 2008; Project SDB, 2006; Heywood, 1988).

Compression Ignition Engine (CI engine) – Dual-fuel Engine (DE)

Dual-fuel engines have been employed in a wide range of application where several gaseous fuels are used. These engines are a retrofit of Diesel engine and their main advantage is the lower emission levels, especially in particulate matter (Boehman & Corre, 2008). Gaseous fuel in DE is called primary fuel, due to the fact that it contributes between 80 % to 90 % of the chemical energy in the combustion process, the rest of the energy is supplied by Diesel fuel.

MATERIALS AND METHODS

The methodology of this research was focused on defining the main technical and economic variables. Those variables were defined taking into account several project about technical and economic assessment as a model base (Larson & Marrison, 1997; Rodríguez, Faaij, Walter, 2003; Nandi & Ghosh, 2010). The economic variables were analysed with two financial Indexes, net present value (NPV) and internal rate of return (IRR). Due to the fact that the transport of biosolid is expensive because it contains high percent of moisture, this paper arises in a scenario in which the gasification and power generation plants are in site of Wastewater Treatment Plant.

Estimation of technical variables

The estimation process of technical variables for this research was as follows: first the power range was selected between 60 kW and 1640 kW, the de-rating of power was got from the technical report "*Strategic Development of Bio-Energy (SDB) Project*" present by the Indian Institute of Science (Project SDB, 2006). Sridhar, Paul and Mukunda (2001) report similar values for the de-rating power in his work.

The power loss by the altitude effect (P_h) was also calculated through the Equation (1). Approximately the power loss is a 4 % per each 300 meters beginning of 100 meters over the sea level.

$$P_h = \frac{(1500-100)m}{300m} \times 4\% \qquad (1)$$

In the Table 1, the syngas composition and all technical variables used in this research are shown, this composition was selected from tests which have highest quality in terms of stability and behaviour of measuring equipment (Burgbacher, Gaiffi & Jodex, 2012).

Table 1. Technical variables

Technical variables		
Technology	GE	DE
Power Capacity [kW]	60-1640	
Operation time [hour/year]	8000	
De-rating of power [%]	0	15
Power loss by the altitude effect [%]	18.3	18.3
Syngas composition		
H_2 [%]	13.3	
CO [%]	13.8	
CH_4 [%]	4.2	
CO_2 [%]	13	
N_2 [%]	Rest	
Flow of Biosolid to gasify on dry basis [TON/DAY]	10-350	
Gasification efficiency [%]	80	
Generation power efficiency [%]	27.5	32

The flow of biosolid to gasify on dry basis (M_{DB}) is calculated using equation 2. this equation takes into account the power plant capacity, the syngas composition, gasification efficiency, power energy generation, volatiles content, power loss factors and the initial moisture of biosolid.

$$M_{BH} = \frac{Cap*p_h*p_d*\rho_g*86.4}{\eta_e*\eta_g*LCV*\%v}\left(1+\frac{1}{\frac{1}{\%M}-1}\right) \quad (2)$$

Where *Cap* is the power plant capacity [kW], P_h y P_d are power loss by the altitude effect and de-rating of power respectively, η_e y η_g are generation power efficiency and gasification efficiency respectively, *LCV* is the low caloric value, %v is the content of volatiles that biosolid has, and *%M* is the initial moisture of biosolid.

Estimation of economic variables

Syngas cost

The main aim of this research is to evaluate the generation power technologies, and not the gasification process. Consequently, it was analysed the cost of producing a cubic meter syngas, and the methodology used was: first step was taking an estimative cost of the equipment that commonly is a part of a gasification plant. This estimative cost was taken from the work carried out by Caputo et al. (2001). In the table 2, the cost correlations of the equipment selected is presented.

Table 2. Cost correlation for each equipment that commonly is part of a gasification plant

Equipment	***Cost correlation***
Gasifier	$1600M_{DB}^{0.917}$
Compressor and Dryers	$11400W_{Cap}^{0.701}$
Total Cost of Equipment	$\mathbf{TCE_{GP}}$
Fumes treatment	
NOx and SOx removal equipments	$126000W_{Cap}^{0.5882}$
Filtration	$66600W_{Cap}^{0.7565}$
Ashes storage	$88300W_{Cap}^{0.3139}$
Ashes extraction	$93500W_{Cap}^{0.4425}$
Fans	$28500W_{Cap}^{0.5575}$
Fumes ductworks	$51500W_{Cap}^{0.5129}$
Discharge stack	$28500W_{Cap}^{0.5575}$
Total Cost of Fumes Treatment	$\mathbf{TCFT_{GP}}$
Civil works costs evaluation	
Buildings yard guard	$70100W_{Cap}^{0.4425}$
Conditioning plant and ventilation system	$23400W_{Cap}^{0.6328}$
Wastewater treatment	$6900W_{Cap}^{0.6107}$
Total Cost of Civil Works	$\mathbf{TCCW_{GP}}$
Direct cost	
Direct installation cost	0.3*TCE
Auxiliary services	0.15*TCE
Total Direct Plant Costs	$\mathbf{TDPC_{GP}}$
Indirect cost	
Engineering	0.12*TCE
Start-up	0.10*TCE
Total Indirect Plant Costs	$\mathbf{TIPC_{GP}}$
Total Capital Investment	$\mathbf{TCI_{GP} = TCE_{GP}+TCFT_{GP}+TCCW_{GP}+TDPC_{GP}+TIPC_{GP}}$
Operating costs	
Maintenance	0.015*TCI
Insurance and general	0.01*TCI
Total Operating Costs	$\mathbf{TCO_{GP}}$

When Total Cost Investment of Gasification Plant (TCI_{GP}) and Total Cost Operation of Gasification Plant (TCO_{GP}) are calculated, Total Capital Investment of Gasification Plant (*TCI-GP*) has been evaluated as the sum of TCI_{GP} and TCO_{GP}. Therefore in this work, one of the important questions is what is the annual cost of total capital investment of gasification plant? In response to the question, a loan analysis was applied. Loan analysis was carried out like a loan amortization schedule with fixed annual payment, where loan account is *TCI-GP* with an annual increase of TCO_{GP}, an annual interest rate of 10% and with a loan period of 15 years. The loan analysis result is the fixed annual payment and also is the annual cost of total capital investment of gasification plant. Now, annual cost of syngas was estimated dividing the loan analysis result between the syngas generated per year [m^3/year].

Power generation plant cost

The power generation plant cost has been estimated using cost scale-up factors method (Remer, et al., 2008). This method is widely used by chemical engineers for estimating equipment costs for several industrial processes (Remer & Idrovo, 1993; Vatuvuk, 1981). The cost scale-up factor is calculated using Equation 3.

$$Cost_{Cap2} = Cost_{Cap1}(I_{inf})(I_{loc})\left(\frac{Cap\ 2}{Cap\ 1}\right)^{R_S} \quad (3)$$

Where: $Cost_{Cap2}$ is the cost of the equipment to estimate; $Cost_{Cap1}$ is the cost equipment basis; I_{inf} and I_{loc} are the inflation and location indexes respectively; C_{ap2} is the power generation capacity whose cost will be estimated; C_{ap1} is the power generation capacity basis and R_S is scale-up factor. R_S can be obtained by two ways, one way is through tables that have a relation between equipment and scale-up factors, and a second alternative is through an iterative process using site data. $Cost_{Cap1}$ and C_{ap1} were taken from a technical report by Gas Research Institute (Darrow, 2000); I_{inf} was obtained from US Department of Labor and I_{loc} was taken from the book "*Project and cost engineer´s handbook*" (Kenneth, M.D., 2004). In the Table 3 is presented a compilation of these variables.

In the Table 4 is showed an extract of operation costs of power generation plant. Maintenance and operation costs (*M&O*) were taken from the state of the art.

Table 3. Cost scale-up factors method variables for each technology evaluated

	MG	MD
Inflation index [2000-2010]	1,36	1,36
Location index	1,09	1,09
$Cost_{Cap1}$ [US$]	60.800,0	52.660,0
C_{ap1} [kW]	280	365
Scale-up factor	1,14	1,16

Table 4. Operation cost of power generation plant

M&O	
Maintenance	0.015*TIC
Insurance and general	0.01*TIC
Import factor	1.77
Annual cost of syngas	Fixed annual payment
Annual cost of Diesel	4.1 US$/gal*$M_{diesel}$
Total Operation Cost	**TOC_{PP}**

The annual cost of syngas was obtained as a fixed annual payment of the Total Capital Investment and Total Operating Costs annually of the gasification plant (Table 2).

Financial Analysis

Finally, having all the economic variables results, each technology is assessed by two financial indexes: *NPV* and *IRR*, the *NPV* index has been evaluated as follows (Equation 4):

$$NPV = \sum_{k=1}^{N} \frac{Cf_k}{(1+i)^k} - TIC \quad (4)$$

Where *N* is the plant lifetime, assumed as 15 years, *i* is the discount rate or opportunity rate (*OR*), proposed as 15 % (Rentizelas, 2009; Darrow, 2000), and Cf_k is the annual cash flow at the k^{th} year equal to (Equation 5):

$$Cf_k = CEG - TOC_{PP} \quad (5)$$

Where *CEG* is cost of energy generated, *CEG* has been calculated taking into account an average of kWh cost for the industrial sector in Colombia (Medellín), which is 0.1976 US$/kWh. Internal rate of return was provided from the series of cash flows, and Microsoft® Office Excel was used for do this procedure.

RESULTS AND DISCUSSION

Economic Performances of GE vs. DE solution

The economic assessment of both power generation technologies have been investigated and compared over a capacity range of 60–1640kW. The analysis has been carried out assuming the reference values of the influencing economic parameters described in the previous section, and using cost scale-up factor method. The obtained results are plotted in Figs. 1 to 6. Fig. 1 depicts the reduction of the Syngas cost as the capacity of energy production plant increases, showing the reduction of total investment cost of gasification plant when power capacity plant grows.

In particular, when the plant size increases from 60–1640KW the specific investment costs decreases from 2412.4 to 1728.5 US$/kW in case of *GE* technology, in the case of the *DE* technology decreases from 1752.1 to 714.4 US$/kW. Nevertheless, at any scale *GE* technology is characterized by higher TCI compared with *DE* technology. Such behaviour is enhanced as the power output increases (Fig. 2). The reason of this lack of competitiveness is that capital costs also depends on technological developments.

The reverse situation occurs when operating costs are examined, see Fig. 3, where *GE* technology is characterized by lower *TOC* with respect to *DE* technology. Such trend is argued due to consumption of Diesel fuel by *DE* technology.

When costs of generated energy are analyzed, *CEG* tendency shows that *GE* technology is characterized by a higher cost of generated energy than the *DE* technology. Such trend is supported by the results for energy generated and the technical variable like de-rating power (Fig. 4).

Also, the NPV trend in the considered size range has been investigated. As shown in Fig. 5 the economic performance of both technological solutions are strongly influenced by the scale effects: in particular over a capacity range of 60–1200kW in case of *GE* technology and a capacity range of 60–1640kW in case of *DE* technology only negative *NPV* values are reached, while positive *NPV* are associated to installed power in the range 1215–1640kW in case of *GE* technology and in any range in case of *DE* technology.

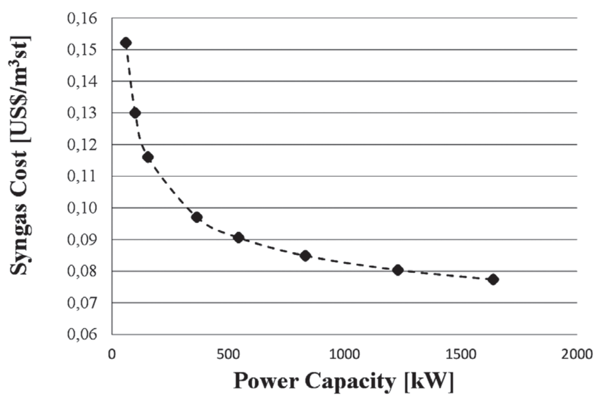

Figura 1. Cost of syngas per m^3 for different plant sizes

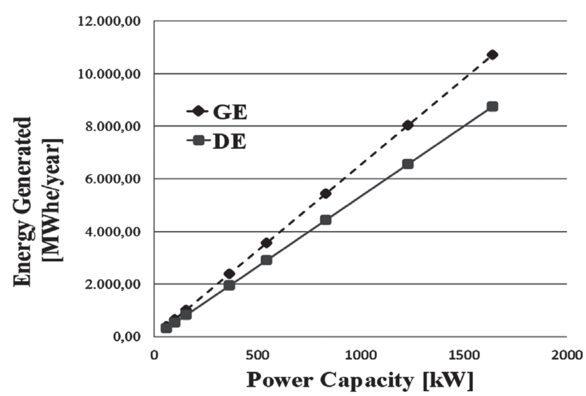

Figura 2. Energy generated for different plant sizes and technologies

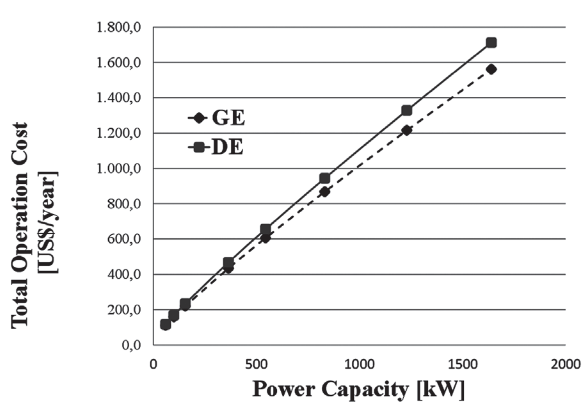

Figura 3. Total operation cost for different plant sizes and technologies

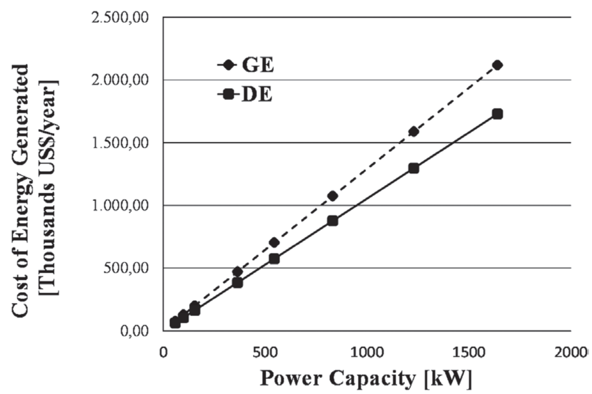

Figura 4. Cost of energy generated for different plant sizes and technologies

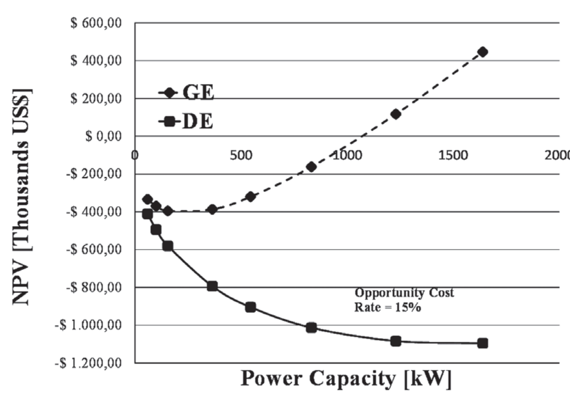

Figura 5. Effect of plant size and technology on NPV

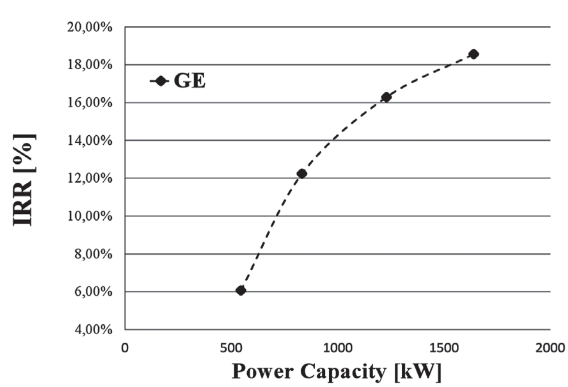

Figura 6. Effect of plant size and technology on IRR

Furthermore, Fig. 5 shows that at any size *GE* technology reaches higher *NPV* values compared to *DE* technology: such behaviour highlights the higher influence of TCI trend with respect to *TOC* trend on the *NPV* of analysed solutions.

Finally, *IRR* behaviour is showed in the Fig. 6, where over a capacity range of 545–1640kW, in case of *GE* technology, and any range of power, in case of *DE* technology, positives *IRR* values are reached. However, in this economic assessment a 15 % opportunity rate (*OR)* was used, hence IRR should be higher than *OR* to make this project viable. Therefore, this project is feasible in capacity range over 545kW for GE technology.

CONCLUSIONS

In this paper, an analysis has been carried out with the aim to investigate the economical profitability of biosolid utilization for direct production of electric energy. In particular, the economic assessment of two technologies (Gas Engine and Dual-fuel Engine) have been evaluated and compared over a capacity range from 60 to 1640kW. At the same time, taking into account the technical and economic variables of gasification plant and power generation plant.

The developed analysis has highlighted that scale effects are very significant for both the economic and logistic performances of considered bio-energy systems. More specifically, profitability of both GE and DE plant strongly improves with scale-up of plant size; at the same time logistic constraints on economic performances become less restrictive with increasing sizes. Furthermore, the comparison between the two analysed plant configurations in terms of capital and operating costs shows that DE is characterized by lower TCI but, at the same time, higher TOC respect to GE. However, under current technological and market conditions, without financing supports and taking into account modal values for the main economic and logistic parameters. As a result, at present, GE shows a better profitability. Nevertheless, from a TCI point of view and in a short time horizon (if adequate) a decrease of Diesel cost is adopted the investment profitability of DE strongly improves, becoming comparable with economic performance of GE. Furthermore, over a long-time perspective, technological developments and improvements related to the learning effects will reduce the capital costs of biomass gasification processes increasing the viability of both technologies.

The results suggested that a system of power generation by mean biosolids gasification, where the biosolids have high ash and moisture percentages in its composition, should be mixed with carbonaceous materials as coal, that increase the calorific value of the material; more energy available allows more stability of the pilot-scale process.

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