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Full Length Research Paper

Distribution of biomass and site location of combustion and gasification power plants in western Sicily

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The substitution of conventional fossil fuels with biomass for energy production results both in the reduction of greenhouse gases emissions and in the replacement of non-renewable energy sources. The use of biomass for energy production responds to the growing pressure of government policies towards the achievement of better environmental sustainability of power generation processes. This is particularly true for the agricultural areas of Sicily, where the realization of new economic dynamics can lead to development of a local economic system. However, at present, generating energy from biomass is rather expensive due to both technological limits related to low conversion efficiencies, and logistic costs. In particular, the logistics of biomass fuel supply is complex due to the limited period of availability and the scattered geographical distribution over the territory. The conversion of biomass to energy can be achieved using different production processes. In this paper, after an initial estimation of the energetic potential in the territory of Trapani, the size and the location of a biomass plant for direct production of electric energy by means of combustion and gasification conversion processes, has been investigated. GIS data of biomass growing was used to locate the appropriate sites and sizes of the power plants. Finally, the economical feasibility of biomass utilization has been evaluated over a capacity range from 10 to 30 M, taking into account total capital investments, revenues from energy sale and total operating costs. Moreover, the effect of main variable such as vehicle transport and biomass costs has been analyzed.

Key words: Plant location, agro-residues, economical feasibility.

INTRODUCTION

Biomass usage, specifically capturing energy from biomass that would otherwise decay, is one of many options available to mitigate the impact of the build-up of greenhouse gas (GHG) emissions from fossil fuel utilization (Hoffmann et al., 2010). In some locations, including south of Italy, good data on the cost of using biomass is not available, and this leads to a high degree of uncertainty in the cost of GHG credits that would be required to support such a facility. Sicily, in particular the Province of Trapani, is a particularly relevant place to evaluate the economics of generating power from biomass for two reasons. First, the region has abundant biomass resources from agricultural, in particular from wine and oil production. Agro-residue is in fact one of the important biomass resources and its efficient utilization is crucial for providing bio-energy, releasing risk of environmental pollution, and enhancing rural incomes (Chen et al., 2010). Second, the province has a good electrical network that can be used in order to transfer the energy. The combination of these two factors makes Trapani an ideal location for implementing power from biomass at a full commercial scale. The purpose of our research has been to estimate the cost and evaluate the cost sensitivities for major biomass utilization projects located in the Province of Trapani.

Our research has focused on major biomass resources located within oriental Sicily that are available in significant quantities for future power generation. Specifically, two such sources were identified: vineyard and olive residues from harvesting. Each of these

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Table 1. Biomass type in the province of Trapani

TRAPANI	Area[ha]	Productivity [ton/ha]	Productivity[t/a]	Pomace oil [ton]
Citrus groves	3479.7	1.8	6295.8	0
Vineyard	82648.8	2.5	206621.6	0
Olive	11034.9	1.9	20966.4	15724.3
Almond	0	2	0	0
Orchard	0	1.8	0	0

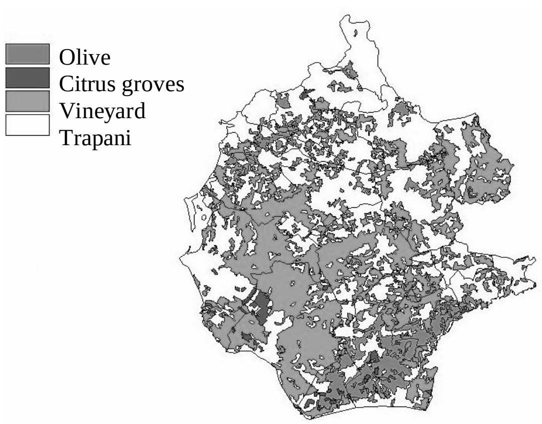

Figure 1. Biomass distribution.

sources is discussed in more detail. It is key to assessing the comparative economic optimum size of a biomass power generation facility, which is fuel specific. The variable component of biomass fuels is related to their transportation cost. Because biomass has a significant variable fuel cost component that varies with plant size. Previous studies have assessed biomass economics from the perspective of general models (Jenkins, 1997; Nguyen and Prince, 1996; Overend, 1982; Larson and Marrison, 1997; McIlveen-Wright et al., 2001). Dornburg and Faaji have developed a detailed study of small to medium scale biomass plants in a Dutch setting (Dornburg and Faaij, 2001). This study applies the general methodology to western Sicily. Good regional data is available on the cost of harvest and transport of biomass. Hence, this study draws on actual data to determine the cost and the optimum plant size and position in the western Sicily. Some earlier studies reported the development of computer programs and/or GIS data to identify the proper locations of power generation based on the geographical availability of biomass fuel, and other energy-related parameters (Papadopoulos and Katsigiannis, 2002; Voivontas et al., 2002; Graham et al., 2000; Mitchell, 2000).

This paper introduces a geographic information system (GIS) model that serves as the first step toward the development of an integrated decision support system for studying the impact of investments in renewable energy. The specific objective of building this GIS model is to locate potential sites for biomass farm installations based on the geographic and regulatory characteristics of the region, as well as to identify and characterize the potential for biomass utilization. In future work, this information will then serve as the basis for analyzing renewable energy policies and investments with respect to the tradeoffs between minimizing costs and minimizing emissions. The process of determining a suitable location for placing a biomass farm is a very specific form of the site selection problem, in which one or more sites are selected for use based on a series of characteristics such as cost or distance. GIS for site selection has been used for many purposes, such as warehouse location (Vlachopoulou et al., 2001), hazardous waste storage facilities (Jensen and Christensen, 1986), and aquaculture (Ross et al., 1993). The use of GIS for renewable energy site selection has also been considered previously at the local, regional, and national level (Short et al., 2009; Domínguez et al., 2007; Biberacher et al., 2008; Voivontas et al., 1998). Such previous research efforts have applied GIS to the individual exploration of solar (Muselli et al., 1999; Ramachandra, 2007; Arán et al., 2008), wind (Voivontas et al., 1998; Himri et al., 2008; Shamshad et al., 2003; Dutra and Szklo, 2008) and biomass (Perpiñá et al., 2009; Panichelli and Gnansounou, 2008; Ayoub et al., 2007) potential, and even to multiple resources simultaneously (Domínguez et al., 2007; Yue and Wang, 2006; Tegou et al., 2007; Schneider et al., 2007). This paper presents the GIS data of biomass in western Sicily. The simulation program was developed to locate suitable sites for the biomass power plants.

Biomass sources and energy content

The largest concentrated source of field-based agricultural residues in western Sicily are waste of the annual and periodic maintenance of the fields and in particular, in quantitative terms, vineyards, olive groves, citrus groves, almond and orchards. This biomass consists of branches that come from pruning, which in general are burned in the field by farmers. The raw material, properly collected, can be chipped or pelleted during harvesting or in another place. In the following table (Table 1), the area and the productivity for the different culture, are reported. The biomass distribution in the province of Trapani, reported in Figure 1, shows that

Table 2. Biomass energy contribution LHV (low heating value).

Type	Productivity[ton/year] dry fraction	LHV [MJ/kg]	Energy [MJ/year]	Pomace [ton/year]	LHV [MJ/kg]	Energy [MJ/year]
Vineyard	165,297	18	2,975,356,800	0	0	0
Olive	16,773	17.60	295,205,644.8	15,724.3	15.5	243,726,650

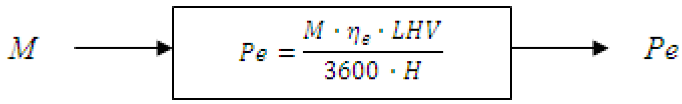

Figure 2. Plant model.

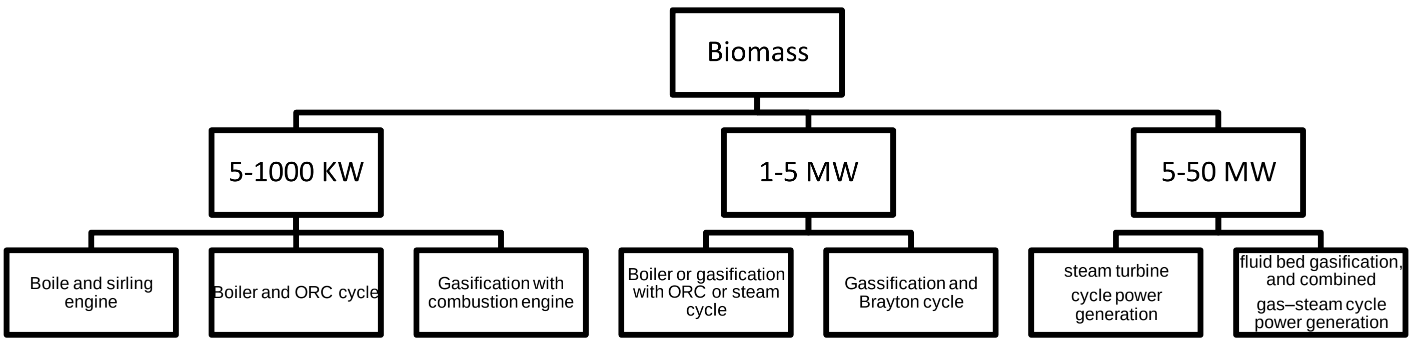

Figure 3. Thermo-chemical technologies.

the main biomass production derive from grapes and olives scraps. For this reason, our work focuses on these two typology of biomass. The maximum energy contribution for each type is reported in Table 2.

Where LHV is the low heating value with which is possible to determine the biomass energy and hence the maximum power plant available. From a system perspective, the techno-economic performances of biomass energy production plants are characterized by the overall energy conversion efficiency, which dictates the required biomass amount for a given power output and, at the same time, is strongly dependent on the adopted technology and the plant size. As a consequence, for the purpose of this work, the plants are simply modelled as black boxes having a transfer function between the input biomass flow rate *M* (t/year) and the net electrical energy power output P_e (MW). More specifically P_e results directly proportional to the biomass amount *M*, the biomass low heating value (LHV) (kJ/kg), and the plant energy conversion efficiency ηe, and inversely proportional to the plant annual operating hours *H* (h/year), as shown in Figure 2. In this work, according to literature (Graham et al., 2000; Mitchell, 2000) we have considered a conversion efficiency value of 0.3. The net electrical energy power output P_e can be calculated with the following equation:

$$Pe = \frac{E_{tot} \cdot \eta_e}{3600 \cdot H} \approx 33 \text{ MW} \quad (1)$$

Plant configuration

Biomass may be used to meet a wide variety of energy needs, including generating electricity, providing process heat for industrial facilities, heating homes and fuelling vehicles. The conversion of biomass to such useful forms of energy, also called bio-energy, can be achieved using a number of different technological solutions that can be separated into two basic categories, namely thermo chemical processes and biochemical/biological processes. Thermal utilization processes have been chosen for analysis because they are quite mature technologically but have not yet reached their full diffusion potential. Figure 3 shows the thermo chemical technologies for the different range of plant power (Riva, 2000). The choice of appropriate conversion process is influenced by many key factors, such as type and quantity of biomass resource, energy carriers and the end-use applications, environmental standards and economic conditions.

In our study, for the power considered, two technological solutions have been selected for the following analysis, which represent typical plant architectures for

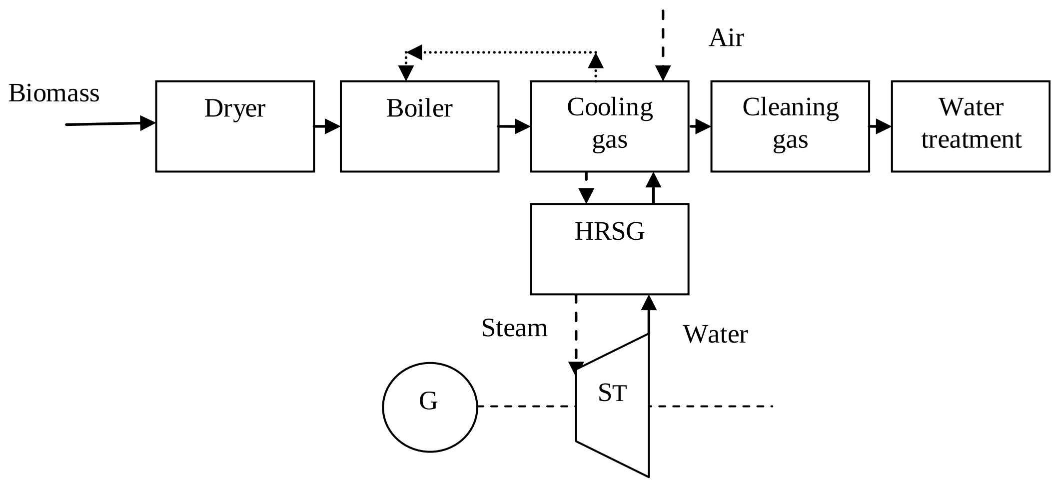

Figure 4. C/St Cycle.

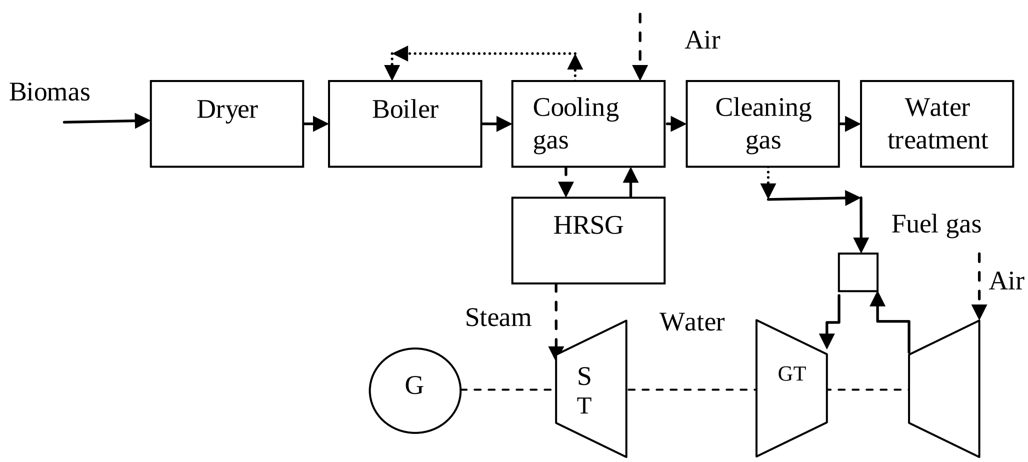

Figure 5. G/CC Cycle.

power generation:

1) Fluid bed combustion, followed by steam turbine cycle power generation (C/ST);
2) Fluid bed gasification, followed by a combined gas–steam cycle power generation (G/CC).

The C/ST configuration (Figure 4) is composed by a biomass storage and handling section, and a combustion and steam generation section constituted by a fluid bed combustor and a boiler that produces steam utilizing the hot gases generated by the combustion process. Finally, the steam is fed into the energy recovery section where it expands in a turbine generating electric energy. The G/CC configuration (Figure 5) is composed by a storage and handling section analogous to C/ST solution; subsequently the biomass is supplied to a heat recovery dryer in order to reach a degree of moisture content compatible with the following gasification process. The obtained dry biomass is then fed into a pressurized fluid bed gasifier and the produced gas stream is then fed into a hot gas filtration section in order to collect the contained dust, and then is utilized as fuel into the combined gas–steam cycle for the electric energy. Considering that the maximum available power is 33 MW, for each plant configuration, we have chosen three different power sizes, 30, 20 and 10 MW, respectively.

Plant location

In order to determine the feasibility of a biomass plant in the western Sicily, the GIS data are used to localize suitable locations for power plants. The biomass procurement area is assigned to be a circle having the power plant at its centre. The centre of the circle moves along the dotted line, where high-voltage transmission line is available for grid connection. It moves in steps of

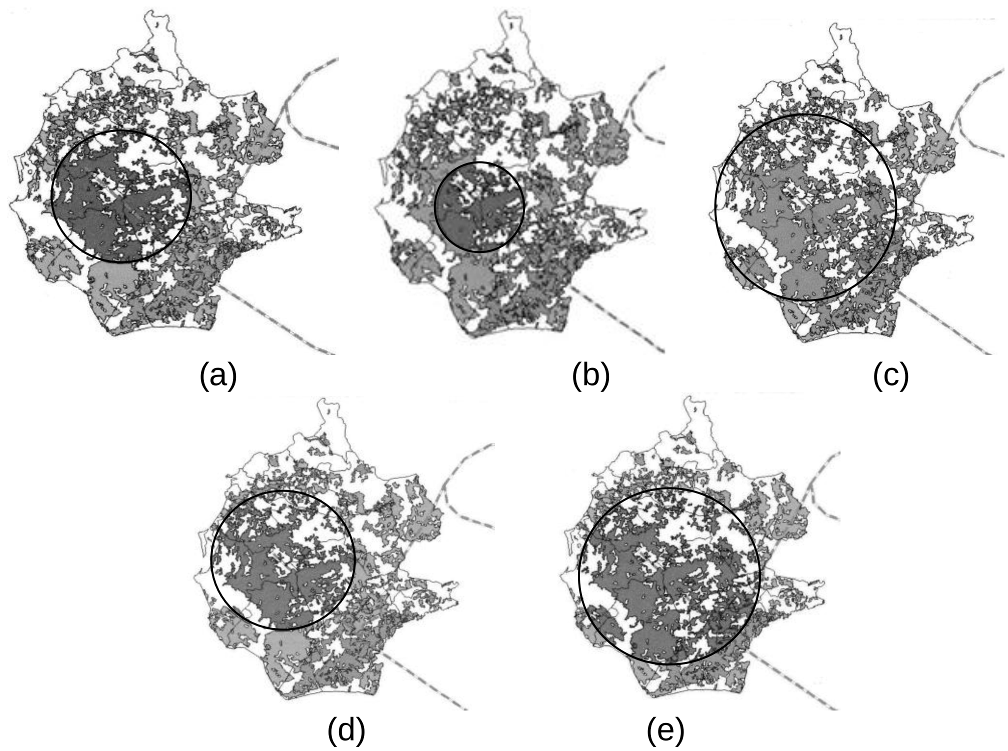

Figure 6. Procurement area for the different configurations. a) C/St 10 MW b) G/CC 10 MW c) C/St 20 MW d) G/CC 20 MW e) G/CC 30 MW.

50 km. The GIS program calculates the area-based fuel availability density and suggests the smallest procurement area radius for the different plant sizes. In Figure 6, for each plant size and type, the procurement area is reported. The procurement area for steam turbine cycle power generation configuration has always a bigger surface than the combined gas–steam cycle power generation configuration. The C/ST configuration for the plant size of 30 MW is not reported because, in order to generate this power, it would need to use the entire biomass of the province of Trapani. Clearly, such solution would be unfeasible because it is always necessary to consider the intrinsic stochasticity in the biomass procurement.

Economical analysis

The economic evaluation of analyzed plant configurations has been carried out on the basis of total capital investment (TCI, €), total operating cost (TOC, €/year) and revenues from sale of produced electric energy (R, €/year). In this way, the economic profitability of both C/ST and G/CC solutions has been evaluated and the results have been presented on the basis of NPV values. More specifically, TCI costs have been evaluated as the sum of all direct and indirect plant costs. In particular, total direct plant costs (DC) include power generation costs, piping costs, electrical costs, civil works costs, direct installation costs, auxiliary services costs, instrumentations costs and site preparation costs, while total indirect plant costs (IC) include engineering and start-up costs. The costs of pieces of equipment that compose the three main plant sections namely power generation, biomass storage-handling and fumes treatment have been calculated utilizing the correlation listed in Table 3. Piping, electrical and civil works costs resulting from interpolation of experimental and literature data (Tsatsaronis et al., 1986; Miccio et al., 1998; Peters and Timmerhaus, 1991; Turton et al., 1998; US Environmental Protection Agency, 2002; Ferrari and Persona, 1993).

Finally direct installation, auxiliary services, instrumentations, site preparation, engineering and start-up costs have been calculated as a percentage of power generation costs. Numerical values for such percentages have been derived from literature data (Turton et al., 1998; US Environmental Protection Agency, 2002; Ferrari and Persona, 1993). All the considered items of cost utilized for TCI costs estimation have been summarized in Table 4. Total operating costs have been determined as the sum of operating labour costs, purchased biomass costs, biomass transport costs, and maintenance costs as reported subsequently.

Table 3. The adopted correlations.

Plant section	Pe correlation	
	Cost correlation [€]	
	C/ST	G/CC
A) Power generation		
Boiler	1 340 000 Pe^0.694	-
Steam turbine	633 000 Pe^0.398	633 000 PST^0.398
Gasifier	**-**	1 600 MG/CC^0.917
Turbo gas group	-	3 800 PGT^0.754
Heat-recovery steam generator	-	6 540 PHRSG^0.81
Condenser	398 000 Pe^0.333	398 000 PST^0.333
Heat exchanger (cooling Pater)	51 500 Pe^0.5129	51 500 PST^0.5129
Alternator	138 300 Pe^0.6107	138 300 PST^0.6107
Fans	35 300 Pe^0.3139	35 300 PST^0.3139
Condensate extraction pumps	9000 Pe^0.4425	9 000 PST^0.4425
Feed pumps	35 000 Pe^0.6107	35 000 PST^0.6107
Pumps	28 000 Pe^0.5575	28 000 PST^0.5575
Biomass storage-handings		
Biomass storage	114 100 Pe^0.5575	114 100 Pe^0.5575
Biomass handing	46 600 Pe^0.9554	46 600 Pe^0.9554
Compressor and dryers	11 400 Pe^0.5575	11 400 Pe^0.5575
Emergency diesel	36 200 Pe^0.1989	36 200 Pe^0.1989
Heat-recovery dryer	-	9 600 MG/CC^0.65
Fumes treatment		
NOx and Sox removal equipments	126 000 Pe^0.5882	126 000 Pe^0.5882
Fumes filtration	66 600 Pe^0.7565	66 600 Pe^0.7565
Ashes storage	88 300 Pe^0.3139	88 300 Pe^0.3139
Ashes extraction	93 500 Pe^0.4425	93 500 Pe^0.4425
Fans	28 500 Pe^0.5575	28 500 Pe^0.5575
Fumes ductPorks	51 500 Pe^0.5129	51 500 Pe^0.5129
Discharge stack	28 500 Pe^0.5575	28 500 Pe^0.5575
B) Piping		
Fire fighting tank	85 700 Pe^0.1040	85 700 Pe^0.1040
Fire fighting components	5300 Pe^0.7565	5300 Pe^0.7565
Fire fighting system	6600 Pe^0.7565	6600 Pe^0.7565
Industrial water tank	9300 Pe^0.7565	9300 Pe^0.7565
Tanks	10 300 Pe^0.5129	10 300 Pe^0.5129
Heat exchanger	34 200 Pe^0.5575	34 200 Pe^0.5575
Degasifier	17 100 Pe^0.5575	17 100 Pe^0.5575
By-pass valves	20 600 Pe^0.5129	20 600 Pe^0.5129
High pressure valves	28 500 Pe^0.5575	28 500 Pe^0.5575
Control valves	10 100 Pe^0.6756	10 100 Pe^0.6756
Valves	28 500 Pe^0.5575	28 500 Pe^0.5575
Pipes	42 300 Pe^0.885	42 300 Pe^0.885
Pipe rack	12 100 Pe^0.686	12 100 Pe^0.686
C) Electrical		
Switches	13 400 Pe^0.3672	13 400 Pe^0.3672
Electric protection	44 700 Pe^0.2266	44 700 Pe^0.2266
Transformer	64 600 Pe^0.4289	64 600 Pe^0.4289
Auxiliary transformer	14 000 Pe^0.4425	14 000 Pe^0.4425
Electrical equipment	409 100 Pe^0.6415	409 100 Pe^0.6415

Table 3. Contd.

Assembling	186 900 Pe^0.7137	186 900 Pe^0.7137
D) Civil works		
Buildings yard guard	70 100 Pe^0.4425	70 100 Pe^0.4425
Conditioning plant and ventilation system	23 400 Pe^0.6328	23 400 Pe^0.6328
Civil works	1 337 400 Pe^0.3672	1 337 400 Pe^0.3672
Personnel of building yard	133 700 Pe^0.3672	133 700 Pe^0.3672
Buildings yard facilities	13 300 Pe^0.7565	13 300 Pe^0.7565
Wastewater treatment	6900 Pe^0.6107	6900 Pe^0.6107

Table 4. Components of total capital investment costs evaluation.

Component of total capital investment costs evaluation	
Cost component	**Factor**
Power generation costs	A
Piping	B
Electrical	C
Civil works	D
Direct installation cost	E = 0.30 A
Auxiliary services	F = 0.15 A
Instrumentation and controls	G = 0.10 A
Site preparation	H = 0.10 A
Total direct plant costs (DC)	DC = A+B+C+D+E+F+G+H = 1.65 A+B+C+D
Engineering	K = 0.12 A
Start-up	W = 0.10 A
Total indirect plant costs (IC)	IC = K + W = 0.22 A
Total capital investment (TCI)	TCI = DC + IC = 1.87 A+B+C+D

Labour costs

$$C_l = C_{ls} \cdot N_l \ (€/anno) \quad (2)$$

C_{ls} is the employed personnel average fee (34 k€/year·unit); N_l is the total annual working personnel, assumed variable with the plant size and calculated considering four shifts in rotation. More specifically, according to literature data (Piano Energetico Regione Sicilia, 2008), the operators number has been varied in the range 12 to 36; For 10 to 30 mW Plant size we have hypothesized a number of 18 N_l.

Purchased biomass costs

$$C_c = \pi \cdot R^2 \cdot p \cdot C_{cs} \ (€/anno) \quad (3)$$

C_{cs} is the specific purchased biomass costs to the producer (€/ton) and p is the density (ton/km^{2}year). C_{cs} can vary between 35 e 60 €/ton. Figure 7 shows the trend in costs according to biomass quantity in the Province of Trapani.

Biomass transport costs

$$C_t = \int_0^R \int_0^{2\pi} \left(C_{ts} \cdot p \cdot R^2\right) dR\, d\alpha = \left(\frac{2}{3} \cdot \pi \cdot p \cdot C_{ts} \cdot R^3\right) \quad (4)$$

C_{ts} is the specific transport costs (€/ton·km). The C_t was calculated assuming that the biomass is concentrated at 2/3 of the radius of the catchment circular area necessary to produce the amount M of biomass feeding the plant, starting from a uniform biomass distribution density p (ton/km^{2}year).In Figure 8, the trend of the transport costs is reported for different vehicles according with the distance in the Province of Trapani.

Maintenance costs

$$C_{mr} = TCI \cdot kr \ (€/year) \quad (5)$$

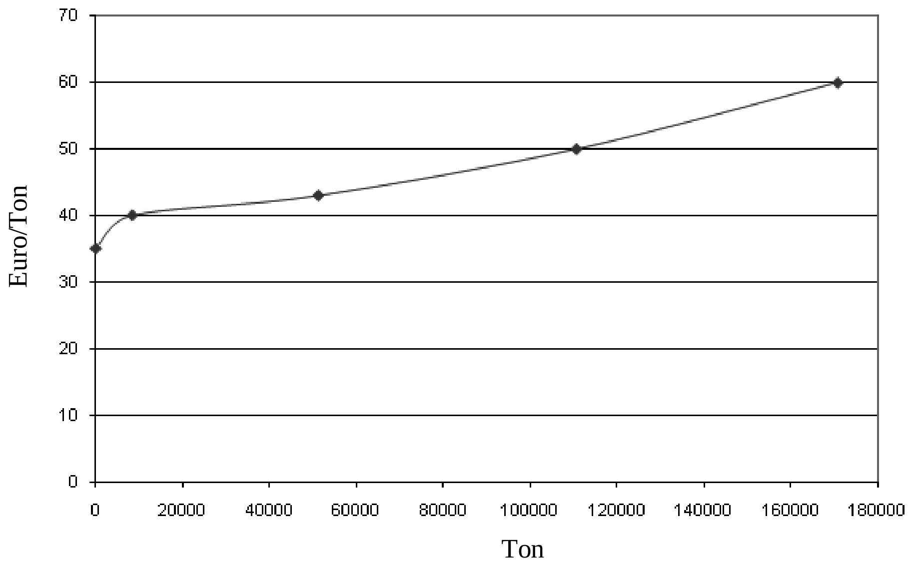

Figure 7. Specific Purchased biomass costs (Alberti et al., 2003).

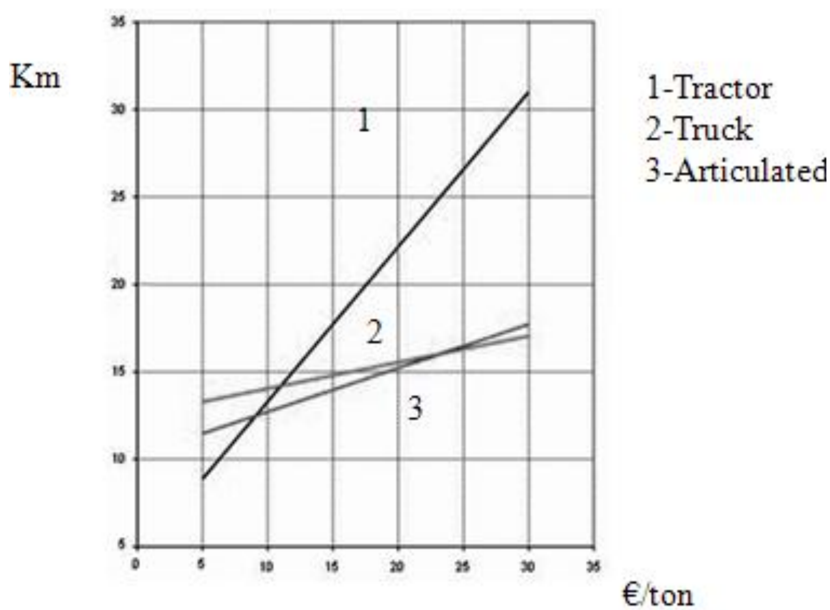

Figure 8. Transport cost (Piano Energetico Regione Sicilia, 2008).

Maintenance costs C_{mr} (€/year) has been calculated as a percentage of *TCI* using the factor *kr* = 0.02. Finally, revenues *R* from sale of produced electric energy have been evaluated as:

$$R=P_e \cdot EP \ (€/year) \quad (6)$$

EP (20 €cent/kWh) is the current market price of produced electricity (Prezzo di riferimento individuato dal Gestore Servizi Elettrici per i certificati verdi per l'anno, 2005), without government subsidies and P_e is the net electric energy power plant output.

RESULTS

The economic performance and profitability of both combustion and gasification based solutions have been investigated and compared over a capacity range of 10 to 30 MW. The analysis has been carried out assuming the

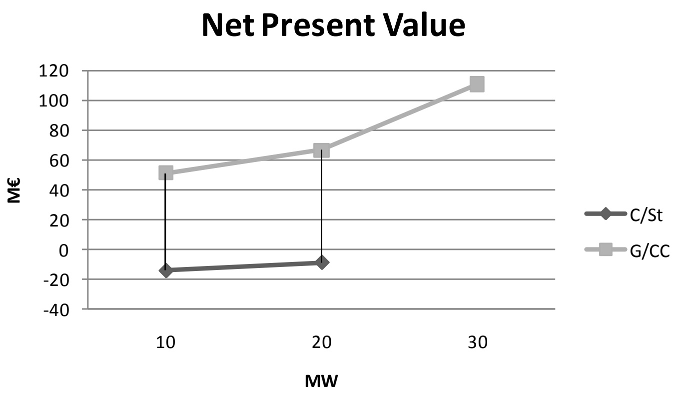

Figure 9. Effect of plant size and production process on NPV.

reference values of the influencing economic parameters described previously. The obtained results are reported in Figures 9. In particular, when the plant size increases from 10 to 30 MW the specific investment costs decrease in both the solutions considered. Such considerations are in good agreement with available literature data (Dornburg and Faaij, 2001; Bridgwater, 1995; Bridgwater et al., 2002). Nevertheless, at any scale G/CC solution is characterized by higher TCI compared with C/ST solution. Such behavior is enhanced as the power output increases. The reason of this lack of competitiveness is that capital costs also depend on technological developments. Particularly under current technological conditions, combustion systems can be considered a mature approach to electric generation from biomass, while gasification is still an emerging technology, representing the latest generation of bio-energy conversion processes. As shown in Figure 9, the economic performance of both technological solutions are strongly influenced by the scale effects: in particular in the case of C/ST solution for both the size considered only negative NPV values are reached, while positive NPV are associated to installed G/CC solution in the range 10 to 30 MW.

In order to evaluate the effect of biomass cost and vehicle transport cost to the feasibility of the three G/CC plants, the payback time for each solution has been analyzed. Considering a range between 42 and 60 €/ton for biomass cost, the payback time undergoes small changes for all the solution analyzed. In particular for 10 MW plant the payback vary between 5 and 6 years, for 20 MW is always 4 years and finally for 30 MW is between 2 and 3 years. On the other hand, considering a range between 5 and 25 €/ton for transport cost, the payback time for the first two scenarios (10 and 20 MW) is strongly influenced by it (between 4 and 13 years in the first case and between 3 and 6 years in the second). While for 30 MW plant the payback time vary between 2 and 3 years. As a result, at present, gasification-based solution shows a better profitability for 30 MW size.

Conclusions

In this paper, an extensive analysis has been carried out with the aim to investigate the economical profitability of biomass utilization for direct production of electric energy in western Sicily. In particular, the economic performances and profitability of both combustion and gasification based approaches have been evaluated and compared over a capacity range from 10 to 30 MW. At the same time, taking into account the critical logistic aspects related to the overall bioenergy chain, the impact of main logistic variables on the economics of such technological solutions has also been examined in function of conversion plant capacity.

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 C/ST and G/CC plant configurations strongly improves with scale-up of plant size; at the same time logistic constraints on economic performances become less restrictive with increasing sizes. Gasification-based solution more effectively responds to adverse logistic conditions, characterized by high biomass specific purchased costs and biomass specific transport costs, especially in case of large plant capacity (30 MW).

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