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Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables

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Abstract

The substitution of conventional fossil fuels with biomass for energy production results both in a net reduction of greenhouse gases emissions and in the replacement of non-renewable energy sources. However, at present, generating energy from biomass is rather expensive due to both technological limits related to lower conversion efficiencies, and logistic constraints. In particular, the logistics of biomass fuel supply is likely to be complex owing to the intrinsic feedstock characteristics, such as the limited period of availability and the scattered geographical distribution over the territory. In this paper, the economical feasibility of biomass utilization for direct production of electric energy by means of combustion and gasification-conversion processes, has been investigated and evaluated over a capacity range from 5 to 50 MW, taking into account total capital investments, revenues from energy sale and total operating costs, also including a detailed evaluation of logistic costs. Moreover, in order to evaluate the impact of logistics on the bio-energy plants profitability, the effects of main logistic variables such as specific vehicle transport costs, vehicles capacity, specific purchased biomass costs and distribution density, have been examined. Finally, a mapping of logistic constraints on plant profitability in the specified capacity range has been carried out.

Keywords: Biomass energy; Combustion; Gasification; Economic analysis; Logistics.

1. Introduction

Biomass energy utilization has gained particular interest in recent years due to the progressive depletion of conventional fossil fuels, that calls for an increased use of renewable energy sources. Moreover, the moderate sulphur and greenhouse gas emissions associated with the use of biomass for energy production respond to the growing pressure of government policies about achievement of better environmental sustainability of power generation processes in terms of air pollution control [1].

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Nomenclature

AD	ash disposal costs (€ year^{-1})
AT	ash transport costs (€ year^{-1})
C_{AD}	ash landfilling fee (€ t^{-1})
C_{AT}	specific ash transport cost (€ t^{-1})
C_{B}	specific purchased biomass cost (€ t^{-1})
C_{P}	employed personnel average fee (€ year^{-1})
C_{TP}	transport operations employed personnel fee (€ year^{-1})
C_{VT}	specific vehicle transport cost (€ km^{-1})
D_{B}	biomass distribution density (t km^{-2} year^{-1})
d_{T}	total annual travelled distance (km year^{-1})
DC	total direct plant costs (€)
EP	market price of produced electricity (€ kWh^{-1})
F_k	annual cash flow at kth year (€ year^{-1})
FC	financial charges (€ year^{-1})
$I\&G$	insurance and general costs (€ year^{-1})
i	discount rate (% year^{-1})
IC	total indirect plant costs (€)
L	operating labour costs (€ year^{-1})
LHV	low heating value (kJ kg^{-1})
M	biomass flow rate (t year^{-1})
M_{A}	ash flow rate (t year^{-1})
M_{HRSG}	steam flow rate produced by heat-recovery steam generator (kg h^{-1})
MAN	maintenance costs (€ year^{-1})
n	number of employed personnel
n_{T}	number of employed personnel in transport operations
N	plant life (year)
NPV	net present value (€)
OH	plant annual operating hours (h year^{-1})
PB	purchased biomass costs (€ year^{-1})
PE	purchased equipment costs (€)
R	revenues from sale of produced energy (€ year^{-1})
s	interest rate for borrowed capital (% year^{-1})
T	taxes (€ year^{-1})
TB	biomass transport costs (€ year^{-1})
TCI	total capital investment (€)
TOC	total operating costs (€ year^{-1})
TP	personnel costs (€ year^{-1})
V	vehicles costs (€ year^{-1})
VC	vehicles capacity (t vehicle^{-1})
W_{NE}	net electric energy power output (MW)
W_{ANE}	net electric energy power output available for sale (MW)
W_{GT}	gas turbine power (MW)
W_{ST}	steam cycle net power (MW)

Greek letters

η_{e}	plant overall electrical efficiency (%)
Δ	difference

Acronyms

C/ST	fluid bed combustor and steam turbine cycle
G/CC	fluid bed gasifier and combined gas–steam cycle
MSW	municipal solid waste

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 thermochemical processes and biochemical/biological processes.

A process options classification based on the type of final energy products is presented in Table 1. Focusing the attention on thermochemical processes, the main technological solutions are the following [1–6].

- Combustion, used to convert biomass energy into heat, mechanical power or electricity. Net conversion efficiencies range from 20% to 40%, even if higher values may be obtained when the biomass is co-combusted in coal-fired power plants. The most utilized combustors for biomass applications are either stoker-fired and

Table 1
Thermochemical and biochemical processes classification [2]

Conversion processes	Technological solutions	Final products
Thermochemical processes	Combustion	• Steam • Process heat • Electric energy
	Gasification	• Steam • Process heat • Electric energy • Fuel gas methane
	Pyrolysis	• Charcoal • Bio-coal • Fuel gas
Biochemical processes	Fermentation Anaerobic digestion	• Ethanol • Water for irrigation • Compost • Biogas

fluid bed designs, even if the latter are rapidly becoming the preferred technology because of low amount of NO_x emissions.

- Gasification, which converts biomass into a combustible gas mixture of carbon monoxide, hydrogen and methane, characterized by a low calorific value, that can be burnt to produce heat and steam, or used in gas turbines cycles to obtain electricity. Conversion efficiencies up to 50% may be reached if biomass integrated gasification/combined gas–steam cycles are utilized. Although many biomass gasification processes have been developed commercially, only the fluid bed configurations are being considered in application ranging from 5 to 300 MW.
- Pyrolysis, that is the conversion of biomass into a liquid fraction (bio-oil), a solid fraction (charcoal) and a gaseous fraction, by heating the biomass in absence of air.

As far as biochemical processes are concerned, the main conversion options are the following [1,2,7]:

- Fermentation, that is used to produce ethanol from biomass containing sugar. Usually sugar is extracted through a crushing process; then it is mixed with water and yeast, and kept warm in a fermentator. The yeast breaks down the sugar, converting it to methanol. A distillation process removes the water and produces concentrated ethanol which is drawn off and condensed into a liquid form.
- Anaerobic digestion, that is the conversion of biomass into biogas, mainly composed of methane and carbon dioxide, by means of bacterial action in the absence of oxygen. This is a commercially proven technology widely used for treating high moisture content biomass such as MSW.

Another technology is represented by mechanical extraction processes, able to produce energy in forms of bio-diesel. However, currently the cost of bio-diesel compared with fossil fuel makes this last conversion option strongly uncompetitive, even if an increasing attention of government policies about achievement of better air-quality standards may rapidly change this situation [2].

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, economic conditions.

Biomass resources include wood and wood waste, agricultural crops (i.e. short rotation woody, herbaceous woody, sugar and oilseed crops) and their waste by-products, municipal solid waste, residues from agro-industrial and food processes, aquatic plants such as algae and water weeds.

Apart from the amount of energy potentially available from given biomass species, other properties that dictate the most suitable form of energy conversion process are represented by moisture content, cellulose/lignin ratio and ash content. More specifically high moisture content biomass ($>50\%$), such as herbaceous plants and sugarcane, lends itself to "wet" conversion process, for example fermentation and anaerobic digestion, while a "dry" biomass (moisture content $<50\%$), i.e. wood chips, is more suited to thermochemical processes such as combustion and gasification. As far as the cellulose/lignin ratio is concerned, this parameter affects only biochemical conversion processes; in particular biomass with high proportion of cellulose instead of lignin, such as hardwood characterized by 25–50% of cellulose and 20–25% of lignin, is more compatible with fermentation processes. Finally, with regards to ash content, low percentages are preferred for both thermochemical and biochemical processes because, given the available energy output of the adopted conversion technologies, the resulting end-product amount is proportionately reduced [8]. However, it is frequently the form in which the energy is required that drives the technology solution selection, followed by the type and quantity of available biomass.

Despite the widely agreed potential of bio-energy utilization, key problems regarding the use of biomass remain the limited availability in terms of time, owing to biomass seasonality, and the scattered geographical distribution over the territory that make the collection, transport and storage operations complex and expensive. These critical logistic aspects strongly affect the economic and energy performances of bio-energy conversion systems, introducing limitation on their suitability.

Furthermore, the large number of possible combination of various biomass sources (such as wood and wood waste, agricultural crops and their by-products, energy crops, municipal solid waste (MSW), residues from agro-industrial and food processes), the different available conversion approaches, and diverse end-use applications (power/heat generation and transport fuel) make difficult the choice of the optimal solution from either a cost and energy point of view [2].

Having this in mind, in the present work a system analysis is presented in order to investigate the economical feasibility of biomass utilization for direct production of electric energy through combustion and gasification processes, considering the technical, organizational and logistical issues related to the overall bio-energy chain. Thermal utilization processes have been chosen for analysis because they are quite mature technologically but have not yet reached their full diffusion potential. Furthermore, they enable direct production of electric energy in a fairly wide range of plant sizes, thus allowing either centralized or decentralized applications representing the most promising solutions for biomass-to-energy industrial applications. More specifically in the paper the two considered reference thermochemical utilization processes, have been at first characterized in terms of plant configuration and performances. A biomass composed of agricultural crops by-products, agro-industrial and wood wastes, has been assumed, while energy recovery sections based on steam or combined gas–steam cycles have been considered. Afterwards, plant costing models have been developed, together with an overall economic model taking into account total capital investments, revenues from energy sale and total operating costs including logistic costs.

Economic profitability of bio-energy plants has been then evaluated in terms of net present value (NPV) over a capacity range of 5–50 MW, also considering the influence of project financing policy. Furthermore, the effect of main logistic variables, such as specific vehicle transport costs, vehicles capacity, specific purchased biomass costs and distribution density, has been examined in function of plants size. Finally, a mapping of logistic constraints on plant profitability in the specified capacity range has been carried out. As an example, for each plant size, the maximum specific vehicle transport costs and the minimum biomass distribution density associated to a non-negative NPV values have been identified.

2. Performances and costs estimation

In order to assess bio-energy plants profitability and the impact of logistic variables, at first a comprehensive cost-estimating procedure has to be established with reference to the considered energy production processes, followed by an overall economic evaluation model able to capture the effects of varying parameters values on plant costs and revenues. In the following, such models are developed and numerical results are given assuming at first modal values of the influencing variables representative of usual applications, regardless of a specific time or place. To give more generality to the analysis the influence of the major parameters will be evaluated resorting to a sensitivity analysis, while a thorough parametric analysis over a wide range of values of the logistic variables completes the study.

2.1. Plant configurations

As aforementioned two technological solutions have been selected for the following analysis which represent typical plant architectures for power generation:

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

As far as the *C*/ST solution is concerned the assumed plant configuration 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. Fumes generated by combustion process are treated in an air pollution control section constituted by a dry adsorption system and a catalytic reactor for SO_x and NO_x removal, respectively, together with a fabric filter for dust collection before the discharge to the stack.

As far as the *G*/CC solution is concerned the assumed plant configuration is composed by a storage and handling section analogous to that of *C*/ST solution; subsequently the biomass is supplied to a heat recovery dryer in order to reach a degree of moisture content (about 20%) compatible with the following gasification process. The obtained dry biomass is then fed into a pressurized fluid bed gasifier (15 bar) with the aim to produce a gas stream having a low heating value of 5.4 MJ/Nm^3. 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 generation. An air pollution control section similar to the one described for *C*/ST solution assures combustion fumes depuration before the discharge to the stack.

2.2. Plant performances evaluation

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 $year^{-1}$) and the net electrical energy power output W_{NE} (MW). More specifically W_{NE} results directly proportional to the biomass amount M, the biomass low heating value (LHV) (kJ kg^{-1}), and the plant energy conversion efficiency η_e, and inversely proportional to the plant annual operating hours OH (h $year^{-1}$), as shown in Fig. 1.

Nevertheless, the choice of η_e values that will be assumed for W_{NE} computation strongly depends both on the assumed plant configuration and the considered plant size. In other words, η_e is a function of W_{NE}. Having this in mind, in this work, relying on literature data [9,10], proper trends of overall efficiency vs. plant size have been assumed for both conversion processes as shown in Figs. 2 and 3. Reference literature data are reported as dashed lines for comparison purposes.

Therefore the algorithm adopted to estimate the biomass flow rate M, required to produce the desired electrical energy power output W_{NE}, is shown in Fig. 4, resorting to the assumed

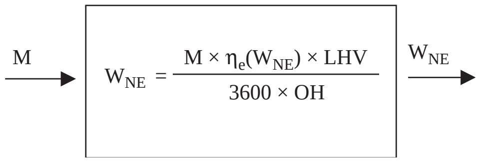

Fig. 1. Plant model and the relative transfer function.

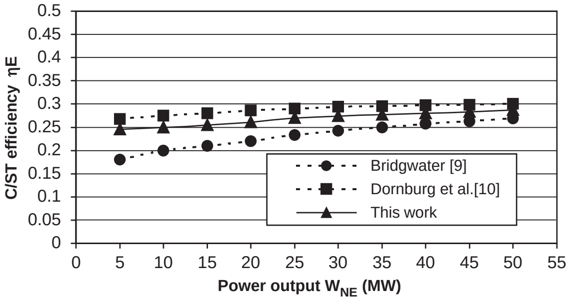

Fig. 2. Overall efficiency vs. plant size for C/ST solutions.

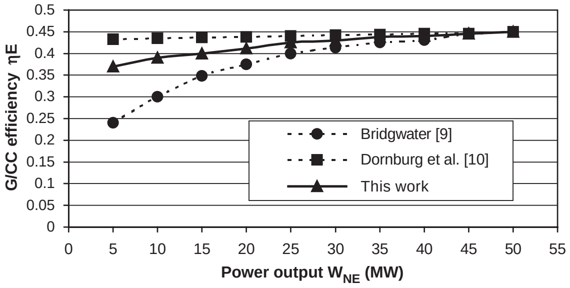

Fig. 3. Overall efficiency vs. plant size for G/CC solutions.

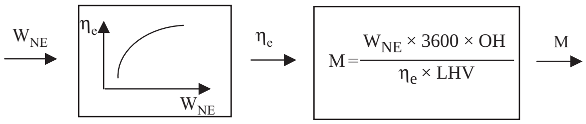

Fig. 4. Flow-chart of adopted algorithm.

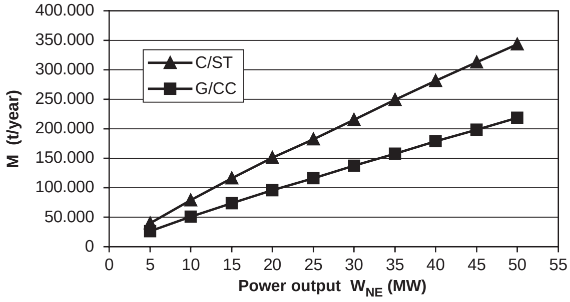

Fig. 5. Estimated yearly biomass consumption (M [t year^{-1}]) for different plant sizes and production processes.

efficiency–power output relationship (Ref. to Figs. 1–3).

The obtained biomass consumptions values for both C/ST and G/CC solutions are shown in Fig. 5, considering a capacity range from 5 to 50 MW, a biomass LHV of 14 630 kJ kg^{-1} referring to biomass with an average moisture content of 30%, and a full-load plant operation time of 8000 h year^{-1}.

2.3. Equipment costs evaluation

Purchased equipment costs PE (€) have been evaluated on the basis of correlations resulting from interpolation of experimental and literature data [11–16] having the following general expression

$$PE = aS^b, \tag{1}$$

where a and b are specific coefficients, while S is a characteristic equipment parameter. In particular, equipment costs have been parameterized in function of the plant net electric power output W_{NE} (MW), the power generated by steam cycle W_{ST} (MW), the gas turbine power W_{GT} (kW), the biomass flow rate $M_{G/CC}$ (kg h^{-1}) feeding the gasifier, the steam flow rate produced by heat-recovery steam generator M_{HRSG} (kg h^{-1}). The adopted correlations for purchased equipment costs evaluation are illustrated in Table 2. The reliability of such equations has been verified by resorting to a comparison between calculated costs and actual cost data obtained from vendors.

2.4. The overall economic model

The economic evaluation of analysed plant configurations has been carried out on the basis of total capital investment (TCI, €), total operating cost (TOC, € year^{-1}) and revenues from sale of produced electric energy (R, € year^{-1}). 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 total PE costs, piping costs, electrical costs, civil works costs, direct installation costs, auxiliary

Table 2
The adopted purchased equipment correlations [11–16]

Plant sections	PE correlation (€)	
	C/ST	G/CC
Power generation		
Boiler	$1\,34\,0000\,W_{\mathrm{NE}}^{\;0.694}$	—
Steam turbine	$633\,000\,W_{\mathrm{NE}}^{\;0.398}$	$633\,000\,W_{\mathrm{ST}}^{\;0.398}$
Gasifier	—	$1600\,M_{G/\mathrm{CC}}^{\;0.917}$
Turbogas group	—	$3800\,W_{\mathrm{GT}}^{\;0.754}$
Heat-recovery steam generator	—	$6540\,M_{\mathrm{HRSG}}^{\;0.81}$
Condenser	$398\,000\,W_{\mathrm{NE}}^{\;0.333}$	$398\,000\,W_{\mathrm{ST}}^{\;0.333}$
Heat exchanger (cooling water)	$51\,500\,W_{\mathrm{NE}}^{\;0.5129}$	$51\,500\,W_{\mathrm{ST}}^{\;0.5129}$
Alternator	$138\,300\,W_{\mathrm{NE}}^{\;0.6107}$	$138\,300\,W_{\mathrm{ST}}^{\;0.6107}$
Fans	$35\,300\,W_{\mathrm{NE}}^{\;0.3139}$	$35\,300\,W_{\mathrm{ST}}^{\;0.3139}$
Condensate extraction pumps	$9000\,W_{\mathrm{NE}}^{\;0.4425}$	$9000\,W_{\mathrm{ST}}^{\;0.4425}$
Feed pumps	$35\,000\,W_{\mathrm{NE}}^{\;0.6107}$	$35\,000\,W_{\mathrm{ST}}^{\;0.6107}$
Pumps	$28\,000\,W_{\mathrm{NE}}^{\;0.5575}$	$28\,000\,W_{\mathrm{ST}}^{\;0.5575}$
Biomass storage-handing		
Biomass storage	$114\,100\,W_{\mathrm{NE}}^{\;0.5575}$	$114\,100\,W_{\mathrm{NE}}^{\;0.5575}$
Biomass handing	$46\,600\,W_{\mathrm{NE}}^{\;0.9554}$	$46\,600\,W_{\mathrm{NE}}^{\;0.9554}$
Compressor and dryers	$11\,400\,W_{\mathrm{NE}}^{\;0.5575}$	$11\,400\,W_{\mathrm{NE}}^{\;0.5575}$
Emergency diesel	$36\,200\,W_{\mathrm{NE}}^{\;0.1989}$	$36\,200\,W_{\mathrm{NE}}^{\;0.1989}$
Heat-recovery dryer	—	$9600\,M_{G/\mathrm{CC}}^{\;0.65}$
Fumes treatment		
NO_x and SO_x removal equipments	$126\,000\,W_{\mathrm{NE}}^{\;0.5882}$	$126\,000\,W_{\mathrm{NE}}^{\;0.5882}$
Fumes filtration	$66\,600\,W_{\mathrm{NE}}^{\;0.7565}$	$66\,600\,W_{\mathrm{NE}}^{\;0.7565}$
Ashes storage	$88\,300\,W_{\mathrm{NE}}^{\;0.3139}$	$88\,300\,W_{\mathrm{NE}}^{\;0.3139}$
Ashes extraction	$93\,500\,W_{\mathrm{NE}}^{\;0.4425}$	$93\,500\,W_{\mathrm{NE}}^{\;0.4425}$
Fans	$28\,500\,W_{\mathrm{NE}}^{\;0.5575}$	$28\,500\,W_{\mathrm{NE}}^{\;0.5575}$
Fumes ductworks	$51\,500\,W_{\mathrm{NE}}^{\;0.5129}$	$51\,500\,W_{\mathrm{NE}}^{\;0.5129}$
Discharge stack	$28\,500\,W_{\mathrm{NE}}^{\;0.5575}$	$28\,500\,W_{\mathrm{NE}}^{\;0.5575}$

services costs, instrumentations costs and site preparation costs, while total indirect plant costs (IC) include engineering and start-up costs.

Total PE costs have been calculated as the sum of PE costs of pieces of equipment that compose the three main plant sections, namely power generation, biomass storage-handling and fumes treatment utilizing the correlation listed in Table 2.

Piping, electrical and civil works costs have been estimated by resorting to the relationships illustrated in Table 3, resulting from interpolation of experimental and literature data [11–16]. Finally direct installation, auxiliary services, instrumentations, site preparation, engineering and start-up costs have been calculated as a percentage of total PE costs. Numerical values for such percentages have been derived from literature data [13–15]. All the considered items of cost utilized for TCI costs estimation have been summarized in Table 4.

In order to validate the TCI estimation model a comparison of computed costs with actual investments for specific plants described in the literature [9,11,12,16] has been performed. As shown in Table 5 the agreement with comparison data is quite good.

Total operating costs have been determined as the sum of operating labour costs, ash transport costs, ash disposal costs, purchased biomass costs, biomass transport costs, maintenance costs, insurance and general costs, as listed in Table 6.

In particular, operating labour costs L (€ year^{-1}) have been computed in function of the

Table 3
The adopted correlations for piping, electrical and civil works costs evaluation [11–16]

Piping (B)	Cost correlation (€)
Fire fighting tank	$85\,700\,W_{\mathrm{NE}}^{\ 0.1040}$
Fire fighting components	$5300\,W_{\mathrm{NE}}^{\ 0.7565}$
Fire fighting system	$6600\,W_{\mathrm{NE}}^{\ 0.7565}$
Industrial water tank	$9300\,W_{\mathrm{NE}}^{\ 0.7565}$
Tanks	$10\,300\,W_{\mathrm{NE}}^{\ 0.5129}$
Heat exchanger	$34\,200\,W_{\mathrm{NE}}^{\ 0.5575}$
Degasifier	$17\,100\,W_{\mathrm{NE}}^{\ 0.5575}$
By-pass valves	$20\,600\,W_{\mathrm{NE}}^{\ 0.5129}$
High pressure valves	$28\,500\,W_{\mathrm{NE}}^{\ 0.5575}$
Control valves	$10\,100\,W_{\mathrm{NE}}^{\ 0.6756}$
Valves	$28\,500\,W_{\mathrm{NE}}^{\ 0.5575}$
Pipes	$42\,300\,W_{\mathrm{NE}}^{\ 0.885}$
Pipe rack	$12\,100\,W_{\mathrm{NE}}^{\ 0.686}$
Electrical (C)	Cost correlation (€)
Switches	$13\,400\,W_{\mathrm{NE}}^{\ 0.3672}$
Electric protections	$44\,700\,W_{\mathrm{NE}}^{\ 0.2266}$
Transformer	$64\,600\,W_{\mathrm{NE}}^{\ 0.4289}$
Auxiliary transformer	$14\,000\,W_{\mathrm{NE}}^{\ 0.4425}$
Electrical equipment	$40\,9100\,W_{\mathrm{NE}}^{\ 0.6415}$
Assembling	$18\,6900\,W_{\mathrm{NE}}^{\ 0.7137}$
Civil works (D)	Cost correlation (€)
Buildings yard guard	$70\,100\,W_{\mathrm{NE}}^{\ 0.4425}$
Conditioning plant and ventilation system	$23\,400\,W_{\mathrm{NE}}^{\ 0.6328}$
Civil works	$1\,337\,400\,W_{\mathrm{NE}}^{\ 0.3672}$
Personnel of building yard	$133\,700\,W_{\mathrm{NE}}^{\ 0.3672}$
Buildings yard facilities	$13\,300\,W_{\mathrm{NE}}^{\ 0.7565}$
Wastewater treatment	$6900\,W_{\mathrm{NE}}^{\ 0.6107}$

Table 4
Components of total capital investment costs evaluation [13–15]

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

Table 5
Total capital investment costs model validation

Plant power output (MW)	Literature data[a] (M€)	This work (M€)	Δ%
C/ST configuration			
10	33.7	32.5	−3.6
20	41.3	48.9	+18.4
50	89.9	85.4	−5
G/CC configuration			
10	42	37.9	−9.8
30	74.2	78.5	+5.8

[a] [9,11,12,16].

employed personnel average fee C_{P}, fixed to 26.000 € unit^{-1} year^{-1} [17], and the number n of total annual working personnel, assumed variable with the plant size and calculated considering four shifts in rotation. More specifically, according to literature data [18], the operators number has been varied in the range 12–36. Therefore, the adopted equation for operating labour costs evaluation is the following:

$$L = C_{\mathrm{P}} \times n. \tag{2}$$

Ash transport costs AT (€ year^{-1}) have been calculated assuming a specific ash transport cost C_{AT} of 62 € t^{-1} using the following expression:

$$\mathrm{AT} = C_{\mathrm{AT}} \times M_{\mathrm{A}}, \tag{3}$$

where M_{A} (t year^{-1}) is the ash flow rate evaluated as 2% of the total annual biomass flow rate, according to literature data [18]. In the same manner, ash disposal costs AD (€ year^{-1}) have been computed as

$$\mathrm{AD} = C_{\mathrm{AD}} \times M_{\mathrm{A}}, \tag{4}$$

where C_{AD} is the ash landfilling fee, assumed as 24 € t^{-1}.

Table 6
Components of total operating costs evaluation

Cost component	Factor
Operating labour	L
Ash transport	AT
Ash disposal	AD
Purchased biomass cost	PB
Biomass transport cost	TB
Maintenance	$\mathrm{MAN}_{C/\mathrm{ST}} = 0.015$ TCI; $\mathrm{MAN}_{G/\mathrm{CC}} = 0.03$ TCI
Insurance and general	$I\&G = 0.01$ TCI
Total operating costs (TOC)	$\mathrm{TOC} = L + \mathrm{AT} + \mathrm{AD} + \mathrm{PB} + \mathrm{TB} + \mathrm{MAN} + I\&G$

Purchased biomass costs PB (€ year^{-1}) have been determined in function of the annual biomass flow rate M (t year^{-1}) and the specific purchased biomass cost C_B (€ t^{-1}) as follows:

$$\mathrm{PB} = C_\mathrm{B} \times M \tag{5}$$

while biomass transport costs TB (€ year^{-1}) have been evaluated as the sum of vehicles costs V (€ year^{-1}) and transportation personnel costs TP (€ year^{-1}):

$$\mathrm{TB} = V + \mathrm{TP}. \tag{6}$$

More specifically, vehicles costs V are function of the total annual travelled distance d_T (km year^{-1}) and the specific vehicle transport cost C_VT (€ km^{-1}), as follows:

$$V = d_\mathrm{T} \times C_\mathrm{VT} \tag{7}$$

where d_T is calculated as the number of travels required to transport the total amount biomass flow rate M by resorting to vehicles having a capacity VC (t vehicle^{-1}), times the average round trip transportation distance, computed assuming that the biomass is concentrated at $\frac{2}{3}$ 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 D_B (t km^{-2}year^{-1}). Therefore the adopted equation for d_T estimation is

$$d_\mathrm{T} = \frac{4}{3}\left(M/D_\mathrm{B}\pi\right)^{0.5} \times \left(\frac{M}{\mathrm{VC}}\right), \tag{8}$$

where the ratio M/VC represents the number of required travels.

As far as transportation personnel costs TP (€ year^{-1}) is concerned a transport operations employed personnel fee C_TP equal to 21 080 € unit^{-1} year^{-1} has been assumed, and a number of operators employed in transport operations n_T proportional to the number of required travels has been considered; so the adopted equation for TP evaluation is

$$\mathrm{TP} = C_\mathrm{TP} \times n_\mathrm{T} \tag{9}$$

Finally, maintenance costs MAN (€ year^{-1}) and insurance and general costs $I\&G$ (€ year^{-1}) have been calculated as a percentage of TCI using the factors given in Table 6. Numerical values for such percentages have been derived from literature data [11–13,17]. In particular referring to maintenance costs estimation, given the low maturity of biomass gasification systems respect to biomass combustion systems, a higher percentage factor has been assumed for G/CC plant configuration (equivalent to a specific maintenance cost of 0.009 € kWh^{-1}) respect to C/ST plant configuration (equivalent to a specific maintenance cost of 0.004 € kWh^{-1}), according to literature data [17].

Revenues from sale of produced electric energy have been evaluated as

$$R = W_\mathrm{ANE} \times \mathrm{OH} \times \mathrm{EP} \tag{10}$$

where OH (h year^{-1}) are the plants annual operating hours, assumed as 8000 h year^{-1}, EP (€ kWh^{-1}) is the current market price of produced electricity, without government subsidies, while W_ANE represents the percentage of the net electric energy power plant output W_EN that is effectively available for sale, assumed as 90% of W_EN in order to take into account the energy needs of auxiliary pieces of equipment.

Finally, the NPV index has been evaluated as follows:

$$\mathrm{NPV} = \sum_{k=1}^{N} \frac{F_k}{(1+i)^k} - \mathrm{TCI}, \tag{11}$$

where N is the plant life, assumed as 20 years, i is the discount rate and F_k is the annual cash flow at the kth year equal to

$$F_k = R - \mathrm{TOC} - T - \mathrm{FC}, \tag{12}$$

where T and FC are the taxes and financial charges. As far as the borrowed capital is concerned, a low interest rate $s = 1\%$ has been considered, while a 50% tax rate has been assumed for the evaluation of FC. Moreover, the TCI has been amortized over a time span of 15 years. The reference values assumed for the main economic and logistic parameters are listed in Table 7. In particular, the assumed price of produced electricity is in line with the average retail consumer power price and consistent with the competitive generation cost of biomass technologies [19], and also representative of the effect of possible state subsidies or green pricing policies. The biomass purchase cost is comparable with the ranges appearing in the literature [8,17,18,20], considering that most of such authors give an overall delivered biomass cost including transport costs, which are treated separately in this work and usually account for 50–70% of the delivered biomass cost. As far as the biomass density value is concerned it should be pointed out the following. In this work it is hypothesized that biomass feeding the energy producing plant is collected over a greater geographical basin having a circular shape and centred on the biomass plant. Inside this collection basin the actual land areas utilized for growing biomass (which may have a biomass yield as high as 50 t km^{-2} year^{-1} for residual biomass and up to more than 2000 t km^{-2} year^{-1} in case of dedicated energy crops cultures [8,10]) represent only a small fraction of the total area of collection basin and may be unevenly distributed and disseminated in a number of different sites. Therefore, it has been assumed in the paper that the entire yield of biomass is distributed as an average equivalent biomass surface density over the entire area of the collection basin. This means that the figure indicated (5 t km^{-2} year^{-1}) is not the yield of the biomass producing areas, but rather the average equivalent yield of the entire circular geographical catchment area encircling all the biomass producing sites and thus defining the average biomass transport distance.

Table 7
Reference values of main economic and logistic parameters

Parameter	Reference value
Market price of produced electricity (EP)	0.103 € kWh^{-1}
Discount rate (i)	9% year^{-1}
Specific biomass purchased cost (C_B)	26 € t^{-1}
Biomass distribution density (D_B)	5 t km^{-2} year^{-1}
Vehicles capacity (VC)	20 t vehicle^{-1}
Specific vehicle transport costs (C_{VT})	1.14 € km^{-1}

3. Economic Performances of C/ST vs. G/CC solution

The economic performance and profitability of both combustion- and gasification-based solutions have been investigated and compared over a capacity range of 5–50 MW. The analysis has been carried out assuming the reference values of the influencing economic parameters described in the previous section, and under the hypothesis of equity capital at first. The obtained results are plotted in Figs. 6–8. Fig. 6 depicts the growth of the Total Capital Investment as the capacity of energy production plant increases, showing the presence of strong economies of scale for both technologies, as passing from small-scale to large-plants the specific investment costs decrease.

In particular, when the plant size increases from 5–50 MW the specific investment costs decrease from 4400 to 1700 € kW^{-1} in case of combustion-based solution, while decrease from 4900 to 2200 € kW^{-1} in case of gasification-based solution. Such values are in good agreement with available

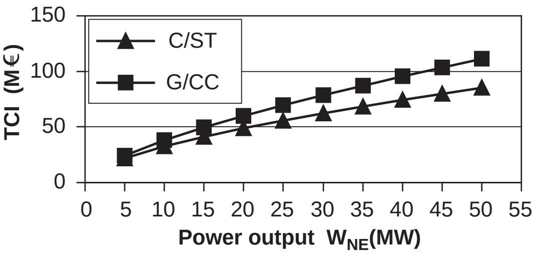

Fig. 6. Total capital investment for different plant sizes and production processes.

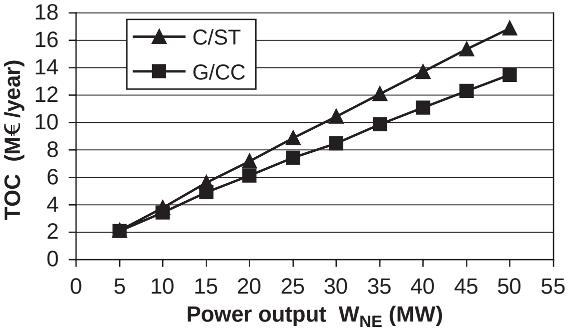

Fig. 7. Total operating costs for different plant sizes and production processes.

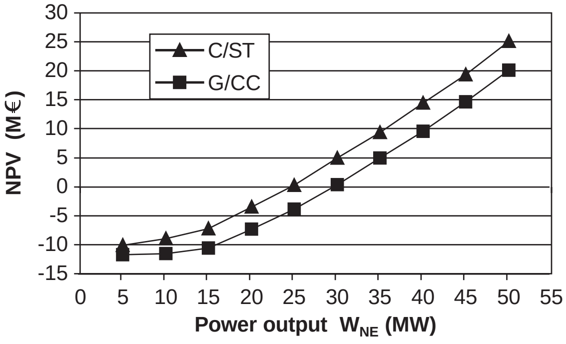

Fig. 8. Effect of plant size and production process on NPV.

literature data [9,10,17]. Nevertheless, at any scale *G*/CC solution is characterized by higher TCI compared with *C*/ST solution. Such behaviour 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. Therefore, the *G*/CC solution is penalized by the typical drawbacks of a novel technology, such as high capital costs, high labour and low reliability; however, its performance is likely to improve more strongly compared to commercial technologies because of learning effects over time [17,21].

The reverse situation occurs when operating costs are examined, see Fig. 7, where *G*/CC solution is characterized by lower TOC with respect to *C*/ST solution.

Such trend, that is enhanced with the scale-up of analysed plants, may be justified analysing the percentage composition of TOC: in particular for both the analysed plant configurations the percentage of TOC due to biomass logistic costs, namely purchase and transport cost (PB, TB) is much more significant respect to that one associated to the other cost items considered for the TOC estimation, namely operating labour, maintenance and ash transport/disposal costs.

Therefore the greater biomass consumptions characterizing the combustion-based approach for a given power output and biomass distribution density (see Fig. 5) generates higher biomass logistic costs attributed to such solution respect to gasification-based approach and, as a consequence, higher TOC. As an example in case of 40 MW plant power output, and assuming the values of economic and logistic parameters described in the previous section, the sum of PB and TB costs is about 10.5 M€ year^{-1} and 6.3 M€ year^{-1}, respectively, for *C*/ST and *G*/CC solutions. Furthermore, at the same scale, the percentage of TOC due to the biomass logistic costs is around 76% for *C*/ST solution, while it is around 56% for *G*/CC solution.

Finally, the NPV trend in the considered size range has been investigated. As shown in Fig. 8 the economic performance of both technological solutions are strongly influenced by the scale effects: in particular over a capacity range of 5–25 MW only negative NPV values are reached, while positive NPV are associated to installed power in the range 25–50 MW in case of *C*/ST solution and in the range 30–50 MW in case of *G*/CC solution. However, generally speaking, the value of plant power output that represents a break-even point for the NPV trend for both the assumed plant configurations will move towards lower values in case of an optimistic economic scenario, characterized by lower TCI, TOC and discount rate, and by high electric energy price, while it will move towards higher values in case of a pessimistic economic scenario.

Furthermore, Fig. 8 shows that at any size *C*/ST configuration reaches higher NPV values compared with *G*/CC configuration: such behaviour highlights the higher influence of TCI trend with respect to TOC trend on the NPV of analysed solutions. Hence, it is possible to deduce that under current technological and market conditions, and without financial supports, the combustion-based approach shows a better profitability.

However, in a short time horizon, the economic performance of bio-energy systems based on gasification can be enhanced by adequate financial government policies and project-financing measures. In particular higher percentage of capital grants, preferential conditions of depreciation for investment, governmental credits with especially low interest rates, can strongly contribute to reduce the TCI impact associated to *G*/CC solutions and, as a consequence, to improve the *G*/CC economic performances also considering the lower TOC associated to this conversion approach. Moreover, taking into account that under the existing energy market the bio-energy generation is not competitive respect to traditional conversion processes due to the low prices of fossil fuels, the relatively high efficiency of the traditional conversion technologies, and the feedstock characteristics which make biomass more difficult to handle, higher profits from electricity generation by means of premium electric energy prices may strongly improve the economic performance of biomass energy systems, especially for gasification-based solutions [22].

Therefore, the impact of main economic parameters, namely TCI, TOC, discount rate, energy market price and project financing percentage, on the investment profitability of both *C*/ST and *G*/CC solutions, has been investigated. More specifically for each parameter a percentage variation with respect to modal values (see Table 7) has been assumed and the related percentage variation of NPV values (% ΔNPV) has been estimated for both *C*/ST and *G*/CC solutions over the capacity range 5–50 MW.

The obtained results in case of 40 MW plant power output are summarized in Table 8. As expected the economic profitability of *G*/CC solution is strongly affected by the percentage variation of all the considered parameters respect to economic profitability of *C*/ST solution. This trend is emphasized in case of large-scale plants, where the NPV modal value of *G*/CC is lower than *C*/ST solution and, at the same time, TCI are greater while TOC are lower than combustion-based approach. Furthermore, as shown in Table 8, the most influencing parameters on investment profitability of both analysed plant configurations are capital investments and electric energy price. Finally, the influence of project financing over the economic performance of analysed solutions has been evaluated (Fig. 9). In particular, the NPV assessment has been carried out under the hypothesis of a low interest rate ($s = 1\%$) for the borrowed capital, equal to 100% of the total investment.

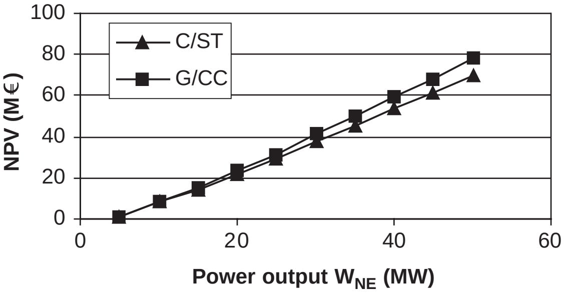

Fig. 9. NPV trend in case of 100% borrowed capital and $s = 1\%$ year^{-1}.

Table 8
Effects of main economic parameters on investment profitability (40 MW)

Parameter	% Δ with respect to modal value	% Δ NPV for *C*/ST	% Δ NPV for *G*/CC
TCI	±30	±121	±236
TOC	±30	±130	±159
Discount rate (*i*)	±22	+91/−73	+162/−131
Electric energy price (EP)	±25	+236/−300	+357/−453

Profitability of both plant configurations is improved: as an example, in case of 50 MW plant power output, the NPV values pass from 25 and 20 M€ in case of financial incentives absence, to 70 and 79 M€ for C/ST and G/CC solutions, respectively.

However, the effects of project financing are much stronger for gasification-based approach, that reaches NPV values higher than NPV values of combustion-based approach at any scale.

4. Impact of logistics on profitability

It is well known that, at present, producing electricity from biomass is far more expensive than from other more traditional sources, such as coal and gas, partly as a result of the logistic costs involved in fuel supply. Biomass power stations are small in terms of generating capacity in comparison with fossil fuel power stations, and at the same time they require significant quantities of feedstock fuel because of the low calorific value of biomass compared to coal or oil. Furthermore the low bulk density, characterizing most biomass fuels, means that the volume occupied by a given quantity will far exceed that occupied by the same quantity of fossil fuels thereby resulting in the need for a much larger number of lorry movements that make logistic activities strongly problematic [10,20]. Moreover the intrinsic biomass characteristics, such as the limited availability in terms of time owing to its seasonality, and the dispersed geographical distribution over the territory, also contribute to make collection, transport and storage operations complex and expensive. These critical logistic aspects strongly affect the economic performances of bio-energy conversion systems: in fact, as pointed out in the previous section, purchased biomass costs and transport biomass costs represent the main cost items contributing to total operating costs trends that may introduce limitation on feasibility of both C/ST and G/CC solutions.

Therefore, in order to evaluate the logistics impact on the bio-energy plant profitability, the effects of main logistic variables, namely specific vehicle transport cost (C_{VT}), vehicles capacity (VC), specific purchased biomass cost (C_B) and distribution density (D_B), have been examined in function of plant size (5–50 MW). In particular, the considered range of variation with respect to the modal value (see Table 7) for each logistic parameter, together with the consequent percentage variation of NPV values for both the analysed plant configurations have been summarized in Table 9. As an example a plant power output of 40 MW has been chosen for results presentation.

As expected the effects of all logistic variables are much stronger for combustion-based solution respect to gasification-based solution owing to the higher biomass consumption characterizing such conversion technology, as previously pointed out (see Section 3). More specifically for a given value of biomass distribution density, the catchment area for biomass resources and consequently the total annual travelled distance over which the biomass will have to be moved from the production point to power station, increase with the quantity of biomass fuel required. Therefore, an increase of vehicle transport cost (C_{VT}) directly results in an higher increment of vehicles costs in case of C/ST solution, while a vehicles capacity (VC) decrease results in the need for a much larger number of lorry movements for the combustion-based solution, thus a much stronger increase of biomass transport costs.

Table 9
Effects of main logistic variables on investment profitability (40 MW)

Parameter	% Δ with respect to the modal value	% Δ NPV for C/ST	% Δ NPV for G/CC
Specific vehicle transport cost (C_{VT})	±30	±28	±22
Vehicle capacity (VC)	+100/−50	+50/−101	+39/−78
Specific purchased biomass cost (C_B)	±60	+142/−133	+137/−128
Biomass distribution density (D_B)	+300/−80	+50/−123	+38/−94

At the same time, an increase of specific purchased biomass cost (C_B) or a decrease of biomass distribution density (D_B) results in a much stronger increase of purchased biomass costs associated to the C/ST solution.

5. Mapping of logistic constraints on economic profitability

Finally, a mapping of logistic constraints on plant profitability has been carried out with the aim of identifying the logistic parameters threshold values able to guarantee a non-negative NPV. The analysis has been conducted taking into account a plant capacity range from 30 to 50 MW, as negative NPV characterizes smaller sized plant (<30 MW) as already discussed. Results are shown in Figs. 10–13. In particular, passing from Figs. 10–13 the solid lines indicate the threshold values of maximum specific biomass transport costs C_{VT}, specific purchased biomass costs C_B, the minimum biomass distribution density D_B and vehicle capacity VC associated to a zero NPV value for either combustion- and gasification-based plants in function of plants capacity.

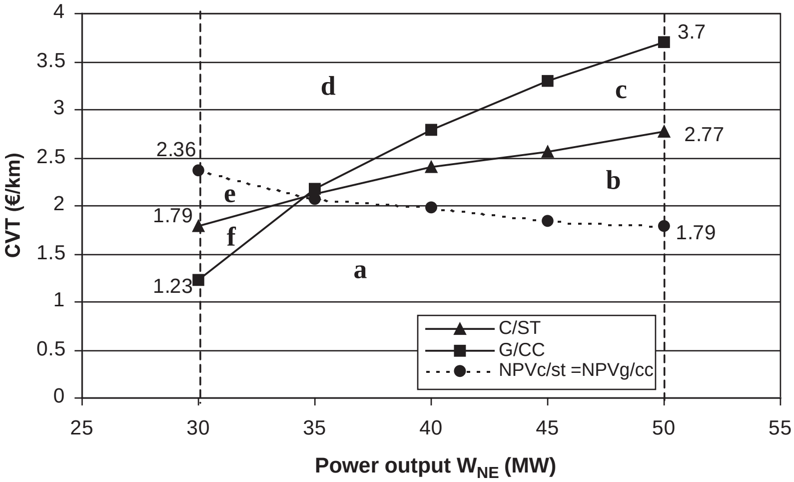

Fig. 10. Maximum specific biomass transport costs associated to a zero NPV value.

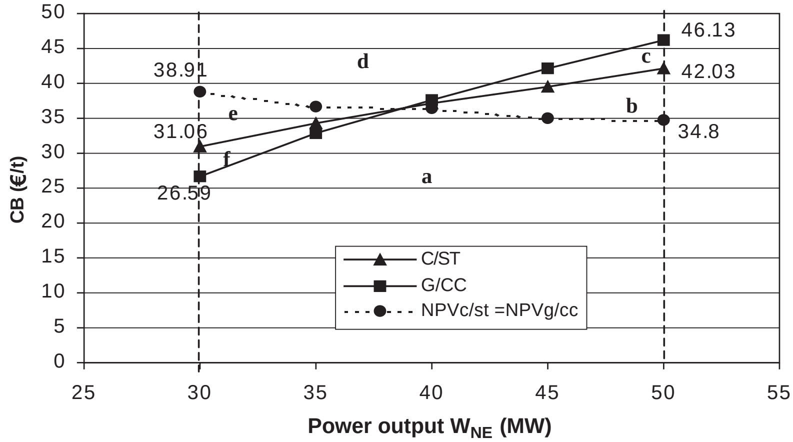

Fig. 11. Maximum specific purchased biomass costs associated to a zero NPV value.

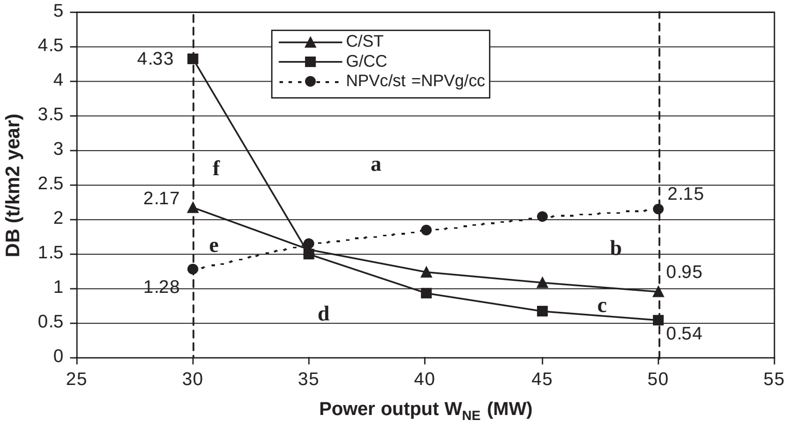

Fig. 12. Minimum biomass distribution density associated to a zero NPV value.

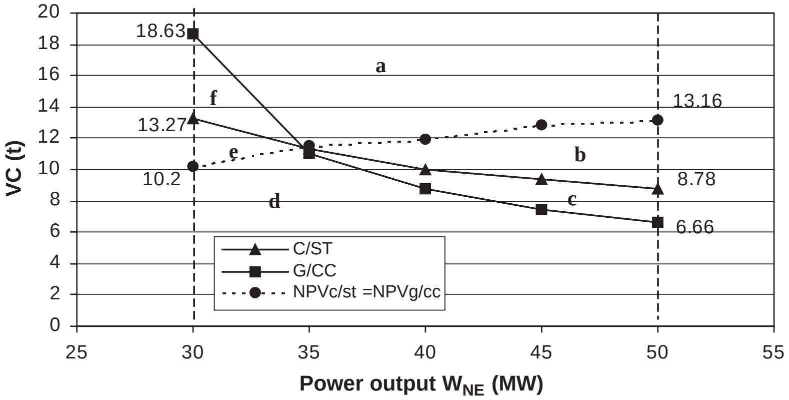

Fig. 13. Minimum vehicle capacity associated to a zero NPV value.

Therefore such lines delimitate for each plant type two half-planes, one characterized by positive NPV and the other by negative NPV. Furthermore, the dashed lines indicate the values of the examined variable giving rise to the same NPV for both plant types.

The lines, therefore, delimitate also the following areas characterized by different profitability conditions namely:

(a) $NPV_{C/ST} > 0$ and $NPV_{G/CC} > 0$ with $NPV_{C/ST} > NPV_{G/CC}$;
(b) $NPV_{C/ST} > 0$ and $NPV_{G/CC} > 0$ with $NPV_{C/ST} < NPV_{G/CC}$;
(c) $NPV_{G/CC} > 0$ and $NPV_{C/ST} < 0$;
(d) $NPV_{C/ST} < 0$ and $NPV_{G/CC} < 0$ with $NPV_{C/ST} < NPV_{G/CC}$;
(e) $NPV_{C/ST} < 0$ and $NPV_{G/CC} < 0$ with $NPV_{C/ST} > NPV_{G/CC}$;
(f) $NPV_{C/ST} > 0$ and $NPV_{G/C} < 0$.

Resorting to analysis of above figures, the following main conclusions may be drawn.

- The logistic constraints on economic performance of both C/ST and G/CC solutions become less restrictive when the plant size increases. In other words, higher threshold values may be accepted in terms of plant profitability. This behaviour is more evident

Table 10
Range of value of logistic parameters associated to $NPV_{G/CC} > 0$ and $NPV_{G/CC} > NPV_{C/ST}$ (power output 45 MW)

Parameter	Range
Specific vehicle transport cost C_{VT} (€ km^{-1})	1.84–3.24
Specific purchased biomass cost C_B (€ t^{-1})	34.98–42.13
Biomass distribution density D_B (t km^{-2} year^{-1})	0.68–2.05
Vehicle capacity VC (t vehicle^{-1})	7.45–12.82

for gasification-based solution, as demonstrated by the slope of curves depicted in Figs. 10–13.

- In case of an adverse logistic scenario, characterized by high biomass specific purchased costs and biomass specific transport costs, and at same time by low vehicles capacity and biomass distribution density, the behaviour of analysed solutions shows a reversal of trend when the plant capacity (W_{EN}) is around 35 MW. In particular, if $W_{EN} < 35$ MW the profitability of both combustion- and gasification-based approach is strongly penalized by the higher TOC owing to the elevated logistic costs. However, *G*/CC solution may be associated to NPV values that are less negative of NPV values reached by *C*/ST solution.
- On the contrary if $W_{EN} > 35$ MW gasification-based approach shows a better performance compared to combustion-based approach. In particular the *G*/CC solution reaches NPV values ever higher than the NPV values of *C*/ST solution, and they remain positive for a wider range of logistic parameters values. Therefore, in case of an unfavourable logistic scenario, the savings in terms of TOC, ensured by the bio-energy gasification plants, are able to offset the negative effects of the larger TCI characterizing the gasification-based approach. As an example if 45 MW plant power output is considered the *G*/CC solution is characterized by positive NPV values that are higher than the corresponding positive NPV value of *C*/ST solution for the ranges of logistic parameters summarized in Table 10.

6. 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 particular, the economic performances and profitability of both combustion- and gasification-based approaches have been evaluated and compared over a capacity range from 5 to 50 MW. At the same time, taking into account the critical logistic aspects related to the overall bio-energy 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. Furthermore, the comparison between the two analysed plant configurations in terms of capital and operating costs shows that combustion-based approach is characterized by lower TCI but, at the same time, higher TOC respect to gasification-based approach. However, under current technological and market conditions, without financing supports and taking into account modal values for the main economic and logistic parameters, the savings in terms of operating expenditures associated to *G*/CC solution, owing to the lower biomass consumption characterizing such bio-energy conversion approach, are not able to offset the higher investment expenditures typical of an emerging technology such as the gasification-based approach. As a result, at present, combustion-based solution shows a better profitability.

Nevertheless, from a TCI point of view and in a short time horizon if adequate fiscal incentives and project financing measures are adopted the investment profitability of gasification-based approach strongly improves, becoming comparable with economic performance of combustion-based solution. Furthermore, over a long-time perspective, technological developments and improvements related to the learning effects will reduce the capital costs of biomass gasification processes, offsetting the lack of competitiveness of such solutions respect to combustion-based approaches.

On the other hand, taking into account that *G/CC* solution is characterized by lower biomass consumptions, and that for both the analysed plant configurations the percentage of TOC due to biomass logistic costs, namely purchased and transport cost (PB, TB) is much more significant respect to the one associated to the other TOC items, namely operating labour, maintenance and ash transport/disposal costs, the logistics may become the key factor able to improve the economic performance and profitability of gasification-based approach. In fact, gasification-based solution more effectively responds to adverse logistic conditions, characterized by high biomass specific purchased costs and biomass specific transport costs, and at same time by low vehicles capacity and biomass distribution density, especially in case of large plant capacity ($>35\,\text{MW}$).

References

[1] Demirbas A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Conversion and Management 2001;42:1357–78.

[2] McKendry P. Energy production from biomass (part 2): conversion technologies. Bioresources Technology 2002; 83:47–54.

[3] Broek R, Faaij A, Wijk A. Biomass combustion power generation technologies. Biomass Bioenergy 1996;11: 271–81.

[4] Overend RP. Biomass gasification: a growing business. Renewable Energy World 1998;1:59–63.

[5] Demirbas A. Yields of oil products from thermochemical biomass conversion processes. Energy Conversion and Management 1998;39:685–90.

[6] Solantausta Y, Bridgwater AT, Beckman D. Feasibility of power production with pyrolysis and gasification systems. Biomass and Bioenergy 1995;9:257–69.

[7] Word Energy Council 1994. New Renewable Energy Resources, London, 1994.

[8] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresources Technology 2002;83: 37–46.

[9] Bridgwater AV. The technical and economic feasibility of biomass gasification for power generation. Fuel 1995;74(5):631–53.

[10] Dornburg V, Faaij A. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass and Bioenergy 2001;21: 91–108.

[11] Tsatsaronis G, Winhold M, Stoianoff CG. Thermoeconomic analysis of a gasification-combined-cycle power plant. EPRI AP-4734, research project 2029-8, Desert Research Institute, Reno, Nevada, 1986.

[12] Miccio F, Coda B, Moersch H, Spliethoff H, Hein KRG. Gassificazione e cogenerazione da combustibili rinnovabili. La Termotecnica 1998;5:97–102 [in Italia].

[13] Peters MS, Timmerhaus KD. Plant design and economics for chemical engineers, 4th ed. New York: McGraw-Hill; 1991.

[14] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA. Analysis synthesis and design of chemical processes. Englewood Cliffs, NJ: Prentice-Hall; 1998.

[15] US Environmental Protection Agency. Air pollution control cost manual. 6th ed. EPA 452/B-02-001, January 2002.

[16] Ferrari E, Persona A. Indicazioni per il dimensionamento di impianti di cogenerazione con turbina a vapore in contropressione Impiantistica Italiana, 1993, p. 6. (in Italian).

[17] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews 2002;6:181–248.

[18] Alberti M, Riva G, Scrosta V, Toscano G, Botta G, Brignoli V. Analisi delle iniziative per la produzione di energia elettrica da biomasse agro-industriali in Italia. Proceedings of the IVth national symposium: utilizzazione termica dei Rifiuti. Abano Terme 12–13 June 2003. p. 267–77 (in Italian).

[19] IEA. Renewables for power generation: status and prospects. International Energy Agency, 2003, (ISBN 92-64-01918-9).

[20] Allen J, Browne M, Hunter A, Boyd J, Palmer H. Logistics management and costs of biomass fuel supply, International Journal of Physical Distribution and Logistics Management 1998;28(6):463–77.

[21] Jelen FC. Cost and optimization engineering. New York: Mcgraw-Hill; 1970.

[22] Rosch C, Kaltschmitt M. Energy from biomass: do non-technical barriers prevent an increased use? Biomass and Energy 1999;16:347–56.