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A Model for the Optimal Dimensioning of Biomass-fuelled Electric Power Plants

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Strategic, agricultural and/or environmental considerations have revived the idea of utilizing biomass for power generation. This poses the problem of defining the optimal size for plants to convert the woody and cellulosic biomass into electric energy. A model has been developed to determine the optimal electric power and corresponding number of plants to install in a given agricultural/forest area, based on the distribution of the biomass available in the area, the technical and operational parameters and the economic objectives associated with the proposed investment. The model is applied to the Italian situation, where there is a net biomass availability of 17 Mt/yr d.m. and the possibility, during the first eight years of the biomass power plant operation, to sell the produced electricity at a price of 141 ECU/MWh. Results show the possibility of installing 170 plants, with a unit power of 14 MW each, for a total electric power of 2,400 MW.

Notation

C_b	annual purchasing cost of biomass	ECU/yr
C_{bs}	specific purchasing cost of biomass	ECU/t d.m.
C_r	annual maintenance and repair cost	ECU/yr
C_t	annual handling cost of biomass	ECU/yr
C_{ts}	specific handling cost of biomass	ECU/t km d.m.
C_w	annual labour cost	ECU/yr
C_{ws}	specific labour cost	ECU/man yr
E_e	electric energy produced per year	MWh/yr
CF	annual plant cash flow	ECU/yr
E_t	thermal energy produced per year	MWh/yr
f_a	discount factor	—
f_u	utilization factor of the thermal energy produced	—
H_b	biomass net calorific value	MWh/t d.m.
i	real discount rate	—
I	total plant investment	ECU
I_o	total investment related to optimal plant size	ECU
I_s	specific plant investment	ECU/MW
I_{slim}	specific plant investment available on European market	ECU/MW
I_{so}	specific investment related to optimal plant size	ECU/MW
IN	cash flow incomes	ECU/yr
IRR	internal rate of return of the plant	—
k_r	annual incidence of repair and maintenance as a proportion of I	—
n_u	number of employees	—
n_p	number of installable plants	—
NPV	net present value of the plant	ECU
OUT	cash flow outgoings	ECU/yr
p_e	selling price of electricity	ECU/MWh
p_t	selling price of thermal energy	ECU/MWh
P_e	plant electric power	MW
P_{eo}	optimal plant electric power	MW
P_t	plant thermal power	MW
P_{to}	optimal plant thermal power	MW
PI	profitability index	—
R	radius of the circular area in the centre of which the plant is located	km
R_o	radius related to optimal plant size	km

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S	surface of the area in which the plant is located	km^2
S_o	surface related to optimal plant size	km^2
S_t	surface related to the studied area	km^2
t	plant annual running time	h/yr
V_u	plant useful life	yr
δ	average biomass yield on the considered area	t/km^2 yr d.m.
η_e	plant efficiency for electricity production	—
η_t	plant efficiency for thermal production	—

1. Introduction

Several studies[1–4] have been carried out in the past 20 years on the availability of woody and cellulosic residues (C/N > 30; H_2O < 30% w.b. m.c.) usable for energy generation in various countries. Over the past decade, in addition, various studies, technical-economic analyses and projects[5–10] have examined the problem of the thermochemical conversion of this biomass to produce electric energy, with or without the recovery of heat produced.

Power generation, using biomass, has failed to move into the implementation phase, however. Only in recent years, in fact, for political and energy-related reasons (decreasing dependence on conventional sources), agricultural reasons (reduction of surpluses, set-aside of cultivated land) and environmental reasons (reduction of harmful gas emissions) has interest in the topic revived, and some thermal plants fed with straw and/or wood have been built and are running.

Among the various projects completed, mention should be made of those in Denmark. These plants, fed with straw and wood,[3] produce electricity (P_e = 9·4 MW at Koge and P_e = 5 MW at Haslov), or thermal output (P_t = 8 MW at Kiback, P_t = 2 MW and P_e = 0·5 MW in cogeneration at Rodby). In Sweden,[11] there are said to be around 50 combustion plants with installed power between $0{\cdot}4 \leq P_e \leq 80$ MW and a programme was launched in 1989 by the Swedish State Power Board for the energy utilization of biomass.

In Italy[5,12] there are some 20 plants for the production of thermal and electric energy with sizes in the range $0{\cdot}5 \leq P_e \leq 2$ MW, fed both with agricultural residues and with waste from food processing and/or the woodworking industry. In addition, recent laws on energy saving have stimulated studies[3] on the energy potential of biomass for electricity production.

In the USA various wood-fired power plants have been designed[6,12,13] and some built, in the range P_e = 11 to 90 MW. The operating parameters of four of them, one located in California, two in Michigan and one in Vermont, have been published.[14] Recently, the Utility Biomass Energy Commercialisation Association was created among the Electric Companies of the USA with the object of partially converting some coal stations to biomass plants.

The latest experiences show that the classical conversion technologies based on steam turbines[8,15] are completely reliable now but that the system (which includes technologies and facilities for biomass collection, treatment and storage) and its optimal organization and operation are not completely well defined. In fact to optimize the overall organization it is necessary to take into account the various and specific local situations (density and type of biomass, farm sizes, etc.) and the fact that, in general, the periods of biomass availability cover only a short part of the year and consequently large storage facilities are required.

This makes it extremely difficult to evaluate the economic aspects[7,16] and investments required, but it has been suggested that the minimum specific investment to create a biomass-fed energy "system" may be estimated[12] to be of the order of 2 200 000 to 2 500 000 ECU/MW for an installed power of the order of P_e = 5 to 10 MW. A model has been developed to determine the optimal electric power, and corresponding number of plants to install in a given agricultural/forest area, based on the distribution of the biomass available in the area, the technical and operational parameters and the economic objectives associated with the proposed investment.

2. The proposed model

2.1. *Basic assumptions and technical dimensioning*

Given this renewed interest in the problem, we have studied, defined and tested a simplified model for identifying the feasibility of biomass energy systems, each of which consists of a conversion plant and the necessary equipment upstream for the collection of raw materials and downstream for distributing the electricity and/or heat produced. This original model is based, on the one hand, on determining the threshold specific investment I_s (ECU per electric MW) below which the plant cannot be built and, on the other, on the obvious correlation between plant power P_e (MW) and the quantity of dry biomass locally available. This last parameter depends on the net density of this biomass δ (t/km^2 yr d.m.) and the area of production S (km^2), assumed to be a circle with the centre represented by the power plant location and a radius R (km).

Thus, given H_b (MWh/t) the net calorific value of the biomass, δ (t/km^2 yr) the dry matter yield and η_e the total mean efficiency of electric generation (which also reflects the energy consumed upstream from the actual conversion process), the electricity produced is equal to

$$E_e = S\delta H_b \eta_e = \pi R^2 \delta H_b \eta_e \quad [\text{MWh/yr}] \qquad (1)$$

from which, assuming a running time of t (h/yr), the installed power would be

$$P_e = \frac{E_e}{t} \quad [\text{MW}] \qquad (2)$$

The same calculation may be set up for the production of thermal energy E_t (MWh/yr) and thermal power P_t (MW); in this case the process efficiency (η_t) changes and a specific utilization factor (f_u), must be introduced to define the proportion of the thermal energy produced throughout the year that is actually used.

Thus,

$$E_t = S\delta H_b \eta_t f_u = \pi R^2 \delta H_b \eta_t f_u \quad [\text{MWh/yr}] \qquad (3)$$

$$P_t = \frac{E_t}{t} \quad [\text{MW}] \qquad (4)$$

2.2. *Economic dimensioning*

The analysis of cost effectiveness proposed in the model is based on the method of discounted cash flow.[17] The annual cash flow (CF) is assumed to be constant during the plant economic life V_u and it is defined by the algebraic sum of incomes (IN) and outgoings (OUT)

$$CF = IN - OUT \qquad (5)$$

In Eqn (5), the incomes are equal to revenues from sale of the energy produced

$$IN = E_e p_e + E_t p_t \quad [\text{ECU/yr}] \qquad (6)$$

where p (ECU/MWh) is the selling price per unit of electric energy (p_e) and thermal energy (p_t).
The outgoings consist of
the cost of purchasing the biomass

$$C_b = \pi R^2 \delta C_{bs} \quad [\text{ECU/yr}] \qquad (7)$$

where C_{bs} the unit cost of biomass (ECU/t d.m.)
the cost of handling the biomass

$$C_t = \int_0^R (2\pi C_{ts} \delta R^2)\, dR = \tfrac{2}{3}\pi C_{ts} \delta R^3 \quad [\text{ECU/yr}] \qquad (8)$$

where C_{ts} is the specific transport cost [ECU/t km d.m.];
the labour cost

$$C_w = C_{ws} n_u \quad [\text{ECU/yr}] \qquad (9)$$

where C_{ws} is the mean annual per capita cost of labour and n_u the number of employees;
the cost of maintenance and repairs

$$C_r = I k_r \quad [\text{ECU/yr}] \qquad (10)$$

where I (ECU) is the total investment and k_r is a coefficient expressing the mean annual incidence of maintenance and repair operations as a proportion of the total investment.

Substituting the expressions (6), (7), (8), (9) and (10) into Eqn (5), the annual cash flow is

$$CF = (E_e p_e + E_t p_t) - (C_b + C_t + C_w + C_r) \quad [\text{ECU/yr}] \qquad (11)$$

The annual cash flow is related to the Net Present Value (NPV), that is the brought up-to-date surplus of benefits versus costs, by the expression

$$NPV = CF f_a - I \quad [\text{ECU}] \qquad (12)$$

where

$$f_a = \frac{(1+i)^{V_u} - 1}{i(1+i)^{V_u}} \qquad (13)$$

is a factor which sums and discounts CF over the useful life V_u (yr) of the plant, assuming CF constant during V_u and a real discount rate i.

An investment is considered economically interesting when NPV is equal to the value desired by the user and when NPV adequately remunerates the investment made. The profitability index (PI) defines the profit (or loss) of the investment operation per unit of investment and it is equal to

$$PI = \frac{NPV}{I} \qquad (14)$$

Consequently, using Eqns (11) and (12)

$$PI = \frac{[E_e p_e + E_t p_t - (C_b + C_t + C_w + C_r] f_a - I}{I} \qquad (15)$$

To calculate Eqn (15), it is advisable to express the total investment I (ECU) as a function of the specific investment I_s (ECU per electric MW). This assumption is justified by the fact that the final object of the method is to evaluate a threshold value of I_s, not to use given values. Therefore

$$I = I_s P_e \quad \text{[ECU]} \tag{16}$$

and using Eqns (1) and (2)

$$I = \frac{\pi R^2 \delta H_b \eta_e I_s}{t} \quad \text{[ECU]} \tag{17}$$

where t is the running time of the plant (h/yr).

Substituting Eqns (1), (3), (7), (8), (9) and (10) in Eqn (15) gives

$$PI = [\pi R^2\, \delta H_b \eta_e p_e + \pi R^2\, \delta H_b \eta_t f_u p_t - (\pi R^2 \delta C_{bs} + \tfrac{2}{3}\pi C_{ts} \delta R^3 + C_{ws} n_u + I k_r)] \frac{f_a}{I} - 1 \tag{18}$$

and then, using Eqn (17)

$$PI = \frac{f_a t}{\pi R^2 \delta H_b \eta_e I_s} \left[\pi R^2 \delta H_b \eta_e p_e + \pi R^2 \delta H_b \eta_t f_u p_t - \pi R^2 \delta C_{bs} - \tfrac{2}{3}\pi C_{ts} \delta R^3 - C_{ws} n_u - \frac{\pi R^2 \delta H_b \eta_e I_s k_r}{t} \right] - 1 \tag{19}$$

$$PI = \frac{f_a t p_e}{I_s} + \frac{f_a t \eta_t f_u p_t}{\eta_e I_s} - \frac{f_a t C_{bs}}{H_b \eta_e I_s} - \frac{2 f_a t C_{ts} R}{3 H_b \eta_e I_s} - \frac{f_a t C_{ws} n_u}{\pi R^2 \delta H_b \eta_e I_s} - f_a k_r - 1 \tag{20}$$

$$PI = -\frac{f_a t C_{ws} n_u}{\pi \delta H_b \eta_e I_s} R^{-2} - \frac{2 f_a t C_{ts}}{3 H_b \eta_e I_s} R + \left(-1 - f_a k_r - \frac{f_a t C_{bs}}{H_b \eta_e I_s} + \frac{f_a t p_e}{I_s} + \frac{f_a t \eta_t f_u p_t}{\eta_e I_s} \right) \tag{21}$$

Simplifying and expressing the terms associated with radius R and its coefficients as follows

$$\alpha = -\frac{f_a t C_{ws} n_u}{\pi \delta H_b \eta_e I_s} \tag{22}$$

$$\beta = -\frac{2 f_a t C_{ts}}{3 H_b \eta_e I_s} \tag{23}$$

$$\gamma = -1 - f_a k_r - \frac{f_a t C_{bs}}{H_b \eta_e I_s} + \frac{f_a t p_e}{I_s} + \frac{f_a t \eta_t f_u p_t}{\eta_e I_s} \tag{24}$$

we can write Eqn (12) as a function of R, as follows

$$PI = \alpha R^{-2} + \beta R + \gamma \tag{25}$$

In Eqn (25) the coefficients α and β always assume negative values, while coefficient γ may theoretically be positive, negative or equal to zero. Consequently, Eqn (25) gives rise to a family of curves.

When the profitability index is nil ($PI = 0$), no profit is made but the costs of the plant are covered; consequently, the net present value is equal to zero ($NPV = 0$) and the discount rate i represents the internal rate of return ($i = IRR$). In this particular economic situation, it is possible to calculate the corresponding specific investment $I_{s(IRR)}$ (ECU/MW)

$$I_{s(IRR)} = \frac{(-3C_{ws} n_u - 3\pi R^2 \delta C_{bs} - 2\pi C_{ts} \delta R^3 + 3\pi R^2 \delta H_b \eta_e p_e + 3\pi R^2 \delta H_b \eta_t f_u p_t) f_a t}{3\pi R^2 \delta H_b \eta_e (1 + f_a k_r)} \tag{26}$$

The optimum radius R_o of the area served is found by differentiating Eqn (25), and putting

$$\frac{\mathrm{d}(PI)}{\mathrm{d}R} = 0.$$

Then,

$$R_o = \sqrt[3]{\frac{2\alpha}{\beta}} = \sqrt[3]{\frac{3 C_{ws} n_u}{\pi \delta C_{ts}}} \quad \text{[km]} \tag{27}$$

This permits determination of the corresponding biomass surface area

$$S_o = \pi R_o^2 \quad \text{[km}^2\text{]} \tag{28}$$

the installable electric power (similarly for the thermal power P_{to})

$$P_{eo} = \frac{\pi R_o^2 \delta H_b \eta_e}{t} \quad \text{[MW]} \tag{29}$$

the total investment required

$$I_o = I_{so} P_{eo} \quad \text{[ECU]} \tag{30}$$

where I_{so} (ECU/MW) is the maximum allowed specific investment, obtained from Eqn (26) replacing R with R_o.

Finally, using Eqn (28) to calculate the area S_o (km^2) served by a plant of optimal size, and given the area S_t (km^2) of the territory under consideration, the number of plants n_p that can be installed in that territory is given by

$$n_p = \frac{S_t}{S_o} \tag{31}$$

In other words, given a set of technical parameters, using Eqn (27), the corresponding optimum radius (R_o) and then, by Eqn (26), the specific investment (I_{so}) are calculated.

Introducing this I_{so} value into the coefficients α β and γ, it is possible to draw the function $PI = f(R)$.

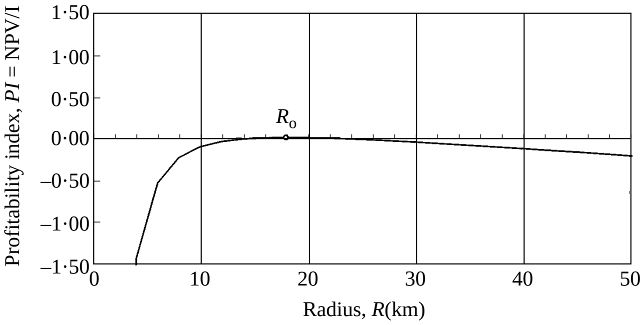

Fig. 1. Function PI = f(R), corresponding to the standard values of technical parameters given in Table 1

As an example, *Fig. 1* represents the pattern of Eqn (25) using the standard values of technical parameters shown in Table 1. This is the particular case, where the investment (I_s) is such that the costs are just covered at the optimum radius (R_o). For other radii, costs are not fully covered.

3. Sensitivity analyses

It has already been shown that the coefficients α β and γ of the function $PI = \alpha R^{-2} + \beta R + \gamma$ are dependent upon a number of technical and economic parameters.

It is interesting to observe how the value of $PI = f(R)$ is affected by these parameters, varying one at a time, within a predetermined range. For each parameter Table 1 shows a "standard" value considered to be typical of most cases as well as a lower limit (minimum value) and upper limit (maximum value).

The standard values and excursions of technical parameters (annual running time, conversion efficiency, useful economic life, number of employees, etc.) were calculated with reference to the applications and performance typical of cogeneration plants with installed power $P_e = 5$–10 MW. The values of economic parameters (investment, selling price of energy produced, average wages of employees, biomass yield,

Table 1
Sensitivity analysis: standard values and relevant ranges

Parameters		*Unit*	*Standard value*	*Min value*	*Max value*
Conversion plant					
Running time	t	h/yr	7 000	4 000	8 000
Useful economic life	V_u	yr	20	8	24
Electric efficiency	η_e	—	0·22	0·10	0·40
Thermal efficiency	η_t	—	0·62	0·72	0·48
Utilization factor (thermal energy)	f_u	—	0·5	0	1·0
Maintenance factor per year	k_r	—	0·03	0·02	0·06
Specific investment	I_s	ECU/MW	2 100 000	1 200 000	3 600 000
Manpower					
Total employees	n_u	units	12	2	20
Average wage per capita	C_{ws}	ECU/yr	30 000	20 000	40 000
Biomass (d.m.)					
Yield	δ	t/km^2 yr	200	50	500
Net calorific value	H_b	MWh/t	4·5	3·8	5·0
Cost (storage included)	C_{bs}	ECU/t	50	20	140
Cost of transport	C_{ts}	ECU/t km	0·30	0·10	0·90
Economic parameters					
Price of electric energy	p_e	ECU/MWh	55	40	140
Price of thermal energy	p_t	ECU/MWh	20	10	60
Interest rate	i	—	0·10	0·05	0·20

Notes: δ, minimum value corresponds to the minimum found in Italy; maximum value corresponds to a hypothetical land utilization of 85% for short-rotation forestry; η_e, 20–25% for steam plants with electrical power $P_e \geq 10$ MW; p_e, range of values that currently apply in Europe; in Italy, the value of p_e for electricity produced from biomass is approximately 141 ECU/MWh; p_t, maximum value for civil residential uses; C_{bs}, the minimum value represents harvesting costs only; the maximum value is related to the price that justifies the cultivation of woody plants for energy purposes; it is calculated on the basis of a net (without subsidies) farmer income of 250–300 ECU/ha yr; C_{ts}, the range is related to the type of transport used; n_u, related to the technology and to the type of biomass management; k_r, related to the number and complexity of plant components.

Table 2
Results of the model application with standard values

Results		*Unit*	*Value*
Optimum radius	R_o	km	17·9
Optimum area	S_o	km^2	1 006
Optimum electric power	P_{eo}	MW	28·5
Corresponding thermal power	P_{to}	MW	80·7
Maximum allowed specific investment	I_{so}	ECU/MW	1 300 000
Total investment required	I_o	MECU	37·1
Net present value	*NPV*	ECU/yr	0
Profitability index	*PI*	—	0

biomass purchase and handling costs, etc.) were calculated with reference to the European situation.

Applying the full set of standard values, optimal conditions (i.e. those associated with economic equilibrium: $PI = 0$) correspond to a plant with installed power $P_{eo} = 28{\cdot}5$ MW serving an area of radius $R_o = 17{\cdot}9$ km and characterized by specific investment $I_{so} = 1\,300\,000$ ECU/MW (Table 2).

This specific investment needs to be approximately 40% lower than the current market cost (in the order of $I_{slim} = 2\,100\,000$–$2\,500\,000$ ECU/MW for plants with installed power P_e between 5 and 30 MW).[18] This highlights the difficulty of utilizing biomass in cogeneration plants without specific economic incentives.

To illustrate the sensitivity of the profitability index (*PI*) as a function of radius (*R*) with respect to variations in a single parameter, five different curves are plotted, in each of *Figs 2–5*, corresponding to different values of a particular parameter within its range of variation.

Table 3 shows the influence of a number of individual parameters for three different plant sizes ($P_e = 5$, 10 and 20 MW).

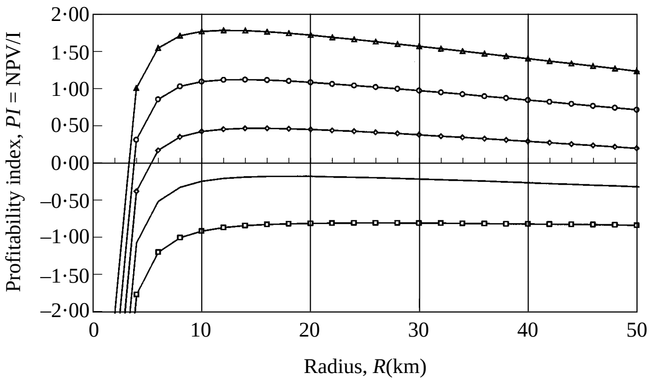

Fig. 3. Variation of profitability index (PI) with radius (R) as a function of electricity price (p_e) –□– 40 ECU/MW; – – 65 ECU/MW; –◇– 90 ECU/MW; –○– 115 ECU/MW; –△– 140 ECU/MW

From the numerical data in Table 3, which shows how profitability index is affected by variations of ±20% in each individual parameter, and from *Figs 2–5* it is clear that running time *t*, thermal energy utilization factor f_u, specific investment *I*, biomass net

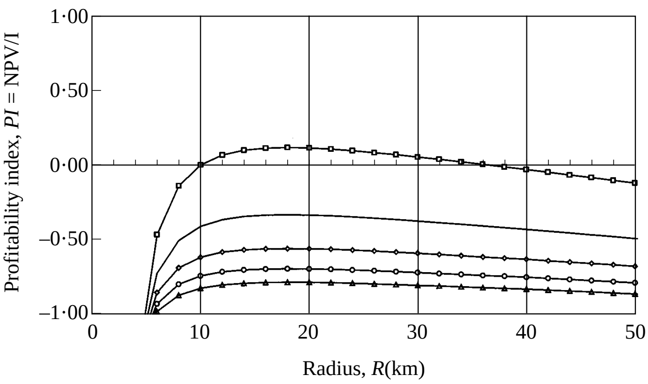

Fig. 2. Variation of profitability index (PI) with radius (R) as a function of specific investment (I_s): –□– 1 200 000 ECU/MW; – – 1 800 000 ECU/MW; –◇– 2 400 000 ECU/MW; –○– 3 000 000 ECU/MW; –△– 3 600 000 ECU/MW

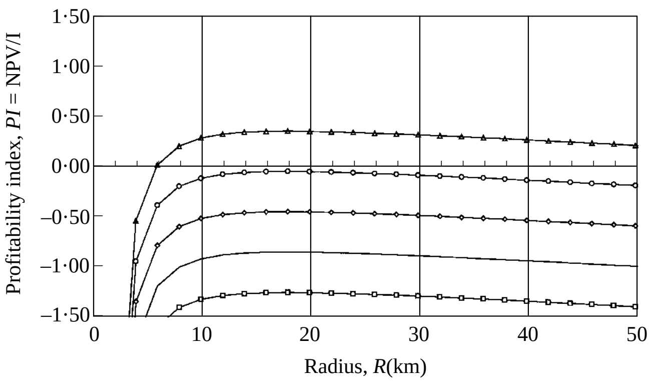

Fig. 4. Variation of profitability index (PI) with radius (R) as a function of thermal energy utilization factor (f_u): –□– 0·00; – – 0·25; –◇– 0·50; –○– 0·75; –△– 1·00

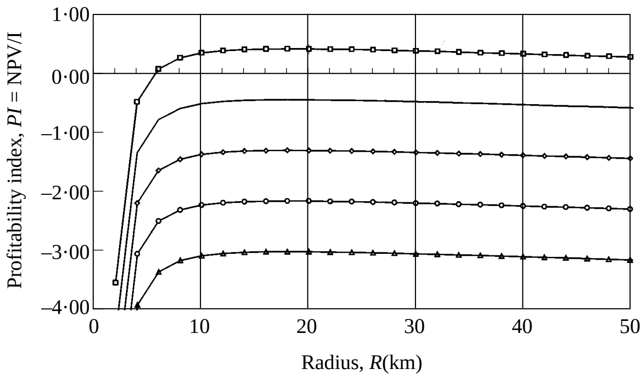

Fig. 5. Variation of profitability index (PI) with radius (R) as a function of specific biomass cost (C_{bs}): –□– 20 ECU/t; – – 50 ECU/t; –◇–: 80 ECU/t; –○–: 110 ECU/t; –△–: 140 ECU/t

calorific value H_b, specific biomass purchasing cost C_{bs} and the price of electric energy p_e and thermal energy p_t have a more than proportional effect on *PI*. It is also interesting to note how the sensitivity of *PI* decreases as plant power increases.

As for the remaining parameters, varying their values from the lower to the upper limit does have an effect on *PI* but with rather less sensitivity. The effect is clearly positive for those parameters that contribute to increasing the cash flow income (useful life V_u, electrical and thermal efficiency η_e and η_t, biomass yield δ) and negative for those parameters that result in increased costs (repairs and maintenance coefficient k_r, number of employees n_u and average pre-tax labour costs C_{ws}, biomass handling costs C_{ts} and real discount rate i).

Table 3
Sensitivity analyses

Parameters		*Parameters (standard values)*	*Parameter variation*	*Corresponding variation in PI* 5 *MW*	10 *MW*	20 *MW*
Running time (h/yr)	t	7 000	−20% +20%	−32% +32%	−32% +32%	−27% +27%
Useful economic life (yr)	V_u	20	−20% +20%	−9% +6%	−9% +6%	−7% +5%
Electric efficiency	η_e	0·22	−20% +20%	−29% +19%	−29% +19%	−29% +19%
Thermal efficiency	η_t	0·62	−20% +20%	−34% +34%	−33% +33%	−31% +31%
Utilisation factor (thermal energy)	f_u	0·50	−20% +20%	−34% +34%	−33% +33%	−31% +31%
Maintenance factor per year	k_r	0·03	−20% +20%	+11% −11%	+11% −11%	+10% −10%
Specific investment (ECU/MW)	I_s	2 100 000	−20% +20%	+41% −27%	+40% −27%	+35% −23%
Total employees (units)	n_u	12	−20% +20%	+3% −3%	+1% −1%	+1% −1%
Average wage per capita (ECU/yr)	C_{ws}	30 000	−20% +20%	+3% −3%	+1% −1%	+1% −1%
Biomass yield (t/km^2 yr d.m.)	δ	200	−20% +20%	−3% +2%	−2% +1%	−1% +1%
Biomass net calorific value (MWh/t d.m.)	H_b	4·5	−20% +20%	−83% +55%	−82% +55%	−78% +52%
Biomass cost (storage included) (ECU/t d.m.)	C_{bs}	50	−20% +20%	+60% −60%	+59% −59%	+55% −55%
Biomass cost of transport (ECU/t km d.m.)	C_{ts}	0·30	−20% +20%	+4% −4%	+5% −5%	+7% −7%
Price of electric energy (ECU/MWh)	p_e	55	−20% +20%	−65% +65%	−64% +64%	−60% +60%
Price of thermal energy (ECU/MWh)	p_t	20	−20% +20%	−34% +34%	−33% +33%	−31% +31%
Interest rate	i	0·10	−20% +20%	+17% −13%	+16% −13%	+14% −11%

Table 4
Input data for the Italian case study

Parameters		*Unit*	*Value*
Conversion plant			
Running time	t	h/yr	7 000
Useful economic life	V_u	yr	8
Electric efficiency	η_e	—	0·22
Thermal efficiency	η_t	—	0·62
Utilisation factor (thermal energy)	f_u	—	0·5
Maintenance factor per year	k_r	—	0·03
Manpower			
Total employees	n_u	units	12
Average wage per capita	C_{ws}	ECU/yr	26 000
Biomass (*d.m.*)			
Yield	δ	t/km^2 yr	57
Net calorific value	H_b	MWh/t	4·5
Cost (storage included)	C_{bs}	ECU/t	50
Cost of transport	C_{ts}	ECU/t km	0·40
Economic parameters			
Price of electric energy	p_e	ECU/MWh	141
Price of thermal energy	p_t	ECU/MWh	10·5
Interest rate	i	—	0·15

Note: 1 ECU = 1910 Italian Lira.

4. Application of the model to the Italian situation

A recent evaluation of the quantity of residual biomass suitable for combustion that is present on Italian territory[12] found the net availability to be in the order of 17 Mt/yr d.m. Of this, approximately 45% comes from agriculture (crop by-products), 45% from wood and forestry residue, and the remaining 10% is industrial waste from raw-materials transformation. The biomass yield, measured in all 95 Italian provinces, ranges from a minimum of $\delta_{min} = 20$ t/km^2 yr d.m. to a maximum of $\delta_{max} = 390$ t/km^2 yr d.m., with a national average of $\delta = 57$ t/km^2 yr d.m.

The model described above was applied to the total area of Italian territory ($S_t = 301\,225$ km^2), using the input values shown in Table 4. The economic parameter that differs most greatly from the standard value given in Table 1 is the price of electricity ($p_e = 141$ ECU/MWh), which is guaranteed for the first eight years of plant operation. It is much higher than the standard price of 55 ECU/MWh.

The results obtained (Table 5) show that it is feasible to operate plants having installed power $P_{eo} = 14$ MW, with associated specific investments that can be as high as $I_{so} = 2\,660\,000$ ECU/MW. Overall, the number of plants (n_o) potentially installable in the whole of Italy would be 172 and would generate a total electric power of approximately 2 400 MW and a

Table 5
Outputs of the Italian case study

Results		*Unit*	*Value*
Optimum radius	R_o	km	23·6
Optimum area	S_o	km^2	1 743
Optimum electric power	P_{eo}	MW	14·1
Corresponding thermal power	P_{to}	MW	39·9
Maximum allowed specific investment	I_{so}	ECU/MW	2 663 000
Total investment required	I_o	MECU	37·4
Net present value	NPV	ECU/yr	0
Profitability index	PI	—	0

thermal power of 6 650 MW. Under the operating conditions described and at the current market costs of plants (I_{slim} = 2 100 000–2 500 000 ECU/MW), the purchase cost of biomass (C_{bs}) with an eight year payback period and an IRR of 15%, could reach 70 ECU/t. At this level, it could represent an interesting source of additional income for farmers.

5. Conclusions

The proposed simplified model is able to determine the effect and technical and economic parameters on the profitability of biomass-fuelled electric power plants. It is particularly suitable for preliminary feasibility assessments of individual plants and for analysing the effectiveness of specific incentives geared to encouraging energy applications of biomass. The use of biomass is directly dependent on containment of its procurement costs (a difficult course to undertake) or on targeted tariff-incentive policies (which have, in practice, become indispensable).

From a technical standpoint and with reference to average European conditions, the key factors for achieving good economic performance are the thermal energy utilization factor, which must be as high as possible, and the investments which, for biomass, are about double those for modern conventional gas-turbine plants.

Due to the high price guaranteed for electricity produced from renewable sources, the application of the model in the Italian situation gives very interesting results, in terms both of number and power of the installable plants. In the near future, the model will be applied to two specific agricultural areas, located in a central and in a northern region of Italy.

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