Model for the economic, energy and environmental evaluation in biomass productions

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Abstract

In the near future, renewable energies will have a decisive role to play in attempts to achieve the ambitious objectives fixed by the European Union. Consequently, not only the economic aspect but also energy and environmental issues of agroenergy chains (AEC) must be carefully evaluated. Software (SE^3A) able to assess economic, energy and environmental performance of AEC has been developed. The aim of this paper is to present SE^3A and show its usefulness in evaluating different AEC and/or different technical solutions. For the moment, the analysis is restricted to: i) field and ii) post-harvest (transport/storage) phases of the AEC. As an example of SE^3A flexibility, economic, energy and environmental costs (EEE costs) related to the cultivation technique used in northern Italy for the poplar short rotation coppice were evaluated.

Introduction

The need to reduce fossil energy consumption and emissions of greenhouse gases (GHG) has led to a huge increase in interest in renewable energy (RE). Considering that the profitability of *traditional* food crops is falling, RE represents an interesting opportunity for the agricultural sector (Foppa, 2010). The increasing demand for energy, the depletion of fossil fuel stocks and the rise in GHG emissions are problems that are being addressed by many governments and international organizations. Common objectives have already been defined: i) reducing consumption of fossil energy; ii) increasing the share of primary demand through the use of RE; and consequently (iii) the reduction in GHG emissions (European Parliament, 2009, 2010).

The development of agroenergy chains (AEC) is linked to their technical feasibility and the achievement of favorable economic results. The agroenergy sector will not be able to expand without economic sustainability and unless this happens, its contribution to the search for renewable energy sources will be lost. Public subsidies guarantee economic results but run the risk of developing chains that do not have a favorable energy and/or environmental profile. Consequently, AEC global sustainability can be defined through the integration of its economic, energy and environmental performances. The first two aspects are easy to identify by the ratio between returns and costs. The environmental aspect is usually harder to assess and its evaluation can include several items such as air/water pollution, water acidification, toxicity, etc. However, the current approach is focused on GHG emissions only. Given this, an AEC is environmentally acceptable when, while producing energy, it emits less GHG with respect to fossil fuels generating the same energy.

AEC global sustainability (economic, energy and environmental aspects) has been a focus of attention for some time. However, a critical issue remains: the lack of uniformly accepted and applied methodologies. In particular, the calculation of GHG emissions is only a recent development and some aspects are still under discussion (Guinée, 2002; AA.VV., 2006; Daviet, 2007; Reap, 2008a, 2008b; Cherubini, 2009). Information about energy and environmental costs is not always reliable and it is often possible to find different results reported for the same AEC. These differences usually come from the use of different methodologies or of non-uniform parameters (Pimentel, 2003; Shapouri, 2003; Farrel, 2006). AEC sustainability cannot be generalized and must be evaluated in its specific context, for example, through on site analysis.

Over the years, many different software programs have been developed to evaluate the energy and environmental aspects related to production processes. The main purpose of these tools is to assess the energy inputs and environmental load associated with the goods produced (ERG, 2006; ARGONNE, 2007; Spugnoli, 2009; Fiala, 2010b; D'Avino, 2010). Nevertheless, these readily-available software programs are generally difficult to apply to AEC because: i) they are not specifically developed to analyze this type of process; ii) they are often complex and difficult for non-experts to use; iii) the whole AEC is rarely analyzed and attention is usually focused only on some phases or operations, neglecting steps that have a big impact on the energy-environmental costs; iv) they are not flexible enough to assess AECs which are very different among themselves; v) this is not freeware and expensive licenses frequently have to be bought.

To address these issues, the Department of Agricultural Engineering of the University of Milan has developed a specific software program able to calculate the economic, energy and environmental (EEE) performances of the most widely used AECs.

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Key words: biomass, energy, chain-supply, sustainability, model, short rotation coppice.

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Materials and methods

The SE^{3}A (Software for Economic, Energetic, and Environmental Analysis) software is based on well-known methodologies: i) fixed and variable costs for economic analysis; ii) gross energy requirement (GER) for energy analysis (Slesser, 1982; Franzese, 2009); iii) IPCC and EU guidelines for environmental assessment (ISO, 2006; IPCC, 2006).

The AEC energy and environmental costs are defined with an *LCA-oriented* approach; the software follows the ISO standards related to the Life Cycle Assessment, ISO 14040 (ISO, 2006) according to which fossil fuel consumptions, as well as the GHG emissions related to the production cycle, are considered.

SE^{3}A has the following basic advantages:
- it allows different AECs and/or different technical solutions in the same AEC to be analyzed;
- it is user friendly;
- it provides easy to understand results that allow quick comparisons to be made between different AECs.

At present, the software manages the first two AEC phases: i) the field phase (biomass production and/or supply); and ii) the post-harvest phase (transport/storage/processing). The third and last phase (conversion into energy) is still under development.

For each phase, the operator must identify the logical sequence characterizing the process (single operations list). For all these operations, the amount of utilized production factors, either direct (DF) or indirect (IF), must be specified. According to ISO 14040, the functional unit (FU) is *a measure of the performance of the functional outputs of the product system*. Materials' and energy flows are related to the selected functional unit, which becomes the reference quantity for every kind of comparison.

Since for the moment assessment is restricted to the first two AEC phases, the possible FUs are:
- the mass (or the volume) of the picked-up (agricultural by-products, animal manure) or produced (energy crop) biomass. In the specific case of biofuels (characterized by different net calorific value, NHV; MJ/kg$_{WB}$), the collected energy is the best FU;
- the area of biomass production under assessment.

Once the software is capable of assessing the energy conversion phase it will be possible to select as FU the generated energy (electrical or thermal) or the energy carrier (bioethanol, SVO or biodiesel, biomethane) (Figure 1).

The software requires a huge input of data and information. SE^{3}A can be used for final analysis as well as for first AEC evaluations. In the first case, local and contextualized data, describing in detail the chain under investigation (farm-scale level), are needed. In the second, in which the objective is to achieve general results, input data must be representative of a *standard* AEC.

As far as the field phase is concerned, the EEE performances are calculated as a function of the soil used for biomass production (AUA_{ENERGY}; ha).

The EEE costs of the AEC are expressed by the logical integration of the three following parameters:
- economic costs (€);
- energycosts (MJ);
- environmental costs (kg CO_2eq.).

The mechanization of field operations is assumed to be carried out first by the farm's machinery fleet or, if this is not possible, by contractors. In this latter case, economic (€/ha), energy (€/MJ) and environmental (kg CO_2 eq/ha) tariffs must be used as input.

Using farm fleet machines, the EEE costs related to biomass production are computed by also taking into account their possible use over conventional crops (food or feed) cultivated on the farm, dividing all the costs proportionally to their annual use.

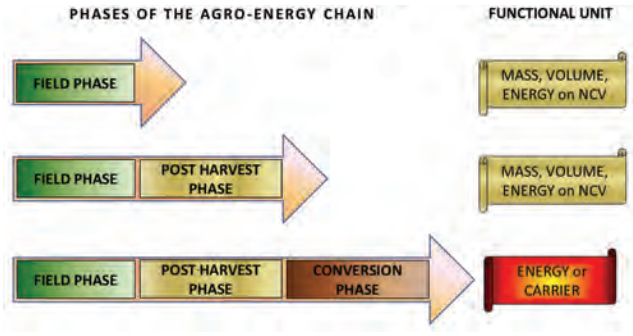

Figure 1. The functional unit choice depends on the chain phases under analysis.

The software takes into account the use of DF and IF production factors, although some of them (*i.e.* land benefit, manpower) are only considered for economic analysis.

The EEE costs linked to DF use are charged exclusively to the energy chain. In fact, they are totally consumed within the AEC and are calculated as:

$$C_{ECO_DF} = M_{DF} \cdot P_{DF} \cdot AUA_{ENERGY} \quad (€/year) \quad (1a)$$
$$C_{ENE_DF} = M_{DF} \cdot EQ_{DF} \cdot AUA_{ENERGY} \quad (MJ/year) \quad (1b)$$
$$C_{ENV_DF} = M_{DF} \cdot FE_{DF} \cdot AUA_{ENERGY} \quad (kg\ CO_2\ eq./year) \quad (1c)$$

where:
M_{DF} = DF amount (kg/ha ·year or m^3/ha ·year);
P_{DF} = DF unit price (€/kg or €/m^3);
EQ_{DF} = DF energy equivalent (MJ/kg or MJ/m^3) (Jarach, 1985);
FE_{DF} = DF emission factor (kg CO_2eq./kg or kg CO_2eq./m^3) (Bini, 2002; Lai, 2004);
AUA_{ENERGY} = farm area used for agriculture dedicated to biomass production (ha).

On the contrary, the EEE costs related to the use of indirect production factors (IF) are not charged entirely to the AEC because the factors involved (*e.g.* machinery, building, etc.) are not completely consumed within a single production cycle. Consequently, the total *embedded values* ($C_{ECO_IF_tot}$; $C_{ENE_IF_tot}$; $C_{ENV_IF_tot}$) are as follows:

$$C_{ECO_IF_tot} = I_0 \quad (€) \quad (2a)$$
$$C_{ENE_IF_tot} = M_{IF} \cdot EQ_{IF} \quad (MJ) \quad (2b)$$
$$C_{ENV_IF_tot} = M_{IF} \cdot FE_{IF} \quad (kg\ CO_2\ eq.) \quad (2c)$$

where:
I_0 = investment (€);
M_{IF} = IF amount (kg or m^3);
EQ_{IF} = IF energy equivalent (MJ/kg or MJ/m^3) (Jarach, 1985);
FE_{IF} = IF emission factor (kg CO_2eq./kg or kg CO_2eq./m^3) (Bini, 2002; Lai, 2004);

On the other hand, because the IF production factors are not completely consumed within a single production cycle, their EEE costs (C_{ECO_IF}; C_{ENE_IF}; C_{ENV_IF}) must be split according to: i) depreciation time (D_E; years); ii) total annual use (H_T; h/year); iii) annual use for the AEC (H_F; h/year):

$$C_{ECO_IF} = (C_{ECO_IF_tot} \cdot H_F)/(H_T \cdot D_E) \quad (€/year) \quad (3a)$$
$$C_{ENE_IF} = (C_{ENE_IF_tot} \cdot H_F)/(H_T \cdot D_E) \quad (MJ/year) \quad (3b)$$
$$C_{ENV_IF} = (C_{ENV_IF_tot} \cdot H_F)/(H_T \cdot D_E) \quad (kg\ CO_2\ eq./year) \quad (3c)$$

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The mechanization costs consider the yearly worked area and the effective field capacity of the different machines (FC; ha/h). The software assumes different FC for the same machine working on the energy crop (AUA_{ENERGY}; ha) or on conventional crop (AUA_{FOOD}; ha). For farm tractors, the total annual use is computed taking into account, besides operations on energy and conventional crops, other generic jobs (farm road maintenance, cleaning ditches, etc.). Although the RES Directive guidelines do not consider the energy and environmental costs related to IF use, the SE^{3}A can also take into account this option. To calculate the EEE performances, specific records, appropriately developed and organized, are used. These records include technical data about the production factors and can be constantly adopted and updated. The main records refer to: prices, energy equivalents, emission factors and technical parameters of machines, plants and buildings.

In addition to the emissions due to use of production factors, according to the IPCC guidelines that provide default values for this kind of emission, the software also computes emissions of nitrous oxide (E_{N2O}) from the use of nitrogenous fertilizers. This other type of GHG emissions strongly depends on: i) soil and climatic conditions; ii) tillage system; iii) amounts of nitrogenous fertilizers:

$$E_{N2O} = N_R \cdot k_{N2O} \cdot GWP_{N2O} \cdot AUA_{ENERGY} \quad \text{(kg } CO_2 \text{ eq./year)} \quad (4)$$

where:
N_R = total amount of nitrogen applied to the soil by means of fertilizers, depending on amount and type of fertilizer (kg_N/ha · year);
k_{N2O} = emission coefficient for nitrogen (kg_{N2O}/kg_N, 0.00125) (IPCC, 2006);
GWP_{N2O} = Global Warming Potential for N_2O (-, 296) (IPCC, 2006).

The three total AEC costs (C_{ECO_C}; C_{ENE_C}; C_{ENV_C}) are obtained by adding the costs linked to each production factor used:

$$C_{ECO_C} = \Sigma\, C_{ECO_DF} + \Sigma\, C_{ECO_IF} \quad (€/\text{year}) \quad (5a)$$
$$C_{ENE_C} = \Sigma\, C_{ENE_DF} + \Sigma\, C_{ENE_IF} \quad (\text{MJ/year}) \quad (5b)$$
$$C_{ENV_C} = \Sigma\, C_{ENV_DF} + \Sigma\, C_{ENV_IF} + E_{N2O} \quad (\text{kg } CO_2 \text{ eq./year}) \quad (5c)$$

The EEE costs of the agro-energy chain can be finally represented as a logical addition of these three terms:

$$(C_{ECO_C} + C_{ENE_C} + C_{ENV_C}) \quad (6)$$

When the AEC also produces co-products (or exploitable byproducts), according to the RES Directive, the software allows EEE costs to be allocated on the basis of the energy contents of: i) the main product (P); ii) the co-product (C) or the byproducts (B).

Nevertheless, the EEE costs can also be divided according to: i) P, C or B quantities; ii) their selling price. Therefore, referring to the main product (P), the EEE costs of the AEC ($C_{ECO_C_P}$; $C_{ENE_C_P}$; $C_{ENV_C_P}$) are expressed as:

$$C_{ECO_C_P} = C_{ECO\ C} \cdot k_A \quad (€/\text{year}) \quad (7a)$$
$$C_{ENE_C_P} = C_{ENE\ C} \cdot k_A \quad (\text{MJ/year}) \quad (7b)$$
$$C_{ENV_C_P} = C_{ENV\ C} \cdot k_A \quad (\text{kg } CO_2 \text{ eq./year}) \quad (7c)$$

where: k_A = coefficient of allocation, share of the cost associated with the main product; consequently, (1-k_A) is allocated to byproducts (B) or co-products (C); for AEC without exploitable co-products/byproducts, k_A=1.

Starting from absolute costs and taking into account the allocation criterion, specific costs ($C_{ECO_C_Ps}$; $C_{ENE_C_Ps}$; $C_{ENV_C_Ps}$) can be calculated according to the FU previously selected. For instance, selecting the wood chip mass (t_{WB}) as FU, we obtain:

$$C_{ECO_C_Ps} = C_{ECO\ C_P}/(Y \cdot AUA_{ENERGY}) \quad (€/t_{WB}) \quad (8a)$$
$$C_{ENE_C_Ps} = C_{ENE\ C_P}/(Y \cdot AUA_{ENERGY}) \quad (\text{MJ}/t_{WB}) \quad (8b)$$
$$CE_{NV_C_Ps} = C_{ENV\ C_P}/(Y \cdot AUA_{ENERGY}) \quad (\text{kg } CO_2\text{eq.}/t_{WB}) \quad (8c)$$

where:
Y = biomass yield (t_{WB}/ha · year).

The specific costs can be also expressed as: i) €/t_{WB}, MJ/t_{WB} and kg CO_2 eq./t_{WB}; ii) €/MJ, MJ/MJ and kg CO_2 eq./MJ; iii) €/ha, MJ/ha and kg CO_2 eq./ha, using as FU the wet biomass, the energy contained in wet biomass, and the area dedicated to biomass production, respectively.

Finally, since sometimes the comparison between different AECs (or technical solutions of the same AEC) does not appear to be immediate, a Global Cost Index (GCI) summarizing the performances achieved on the three aspects is given. The global AEC sustainability is represented by the area of the triangle whose vertices represent the economic, energy and environmental costs. Assuming that the same weight (multi-criteria analysis) is associated with these three aspects, the bigger the triangle area is, the lower the AEC global sustainability is.

The symbols used for the different parameters are shown in Table 1.

A case study

In Italy, much research has been carried out into poplar short rotation coppice (SRC) and there has appeared to be some variation in results. The performances of this ligneous-biomass crop are strongly affected by: soil and climatic conditions, species, clones and cropping systems (Dubuisson, 1998; Matthews, 2001; Heller, 2003, 2004; Gasol, 2009; Fiala, 2010a; Bacenetti, 2011; Gonzales, 2012).

The case study analyzed here considers the field phase of a poplar SRC. The energy crop is located on an irrigated farm in the Po valley (AUA = 100 ha). Part of this total area is dedicated to poplar (AUA_{ENERGY}) while the rest is cultivated with maize for silage (AUA_{FOOD}).

The basic features of poplar SRC are: i) transplanting system (single row); ii) plant density: 5560 plants/ha (0.6 m on the row; 3.0 m intra-rows); iii) poplar clone: AF2; iv) cutting interval (2 years); v) crop duration (10 years); vi) biomass harvesting system (self-propelled forage-harvester equipped with a biomass header) (Fiala, 2011). Two cropping systems are analyzed with and without IF supply (Table 2):

- L: low production factors level, wood-chip yield Y = 20 t_{WB}/ha · year (U = 55% wet basis, LHV 18.5 MJ/kg_{DM});
- H: high production factors level, wood-chip yield Y = 35 t_{WB}/ha · year (U = 55% wet basis, LHV 18.5 GJ/t_{DM}).

As far as the two levels of production factors are concerned, the basic differences refer to: i) the mineral fertilizer rate; ii) the pest-control management; and iii) the mechanical weed control.

A schematic presentation of the AEC field phase is shown in Figure 2, while Table 3 reports the field operations carried out both over poplar SRC and maize.

Poplar transplanting, biomass harvesting and final soil recovery require machines that are not usually part of the farm fleet and are, therefore, carried out by contractors. In this case, from an economic point of view, prices asked by local contractors must be used. Tariffs can be computed with the SE^{3}A, running the calculation with a very long annual use of both tractor and machinery.

To facilitate the comparison between different areas in which the poplar SRC can be cultivated, neither the benefit to the land or the general farm management costs have been considered.

Similarly, the economic returns depend only only the sale of wood chip (average market price: 30 €/t_{WB}), and ignore possible public subsidies.

An example of computation

In order to show in detail how the software SE^{3}A works, the energetic and environmental costs of the mineral fertilization operation are analyzed step by step; the case H+ (see Tables 2 and 3) is considered.

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Table 1. Symbols used in the description of methods.

Symbol	Parameter	Unit of measurement
LHV	Biomass low heat value	MJ/kg_{DM}
NHV	Biomass net heat value	MJ/kg_{WB}
U	Biomass moisture content	% wet basis
Y	Biomass yield	t_{WB}/ha/year
AUA AUA_{ENERGY} AUA_{FOOD}	Total farm agricultural used area Farm agricultural used area addressed to energy crop Farm agricultural used area to conventional crop	ha
C_{ECO_DF} C_{ENE_DF} C_{ENV_DF}	EEE costs related to the DF	€/year MJ/year kg CO_2 eq./year
M_{DF}	DF amount	kg or m^3/ha/year
P_{DF}	DF unit price	€/ kg or €/m^3
EQ_{DF}	DF energy equivalent	MJ/kg or MJ/m^3
FE_{DF}	DF emission factor	kg CO_2eq./kg or kg CO_2eq./m^3
$C_{ECO_IF_tot}$ $C_{ENE_IF_tot}$ $C_{ENV_IF_tot}$	EEE total embedded value related to the IF	€ MJ kg CO_2 eq.
C_{ECO_IF} C_{ENE_IF} C_{ENV_IF}	EEE costs related to the IF	€/year MJ/year kg CO_2 eq./year
I_0	Investment	€
M_{IF}	IF amount	kg or m^3
EQ_{IF}	IF energy equivalent	MJ/kg or MJ/m^3
FE_{IF}	IF emission factor	kg CO_2eq./kg or kg CO_2eq./m^3
D_E	Depreciation time (tractors and machinery)	years
H_T	Total annual use (tractors and machinery)	h/year
H_F	Annual use over AEC (machinery)	h/year
FC	Effective field capacity (machinery)	ha/h
E_{N2O}	GHG emissions related to nitrogenous fertilizers	kg CO_2 eq./ha/year
N_R	Nitrogen applied to the soil by fertilizers	kg_N/ha/year
k_{N2O}	Nitrogen emission coefficient	kg_{N20}/kgN
C_{ECO_C} C_{ENE_C} C_{ENV_C} C_{EEE_C}	AEC economic costs AEC energy costs AEC environmental costs EEE costs of the AEC	€/year MJ/year kg CO_2 eq./year -
$C_{ECO_C_P}$ $C_{ENE_C_P}$ $C_{ENV_C_P}$	AEC economic costs allocated on main P AEC energy costs allocated on main P AEC environmental costs allocated on main P	€/FU MJ/FU kg CO_2 eq./FU
k_A	Coefficient of allocation	%
$C_{ECO_C_Ps}$ $C_{ENE_C_Ps}$ $C_{ENV_C_Ps}$	AEC specific economic costs, related to FU AEC specific energy costs, related to FU AEC specific environmental costs, related to FU	€/FU MJ/FU kg CO_2 eq./FU
η_g	Tractor power coupling efficiency	%
P_M	Tractor maximum power	kW
P_R	Power required by coupled machine	kW

EEE, economic, energy and environmental; DF, direct production factor; IF, indirect production factor; AEC, agroenergy chain; GHG, greenhouse gases; P, product; FU, functional unit.

Table 2. General pattern of the economic, energy and environmental cost analysis.

Cropping system	Indirect production factors	Cases
L	Yes No	L+ L-
H	Yes No	H+ H-

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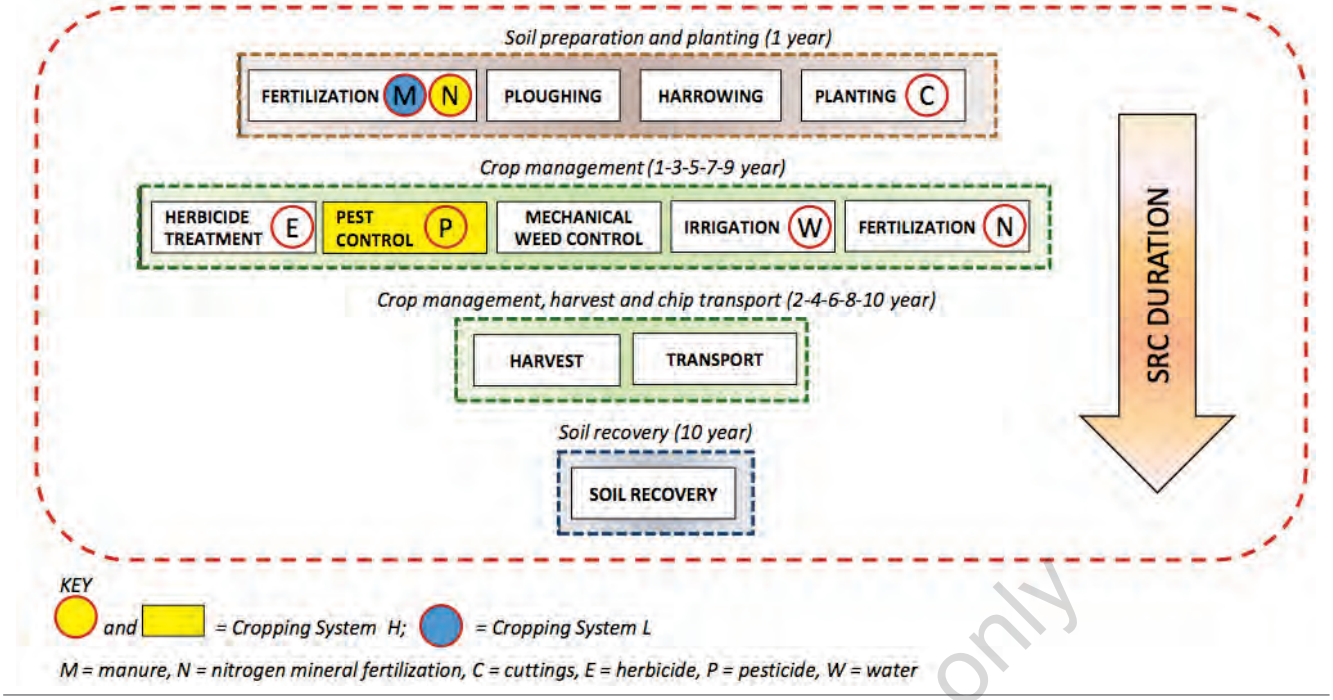

Figure 2. Field phase of the poplar short rotation coppice agroenergy chain: the two cropping systems.

Table 3. Inventory of two cropping systems.

	Operation	CS (*)	Mechanization				Year (No. interventions)		Notes
			Machinery FC (ha/h); P_R (kW)	Tractor P_M (kW)	Owner	Coupling and size (°)	Poplar	Maize	
Pre-planting	Pre-planting fertilization	H	Fertilizer spreader 3.0; 55	90	Farmer	PP, 1500 dm^3	1 (1)	- (-)	150 kg N, 120 kg P_2O_5 250 kg K_2O/ha
		L	Manure spreader 2.0; 40	90	Farmer	TP, 10 t, 10 m^3	1 (1)	From 1 to 10 (1)	50 t/ha manure
	Primary soil cultivation	H; L	Plough 0.6; 85	190	Farmer	P, double shovel	1 (1)	From 1 to 10 (1)	-
	Secondary soil cultivation	H; L	Rotary harrow 0.5; 55	90	Farmer	PP, 2.40 m	1 (1)	From 1 to 10 (1)	- 5560 cuttings/ha
Planting	Planting	H; L	Planting machine 0.7; 65	100	Contractors	T, double row	1 (1)	-	
Crop management	Chemical weed control	H; L	Spraying machine 3.0; 40	90	Farmer	PP, 15 m, 1000 dm^3	1-3-5-7-9 (1)	From 1 to 10 (1)	20 kg/ha
	Pest control	H	Spraying machine 3.0; 40	90	Farmer	PP, 15 m, 1000 dm^3	1-3-5-7-9 (1)	From 1 to 10 (1)	10 kg/ha
		L	Spraying machine 3.0; 40	-	Farmer	PP, 15 m, 1000 dm^3	- (-)	From 1 to 10 (1)	-
	Cover fertilization	H	Fertilizer spreader 3.0; 55	90	Farmer	PP, 1500 dm^3	3-5-7-9 (1)	From 1 to 10 (2)	H = 320 kg/ha (urea)
		L	Fertilizer spreader 3.0; 55	90	Farmer	PP, 1500 dm^3	3-5-7-9 (1)	From 1 to 10 (2)	L = 200 kg/ha (urea)
	Mechanical weed control	H	Rotary harrow 0.5; 55	90	Farmer	PP, 2.40 m	1-3-5-7-9 (2)	-	-
		L	Rotary harrow	90 0.5; 55	Farmer	PP,	1-3-5-7-9 2.40 m	- (1)	-
Harvest	Harvest	H; L	Harvester 1.0; -	-	Contractors	SPM	2-4-6-8-10 (1)	-	H = 35 t_{WB}/ha year L = 20 t_{WB}/ha year
	Transport	H; L	n.3 Trailer 0.33; 30	90	Contractors, farmer	T, PP	2-4-6-8-10 (1)	-	H = 35 t_{WB}/ha year L = 20 t_{WB}/ha year
Final recovery	Soil recovery	H; L	Hoeing machine 0.2; 50	90	Contractors	P, 1.20 m	10 (1)	- -	- -

*CS, cropping system; °PP, coupling with pto (η_s = 0.7); P, coupling without pto (η_s = 0.65); T, trailed coupling (η_s = 0.56); SPM, self-propelled machine.

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Economic costs computation are not reported, taking into account that the methodology (Lazzari, 2005) is well known.

Energy and environmental costs due to direct production factor

Energy and environmental costs depend on nitrogenous fertilizers, fuel and oil consumption. The amount of fertilizer is input data provided by the user while both fuel and oil consumptions are calculated by the software according to: i) required power by the machine (P_R, kW); ii) maximum power of tractor (P_M, kW); iii) type of coupling (coupling efficiency; η_g); iv) minimum specific fuel consumption equal to 220 g/kWh. Given reports in the literature (Jarach, 1985; Bini, 2002; Lai, 2004; Saunders, 2006):

- M_{DF_1, MDF_2}, M_{DF_3} = amounts of nitrogenous fertilizers (urea, 46% N), fuel and oil, respectively equal to 80, 4.05 and 0.02 kg/ha · year;
- EQ_{DF_1}, EQ_{DF_2}, EQ_{DF_3} = energy equivalents for nitrogenous fertilizers, fuel and oil, respectively equal to 33.8, 51.3 and 82.0 MJ/kg;
- FE_{DF_1}, FE_{DF_2}, FE_{DF_3} = emission factors, respectively equal to 4.80, 3.64 and 3.46 kg CO_2eq./kg; bearing in mind (1b) and substituting, the direct energy costs are:

$C_{ENE_DF_1} = (80 \cdot 33.8) \cdot 40 \cong 108{,}160$ MJ/year for urea;
$C_{ENE_DF_2} = (4.05 \cdot 51.3) \cdot 40 \cong 8311$ MJ/year for fuel;
$C_{ENE_DF_3} = (0.02 \cdot 82.0) \cdot 40 \cong 66$ MJ/year for lubricant;

for a total of:

$C_{ENE_DF_FERT} = C_{ENE_DF_1} + C_{ENE_DF_2} + C_{ENE_DF_3} = 116{,}537$ MJ/year.

Then, considering (equation 1c) and substituting, the direct environmental costs are:

$C_{ENV_DF_1} = (80 \cdot 4.80) \cdot 40 \cong 15{,}360$ kg CO_2eq./year for fertilizers;
$C_{ENV_DF_2} = (4.05 \cdot 3.64) \cdot 40 \cong 590$ kg CO_2eq./year for fuel;
$C_{ENV_DF_3} = (0.02 \cdot 3.46) \cdot 40 \cong 3$ kg CO_2eq./year for lubricant.

Now considering: i) to distribute urea (46% N); ii) an emission coefficient for nitrogen $k_{N2O} = 0.00125$; and iii) a $GWP_{N2O} = 296$, the GHG emissions linked to nitrous oxide emission from the soil are (equation 4):

$E_{N2O} = (80 \cdot 0.46) \cdot 0.00125 \cdot 296 \cdot 40 \cong 5446$ kg CO_2eq./year

for a total of:

$C_{ENV_DF_FERT} = C_{ENV_DF_1} + C_{ENV_DF_2} + C_{ENV_DF_3}\ E_{N2O} \cong 21{,}400$ kg CO_2eq./year

Energy and environmental costs due to indirect production factor

Similarly to DF costs, and considering reports in the literature (Jarach, 1985; Fiala, 2011):

- M_{IF} = spreader and tractor masses, equal to 350 and 5050 kg, respectively;
- EQ_{IF} = spreader and tractor energy equivalents, equal[1] to 69.0 and 92.0 MJ/kg, respectively;
- FE_{IF} = spreader and tractor factor emission, respectively equal to 11.0 and 14.7 kg CO_2eq./kg, respectively;
- D_E = spreader and tractor depreciation time, equal to 8 and 12 years, respectively; the embedded energy costs both in fertilizer spreader and coupled tractors are computed (equations 2b and c) as:

$C_{ENE_IF_tot1} = 350 \cdot 69.0 = 24{,}150$ MJ for spreader;
$C_{ENE_IF_tot2} = 5050 \cdot 92.0 = 464{,}600$ MJ for tractor;
$C_{ENV_IF_tot1} = 350 \cdot 11.0 = 3850$ kg CO_2eq. for spreader;
$C_{ENV_IF_tot2} = 5050 \cdot 14.7 = 74{,}235$ kg CO_2eq. for tractor.

[1]*All the embedded energy is assumed as electrical energy (Fiorense, 2007); consequently, the FE_{IF} is calculated on the basis of 0.575 kg CO_2eq./kWh$_e$ (average CO_2 emission for Italian electrical system).*

These embedded energies and GHG must be divided according to the annual use of the two machines over the poplar SRC and maize areas. For instance, taking an AUA_{ENERGY} = 40 ha and a FC = 3.0 ha/h (see Table 3), considering one distribution per year over poplar SRC and two distributions per year over maize, the total annual use of the spreader is HT_1 = 13.3+40.0 = 53.3 h/year.

Supposing that the coupled tractor is used on the farm for a total time of H_{T2} = 800 h/year, the embedded energy chargeable to mineral fertilization for the whole poplar cycle is (equations 3b and c):

$C_{ENE_IF_1} = [(24{,}150 \cdot 13.3)/(53.3 \cdot 8)] \cong 753$ MJ/year for spreader;
$C_{ENE_IF_2} = [(464{,}600 \cdot 13.3)/(800 \cdot 12)] \cong 644$ MJ/year for tractor;
$C_{ENV_IF_1} = [(3850 \cdot 13.3)/(53.3 \cdot 8)] \cong 120$ kg CO_2eq./year for spreader;
$C_{ENV_IF_2} = [(74{,}235 \cdot 13.3)/(800 \cdot 12)] \cong 103$ kg CO_2eq./year for tractor;

for a total of:

$C_{ENE_IF_FERT} = C_{ENE_IF_1} + C_{ENE_IF_2} = 1397$ MJ/year.
$C_{ENV_IF_FERT} = C_{ENV_IF_1} + C_{ENV_IF_2} = 223$ kg CO_2eq./year.

Total energy and environmental costs related to the mineral fertilization carried out during the whole poplar cycle is given by the sum of the above costs (equations 5b and c):

$C_{ENE_FERT} = C_{ENE_DF_FERT} + C_{ENE_IF_FERT} = 117{,}936$ MJ/year.
$C_{ENV_FERT} = C_{ENV_DF_FERT} + C_{ENV_IF_FERT} = 21{,}623$ kg CO_2eq./year.

Since byproducts are not present, the coefficient of allocation is k_A = 1 and the entire energy and environmental costs can be allocated (equations 8b and c) to wood chip mass (*i.e.* $Y \cdot AUA_{ENERGY} = 1400\ t_{WB}$):

$C_{ENE_Ps_FERT} = 117{,}936/1400 = 84.2$ MJ/t_{WB}.
$C_{ENV_Ps_FERT} = 21{,}623/1400 = 15.4$ kg CO_2eq./t_{WB}.

Results

Taking wood chip production (t_{DM}) as functional unit, the specific economic, energy and environmental costs are reported in Table 4 and Figure 3. Their trend clearly shows that under the case study conditions (basically characterized for the operations of planting, harvest and soil recovery made by contractors):

- the EEE costs are substantially independent of AUA_{ENERGY} for both the adopted cropping systems (H and L);
- the best performances are always achieved in an H cropping system (related to a high biomass production). On average, passing from the H to the L system, the 30% increase in EEE costs is due to the fact that the low level of production factors gives a smaller biomass yield;
- the indirect production factors result in an increase in specific energy and environmental costs, for both L and H poplar SRC cropping systems.

In more detail, by increasing the farm AUA_{ENERGY} from 5 to 95 hectares, all the specific costs show a slight decrease:

- economic cost: i) -1.9% for the H cropping system (range 36.2-35.4 €/t_{DM}); ii) -2.2% for the L cropping system (range 48.0-47.1 €/t_{DM});
- energy cost: i) -1.6% for the H cropping system (range 792-779 MJ/t_{DM}, equal to 4.3-4.2% of the wood chip LHV); ii) -1.9% (range 1053-1033 MJ/t_{DM}, equal to 5.7-5.5% of the wood chip LHV) for the L cropping system;
- environmental cost: i) -2.0% (range 105.9-108.1 kg CO_2 eq/t_{DM}) for the H cropping system; ii) -2.3% (range 137.7-1346 kg CO_2 eq/t_{DM}).

Considering now the influence of the indirect production factors

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Table 4. Specific economic, energy and environmental costs and global costs index for the 4 considered cases.

Cost system	Cropping prod.	Indirect factors	SRC poplar area (ha) 5	10	20	30	40	50	60	80	95
Economic €/t_{DM}											
	H	+ or -	36.2	36.2	36.0	35.9	35.8	35.7	35.6	35.5	35.4
	L	+ or -	48.0	47.9	47.7	47.5	47.4	47.3	47.2	47.1	47.1
Energy MJ/t_{DM}											
	H	+	792	791	789	787	785	784	782	780	779
		-					738				
	L	+	1053	1051	1048	1045	1042	1040	1038	1035	1033
		-					967				
Environmental kg CO_2 eq/t_{DM}											
	H	+	108.1	107.9	107.6	107.3	107	106.7	106.5	106.1	105.9
		-					99.3				
	L	+	137.7	137.4	136.9	136.5	136.1	135.7	135.4	134.9	134.6
		-					124.0				
Global cost index											
	H	+	2.39	2.39	2.38	2.37	2.36	2.35	2.34	2.33	2.32
		-	2.23	2.23	2.22	2.22	2.21	2.21	2.21	2.20	2.20
	L	+	3.66	3.65	3.63	3.61	3.60	3.59	3.58	3.56	3.55
		-	3.36	3.36	3.35	3.34	3.34	3.33	3.33	3.33	3.33

SRC, short rotation coppice.

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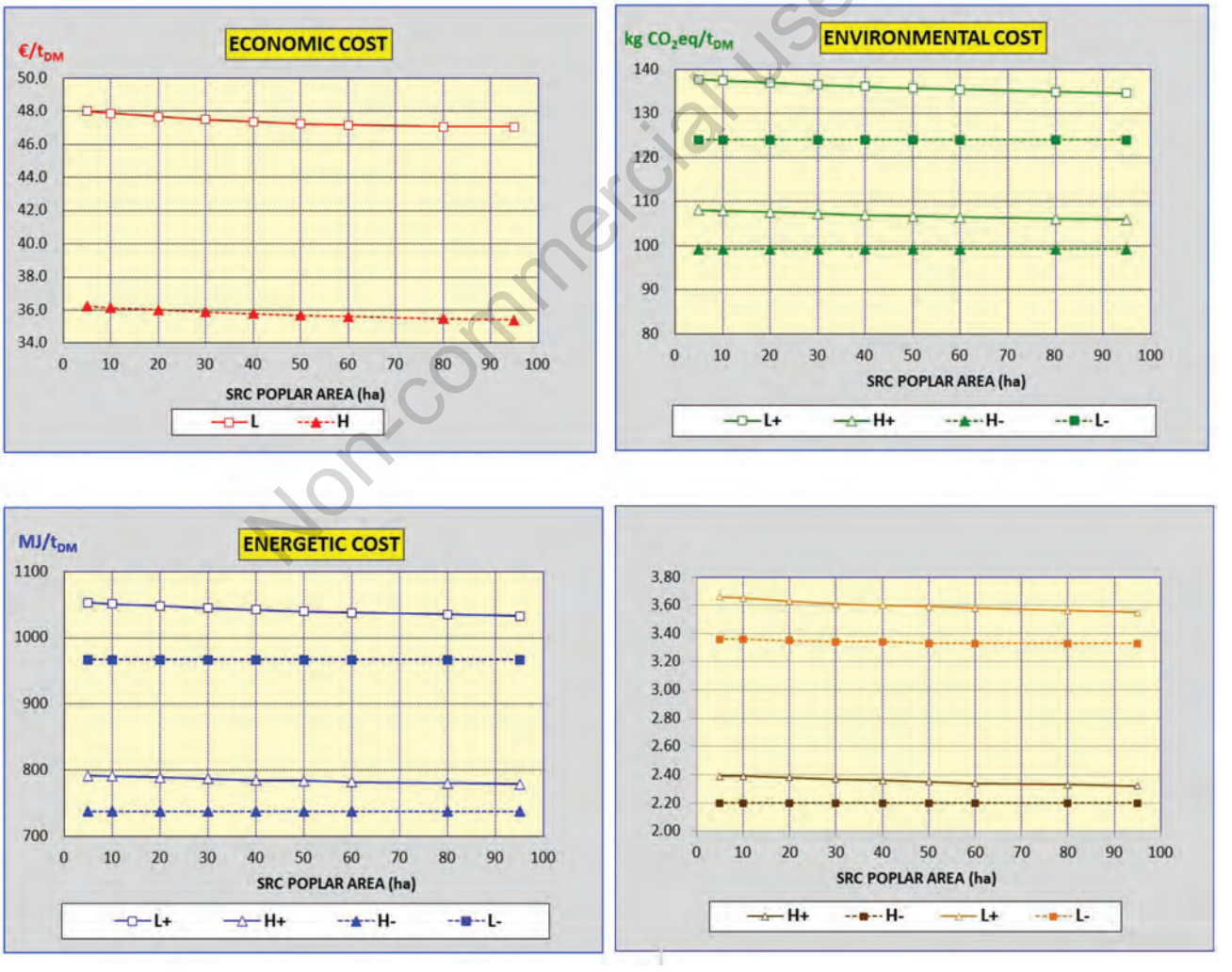

Figure 3. Trend of the three specific costs ($C_{ECO_C_Ps}$, €/t_{DM}; $C_{ENE_C_Ps}$, MJ/t_{DM}; $C_{ENV_C_Ps}$, kg CO_2eq/t_{DM}) which make up the economic, energy and environmental costs and corresponding trend of the global costs index (GCI) *vs* the farm area assigned to poplar short rotation coppice (SRC). (AUA_{ENERGY}; ha).

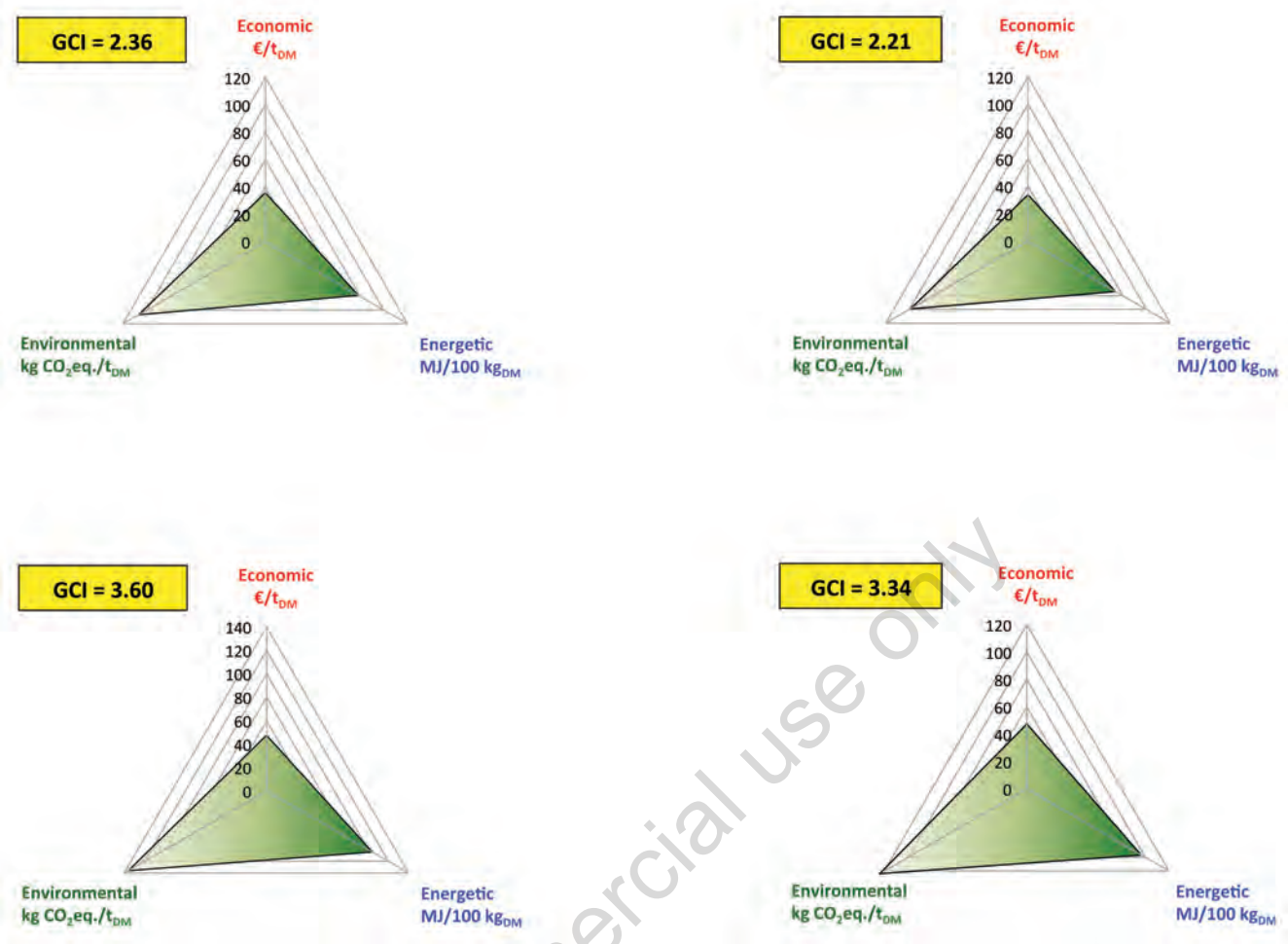

Figure 4. Economic, energy and environmental costs and global costs index (GCI) for the cases analyzed (poplar short rotation coppice area = 40 ha).

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on specific costs, Figure 3 shows that, increasing the farm AUA_{ENERGY} from 5 to 95 hectares, the IF application cause a non-negligible rise for both:

- energy cost: i) +5.3÷6.8%; and ii) +6.4÷8.1%, for the H and L cropping systems, respectively;
- environmental cost: i) +6.2÷8.1%; and (ii) 7.9÷10.0%, for the H and L cropping systems, respectively. Taking AUA_{ENERGY} as functional unit, the specific economic cost is higher for the H cropping system (range 571-558 €/ha, at 5 and 95 ha, respectively) compared with the L cropping system (range 424-432 €/ha). Nevertheless, also considering the economical returns, the H cropping system (due to the higher biomass yield) is more profitable than the L system. In fact, at a wood chip sale price of 30 €/t_{WB}, the profit ranges: i) from 30.4 €/t_{DM} (at AUA_{ENERGY} = 5 ha) to 31.3 (at AUA_{ENERGY} = 95 ha); and ii) from 18.7 to 19.6 €/t_2, for the H and L cropping systems, respectively. Finally, assuming average farm management (*e.g.* AUA_{ENERGY} = 40 ha), Figure 4 shows for each case (L, L+, H- and H+) the EEE costs and corresponding GCI; the better values (lower triangle area, GCI = 2.20 and GCI = 2.36) are found with the H cropping system.

Conclusions

The need to increase energy production from renewable sources and to reduce the use of fossil fuels (the main cause of global warming) could result in the spread of AEC that are not fully sustainable from an economic, energy or environmental point of view. In the past, several software programs were developed to calculate the production costs of many processes. However, the great variability in the AGCs most commonly used in Europe together with the lack of both local information and specific parameters makes their application difficult. New software (SE^3A) has, therefore, been developed to evaluate the AGC performances and sustainability. The SE^3A helps to compare different chains or different technical solutions, and also computes the effect of the indirect production factors.

Although for the moment the analysis is limited to the first and second steps of the chain (field and post-harvest phases), SE^3A is already a useful tool for operators interested in agroenergy production. Its use in the near future with the post-harvest and conversion phases will allow the whole chain to be evaluated, defining its EEE specific costs

per unit of energy produced (€/kWh, MJ/kWh, kg CO_2 eq./kWh) as well as its costs/benefits ratio.

The case study presented here refers to the energy poplar chain adopted in the Po valley by means of SRC plantations with two different cropping systems. The first cropping system (H), is more intensive and aimed at achieving a high yield, while the second (L) is characterized by a lower input and a smaller biomass yield. For both the cropping systems, the computation of the EEE performances (economic, energy, environmental) is made by taking into account the energy and environmental costs of direct and indirect production factors. The selection of the functional unit plays an important role in the definition of the sustainability of the AEC. The specific economic cost depends on the share of farm AUA converted to SRC and, under the assumed conditions, it ranges between 36.2 and 48.0 €/t_{DM}, respectively, for the H and L cropping systems. Economic profits are always greater for the H system due to the higher biomass yield. These profits do not take into account the land benefit, the farm management costs and public subsidies for biofuel production. Also, from the energy and environmental points of view, the best results are found with the H cropping system: the energy cost (MJ/t_{DM}) ranges from 4.2% to 5.7% of the wood chip Lower Heating Value.

IF have an effect on energy and environmental costs which is not negligible, reaching 10% of the total.

Symbology

AEC	Agro-energy chains
DF	Direct production factor
IF	Indirect production factor
FU	Functional unit
GER	Gross energy requirement
GHG	Greenhouses gases
GSI	Global cost index
GWP	Global warming potential
EEE	Economic, energy and environmental
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
P	AEC main product
B	AEC byproduct
C	AEC co-product
RE	Renewable energy
SE^3A	Software for economic, energetic and environmental analysis
SRC	Short rotation coppice

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