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A strategic quantitative approach for sustainable energy production from biomass

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European legislation has created a growing interest in the field of renewable energy production in several countries, including Italy. The applications of biomass and/or biofuel for energy generation have been assumed to provide a high level of sustainability due to the perception that renewable resources are inherently sustainable. Thus, renewable fuels applied to heating and/or electricity generation are potentially carbon dioxide neutral. However, before accepting this assumption, it is essential to analyse the actual level of sustainability in the whole supply chain (SC). This requirement has been clearly identified by the recently updated European Directives on renewable biofuels for transportation. However, there is little evidence that this concern has been directed at energy production from biomass. Thus, approaches derived from Green SC Management (GSCM) methods could provide an effective tool for evaluating, from a strategic perspective, the sustainability level of a specific biomass SC. This paper examines how biomass SC activities can define the overall environmental sustainability level. The approach was based on environmental indicators and the resultant output could support more effective GSCM strategies (e.g. defining logistics carriers, evaluating new biomass suppliers, etc.) for managing biomass SCs. Moreover, the approach could be applied by competent authorities for a quick evaluation of the sustainability level of biomass energy production installations. The approach has been tested in a real case study based on an installation, located in Southern Italy, which uses liquid biomass for energy production.

Keywords: renewable energy generation; liquid biomass; environmental indices

Introduction

A sustainable energy strategy, defined in recent years by the European Union (EU), is mainly based on the promotion of renewable energy sources: firstly, the Biomass Action Plan (Commission of the European Communities 2005), next, the EU Strategy for Biofuels (Commission of the European Communities 2006) have introduced new targets and burdens for bioenergy application to mitigate climate change. This strategy aims to promote the use of fuels made from biomass as well as other renewable fuels in transport and in energy production sectors. These European policies have created a growing interest in renewable energy production in several European countries, including Italy. The economical and environmental benefits for renewable energy are widely reported. However, there are concerns that the use of renewable crops may adversely affect food prices and that the actual sustainability level of renewable resources may not have considered all of the relevant factors. These issues have been addressed in the recent European Directive for the promotion of renewable energy productions (Commission of the European Communities 2009). The Directive has enforced the idea of sustainable renewable energy supply chains (SCs) by introducing evaluation criteria in both the production and energy generation phases. Thus, according to a life cycle approach, an energy company has to evaluate the greenhouse gas impact of its own SC: this analysis has been defined as mandatory for both renewable biofuels used in transportation and for biomass used for electricity and/or heat generation.

Consequently, this analysis requires the definition of strategic models for evaluating quickly, but in an effective way, the whole sustainability level of a renewable energy production chain. One critical issue is that a bioenergy (i.e. biofuel and biomass) SC may differ in fuel type: for example, biofuel type could vary from the so-called ‘first generation’ to the ‘fourth generation’ in the near future. The specific value chain structure depends on several parameters: starting from the high variety of raw materials, to their production regions and the plant size (Dautzenberg and Hanf 2008). Thus, complexity, in conjunction with legislative burdens, is forcing the development of new strategies and models for managing bioenergy SCs. Green SC Management (GSCM) becomes an essential strategy for these SCs. A traditional life cycle analysis (LCA), as defined by the ISO standard, could require high computational effort to evaluate strategic issues in GSCM. Thus, new models could be more efficient in this context. Several models have been defined for the strategic sustainability analysis of biofuel SCs, i.e. the application of renewable fuels (e.g. biodiesel, ethanol, etc.) for transportation activities. In this field, a widely used

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guideline relates the performance of biofuel production processes to the emissions from vehicles. One example is greenhouse gases, regulated emissions and energy use in transportation (GREET), a model (UChicago Argonne, GREET 2, Version 2.7, 2007. Available from: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html) applied in the USA to quickly assess the impact of different combinations of vehicle and renewable biofuel based on life cycle approach. A strategic framework for the analysis and evaluation of renewable fuel SCs is proposed by Kammen *et al.* (2008), where energy and greenhouse gas balances have been interrelated with physical and socioeconomic issues. On the other hand, for a biomass SC (such as solid, liquid or gas fuels applied for energy and heat generation), a simplified approach may be possible. Currently, the International Energy Agency Bioenergy is developing a research project (which will end in 2012) that aims to define guidelines and tools specifically for the evaluation of greenhouse gas balances derived from biomass and bioenergy systems. The proposed tool is the BIOMITRE software (van Dam *et al.* 2005) developed for the scenario analysis of different bioenergy and fossil SCs.

The aim of this paper is to define a quick, quantitative approach for evaluating the sustainability level of a whole bioenergy SC, in order to evaluate the effectiveness of different strategic policies applied to a GSCM for renewable energy production. The proposed tool could be applied in both the feasibility and management phases to evaluate, from a sustainability viewpoint, the criticalities characterising a specific energy production installation that uses renewable biomass. Conventional LCA tools often require high computational effort; thus, a fast but complete alternative analysis could be more effective when strategic decisions are required.

The paper is organised in three sections. In Section 1, an analysis of the main characteristics of bioenergy SCs is presented in order to define a reference schema. The proposed approach for quantitative evaluation of GSCM strategies is detailed in Section 2 after a brief review of environmental sustainability models applied in the field of bioenergy SCs. Finally, in Section 3, a case study is presented for validating the proposed approach.

1. The biomass SC for energy generation: main issues

In recent years, biomass production has received increasing attention from both the scientific community and businesses due to legislative requirements to reduce greenhouse gas emissions and the dependency of countries on imported petroleum resources. However, biomass production has its own problems, because it requires a significant availability of resources in terms of both cultivable land and water. In this respect, it competes with food production and this has contributed to an increase in food prices. A recent study conducted by OECD/FAO (Doornbosch and Steenblik 2007) has highlighted the expectation that food prices will rise by 20 to 50% by the year 2016. This outcome could influence renewable fuel diffusion as an energy source. The debate is quite new; few recent studies have been proposed in the literature for bioenergy sustainability analysis.

From a SC viewpoint, several parameters could affect the environmental sustainability level of a specific installation that applies renewable solid or liquid fuels for energy production. Biomass sources (i.e. liquid or solid) for energy production were traditionally defined as ‘carbon neutral’: it is generally considered that biomass combustion releases a similar amount of CO_2 to the emission captured by the cultivation phase. Due to the increasing attention in the bioenergy SCs, several studies have focused on these issues in order to evaluate impacts derived from the whole life cycle. As highlighted by the recent European Directive for the promotion of the use of energy from renewable sources (Commission of the European Communities 2009), emissions derived from fuel production have to be evaluated in order to estimate the overall sustainability level of a specific installation that applies renewable fuel for energy production. This arises because fossil fuels are often required in several tiers of a bioenergy SC starting from the production and harvesting of the feedstock and continuing through to the combustion process (Cherubini *et al.* 2009, Stoeglehner and Narodoslawsk 2009).

In the past, renewable fuels were used mainly in the region where they were produced; however, international markets are now developing as the demand is quickly increasing (Ericsson and Nilsson 2004). According to this issue, two main SC management policies could be developed: a ‘proximity’ replenishment policy is realised if local (e.g. regional) fuel replenishment is applied; thus, the SC is characterised by a ‘short distance’ SC structure. Otherwise, an ‘extended’ replenishment policy, characterised by a ‘long distance’ SC structure, must be evaluated if an international replenishment policy is applied by an energy company. It is apparent, therefore, that transportation activities represent an important aspect of SC management, both from an environmental and an economic point of view. Furthermore, according to a technological point of view, different renewable fuels (liquid or solid) could be applied for energy generation: the biomass SC is not a typical demand-driven SC, but it is mainly influenced by the availability of raw materials (Rentizelas *et al*. 2009). Thus, energy companies represent the focal point in the SC, because it is their strategies that heavily affect the sustainability of the whole SC (McCormick and Kaberger 2007).

From this brief analysis, common features could be highlighted for a typical biomass SCs applied to renewable energy production (Demirbas 2009). In particular, the focus is on liquid vegetable oil applied in a combustion plant for energy generation: biomass derived from solid fuel could be a variant of this general model.

Two principal process categories can be highlighted in this SC structure and these are defined as the *production* and *logistics stages*. The main *production stages* are:

- *the 'farming' level:* this involves all activities carried out for feedstock production. Several factors, including plant type, geographical area and agronomic techniques, could influence the environmental performance. From a SC viewpoint, impacts due to this level could be slightly modified by the SC focal company, i.e. the energy company.
- *the 'processing level':* usually, this activity is carried out at oil mill plants located in the proximity of the farming areas. There are two main technological alternatives: namely, chemical or mechanical treatment; each of which slightly differs in their transformation efficiency ratio. From an environmental point of view, the first process is characterised by a higher impact due to materials applied for chemical extraction; consequently, the latter is often preferred.
- *the 'energy generation' level:* different types of energy production could be applied (e.g. heat power, electricity). Furthermore, a relevant parameter concerns the combustion technology process; the Best Available Technologies (BAT) guideline represents a guideline for evaluating such a performance.

The *logistics stage* usually includes two main levels defined as:

- *the 'Freight to oil mill' level:* this level refers to transportation activities, usually developed in the proximity area, for delivering seeds from farming areas to processing plants. Transport activity is usually provided by lorries.
- *the 'Freight to power plant' level:* this activity could involve both regional and cross-country transportation activities that depend on the SC policies operated by energy companies, as regional or international replenishment activities are developed. According to the policy type, transport is usually intermodal.

According to SC strategies, different policies could be carried out such as:

- '*short distance' replenishment* characterised by local fuel production, in which lorry emissions affect the whole SC environmental sustainability level;
- '*long distance' replenishment* characterised by a regional or cross-country fuel production, in which transportation alternatives and combustion site location represent intervention areas for optimising the whole SC sustainability level. As an example, plant location is more 'flexible' if rail freight and ship transportation are possible alternatives, as different biomass suppliers could be evaluated by energy companies.

In the context of renewable energy production, GSCM could be an effective strategy to achieve higher sustainability levels. GSCM is defined as an approach that aims to integrate environmental issues into SC management procedure starting from product design, and continuing through material sourcing and selection, manufacturing processes, the final product delivery and end-of-life management (Sarkis 2003, Srivastara 2007). Recent papers have considered both strategic (Gan 2007, Bekkering *et al.* 2010) and operational analysis of GSCM in the energy industry sector (Zhu *et al.* 2008, Cherubini *et al.* 2009, Gabbar 2009).

This analysis highlights a relevant result: if BAT guidelines for combustion technologies are applied as a reference model for a more sustainable technology, GSCM strategies should be mainly oriented to optimise the environmental performance of raw material suppliers in the production stages. However, it has to be noted that these activities, unlike combustion, are not conducted by the SC focal company. Furthermore, the adoption of more sustainable logistics activities could represent an effective GSCM strategy to be applied by the focal company.

2. A strategic GSCM model for the bioenergy SC

Recent studies have evaluated, from a strategic point of view how different renewable fuels could contribute to greenhouse gas emission reductions in the transportation sector. Several papers have focused on the application of biofuel for transportation activities. Mortimer and Elsayed (2006) evaluated the total primary energy inputs and total greenhouse gas emissions associated with biodiesel production. Their case study concerning the application of rapeseed oil in the north-east of England was analysed: the SC strategy is 'short distance' replenishment as fuel is produced in the proximity of the combustion facility. Their results highlighted a positive net primary energy level and a net emission savings in terms of CO_2; different biofuels were compared in order to evaluate their global performances. A study commissioned by the Swiss government (Zah *et al.* 2007) supplies a detailed assessment of environmental costs and benefits derived from the application of different biofuel types for transportation activities based on a life cycle approach. The total environmental impacts of each fuel were assessed by the definition of a single indicator which enabled a comparison of different impacts on legislative

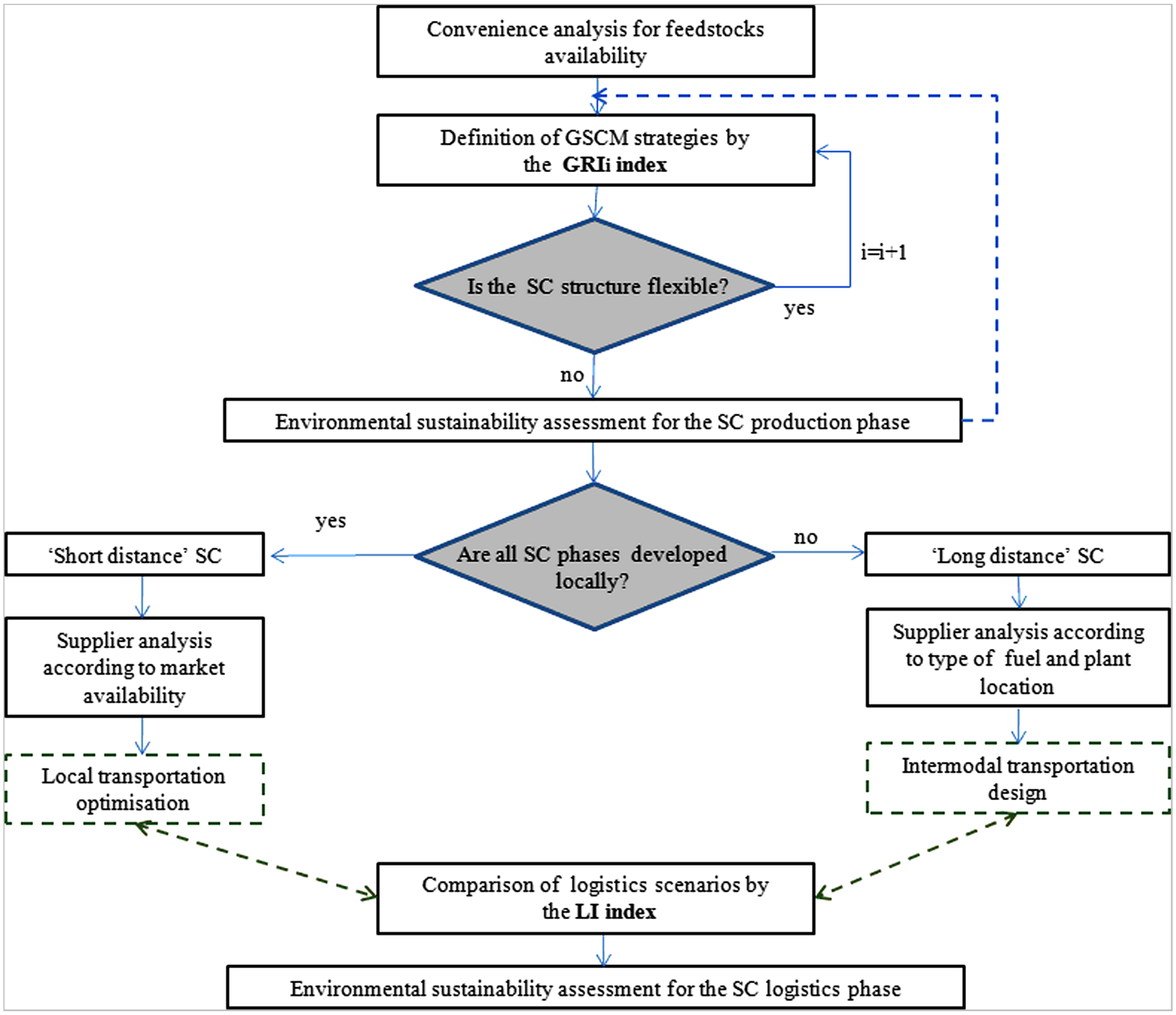

Figure 1. The proposed methodology for GSCM strategy analysis.

targets. A review analysis for biofuel impact assessment models was proposed by Demirbas (2009); economic and environmental viewpoints were also analysed. Stoeglehner and Narodoslawsk (2009) proposed the application of the well known ecological footprint approach for evaluating biofuel SC effectiveness. On the other hand, less effort has been found for bioenergy SC applied for renewable energy production. Cherubini *et al.* (2009) analysed a bioenergy SC according to a traditional LCA; the study focused on evaluating impacts due to alternative design parameters (e.g. end-use applications) on the SC environmental performances.

The aim of this paper is to propose a strategic decision-making tool to support GSCM policies in energy production plants where renewable fuels are used. As previously reported, an integrated view of a bioenergy SC is essential due to legislative and social burdens. The proposed approach could support energy companies in developing effective analysis by implementing lean methods; the approach is not focused on technological issues but on operations' management levels, that often represent the most critical phase for evaluating environmental costs and impacts (EPA 2000, Kainuma and Tawara 2006). The approach is based on a life cycle view, but, differently from traditional LCA models, a synthetic index set is defined to assess environmental implications for alternative SC policies, as a strategic point of view is required. The approach is depicted in Figure 1. Input parameters for the analysis are combustion technologies and plant location. The model evaluates combustion technology as a non-critical factor for SC sustainability analysis; this is mainly due to the application of BAT as a guideline for evaluating an 'optimal' combustion process. On the other hand, feedstock type represents a strategic decision that could affect the environmental performances of different players in the SC. At first, a convenience

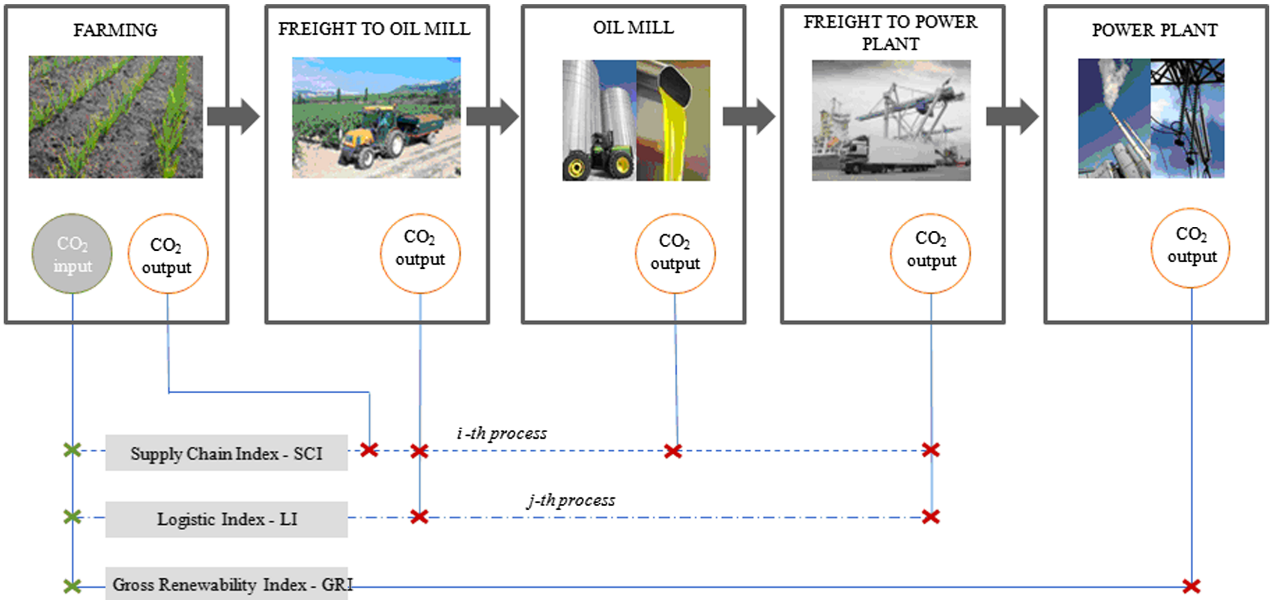

Figure 2. The proposed plant oil SC schema.

analysis is carried out to assess the feedstock availability: the analysis is carried out both at regional (i.e. local) and trans-regional (i.e. international) level in order to evaluate farming production origin areas for such a renewable fuel. The main purpose is to highlight the ability of local farming production to support replenishments for an energy production plant. A feasibility study will be carried out for evaluating the potential flexibility for feedstock replenishment, i.e. if different liquid fuels (see index *i* in Figure 2) could be used in the combustion plant. Then, the process stages defined in Section 1 could be compared by an index calculation defined as the Gross Renewability Index (GRI):

$$GRI = \frac{CO_2 \text{ emitted from combustion}}{CO_2 \text{ fixed by photosynthesis}}. \tag{1}$$

The GRI calculation has been introduced to assess the intrinsic (i.e. the gross) environmental sustainability level but by only considering the fuel using two basic processes, i.e. combustion and photosynthesis. The index enables the weighting of emissions (in terms of CO_2) released during combustion with that adsorbed during the photosynthesis process; it depends on fuel type as combustion technology has been introduced as a predefined value. Usually, the GRI value is less than 1 as renewable fuels are considered 'carbon neutral'. The contribution of each SC level to the overall SC sustainability level can be estimated from the SC Index, SCI:

$$SCI = \sum_{i}^{n} \frac{(CO_2 \text{ emitted})_i}{CO_2 \text{ fixed by photosynthesis}}, \tag{2}$$

where index *i* represents the *ith* process in the specific SC under analysis. Finally, an assessment of the overall sustainability level (in terms of emissions) has to be carried out by using the Net Renewability Index (NRI) introduced in Equation (3):

$$NRI = SCI - (1 - GRI), \tag{3}$$

It has to be noted that if $NRI > 0$, the overall SC process is carbon positive; otherwise, the overall SC process is carbon negative. Different index contributions are described in Figure 2. More effective GSCM strategies could be oriented to minimise the NRI value. A different analysis could be conducted after the first index estimation as critical processes, which contribute mainly to reduce the overall renewability level of a specific SC, are quantified. In the feasibility design phase, indices could contribute to a quick evaluation of alternative logistics options, according to fuel market availability, if the energy production plant's location is yet to be decided.

According to the logistics processes in the biomass SC, a Logistics Index (LI) is introduced, which is defined as follows:

$$\mathrm{LI} = \sum_j \frac{(\mathrm{CO_2\ emitted})_i}{\mathrm{CO_2\ fixed\ by\ photosynthesis}}, \qquad (4)$$

where j represents the *jth* transportation resource type (e.g. train, ship, etc.) applied at different levels of the specific biomass SC. Fuel replenishment policy (i.e. based on regional or international suppliers) could heavily influence the LI estimation. Finally, in order to relate process and logistics stages in the SC, a Net Logistic Index (NLI) is defined by Equation (5) as follows:

$$\mathrm{NLI} = \frac{\mathrm{LI}}{\mathrm{GRI}}. \qquad (5)$$

The NLI estimation could be useful for evaluating GSCM strategies, when multiple fuels have to be compared by a quick but quantitative analysis. As an example, this index could be applied to select 'optimal' site location for implementing more effective GSCM procedures.

Finally, the proposed index approach could be applied by competent (e.g. regional or national) authorities to promote more sustainable energy production from renewable sources: a predefined NRI level could represent the target level defined for combustion plants that apply renewable fuels for energy production; thus, energy companies have to propose solutions for improving sustainability not only for their process plants, but also for their whole SCs.

3. The case study application

The proposed case study regards a specific biomass SC: the energy production from plant oil. The diffusion of renewable fuels for energy generation is increasing in Italy; on the other hand, feedstock replenishment on a regional scale could not be always applied due to reduced resource availability. Energy companies are faced with the need to define new strategies for reducing the overall impact of their activities. These are not just connected to technological investments; they require an innovative consideration of such typical SC issues as optimising replenishment policies and transportation activities, etc. from both economic and environmental viewpoints.

Following a preliminary feasibility study, the energy company has decided to use *Jatropha curcas* plant oil for energy generation. This decision was taken because *Jatropha* oil is not fit for nutritional consumption, due to its toxicity: it has traditionally been used for soap production and medical applications. Fuel availability was also evaluated. Although *Jatropha curcas* originates from tropical areas in America, it is now produced in many tropical and sub-tropical regions throughout Africa and Asia. Its emerging diffusion for energy production has been recently analysed due to the increasing attention required for strategic planning of huge plantation areas in Asia, Africa and America (Jongschaap *et al.* 2008, OECD 2008).

Therefore, the proposed model has been applied to support a more effective strategic analysis as detailed in the following section. At first, the specific biomass SC has been analysed according to the reference model proposed in Section 1, and the main hypotheses are:

- *The 'farming' level*: photosynthesis efficiency has been evaluated according to information deducted by Rowe *et al.* (2009). The estimated GRI value for *Jatropha curcas* plant oil is 0.988. The energy company has determined that only one type of feedstock (i.e. *Jatropha*) will be used in its combustion plant. The energy company has no information about cultivation practices, as it will buy the fuel on international trade markets. Therefore, several assumptions have been made for the model application. Traditionally, the cultivation phase includes agricultural processes such as fertiliser application, harvesting: these processes are usually carried out manually. *Jatropha* crop yield, in terms of seed production, has been estimated to be between 2.5 and 12.5 tonnes/ha/year. The data are presented in Table 1.
- *The 'processing level':* the mechanical oil extraction process has been evaluated as the best option; its efficiency is estimated to be about 30%.
- *The 'energy generation' level*: the combustion plant size has been defined at about 30 MW and the combustion process efficiency has been evaluated on this basis. Combustion process efficiency and

Table 1. Main hypotheses of the case study application.

Scenario parameters	Value
Functional unit	1 MWh
Combustion efficiency	50%
Fuel type	*Jatropha* plant oil
Heating value	38.200 [kJ/kg]
Oil required	189 kg
Oil extraction technique	Cold-press process
Oil extraction efficiency	30%
Seed required	630 kg
Crop yield (seed)	3 tonne/ha/y
Land required	0.21 ha
Ploughing	26.1 kg diesel/ha*
Planting	Manual
Fertiliser application	5.29 kg diesel/ha*
Harvesting	Manual
Irrigation	None

**Source:* Ecoinvent database v. 2.0.

Table 2. The GRI estimation for the proposed case study.

SCENARIO data		Value	Description
Oil quantity [kg]		189	Quantity of oil required to produce 1 MWh
Combustion process	Efficiency [kg $CO_2 \times$ kg oil]	2.482	Data have been estimated according to IPPC directive (Commission of the European Communities 2008) for a generic biofuel
	Emisssions [kg CO_2]	528.26	Emissions are referred to the functional unit
Photosynthesis	Efficiency [kg $CO_2 \times$ kg oil]	2.504	Data are deducted according to Rowe *et al.* (2009).
	Adsorptions [kg CO_2]	533.74	The value represents the CO_2 quantity captured referred by the functional unit
		GRI calculation	0.988

emissions have been estimated assuming that BAT was applied for reducing combustion emissions. The main data are reported in Table 1.

Finally, according to these hypotheses, index evaluation has been conducted by a reference unit (i.e. 1 MWh) and the results are presented in Table 2. The estimated GRI value is 0.988; thus, the application of *Jatropha* oil could be effective from a sustainability viewpoint.

Next, depending on specific plant location, a ‘long distance’ replenishment policy was evaluated; three different logistics scenarios were compared to establish the most effective GSCM strategy and the details follow.

- *Scenario 1*: fuel replenishment could be achieved by applying an intermodal transportation based on three transportation carriers: in detail, international delivery (i.e. the distance is about 4000 km) is conducted by freight ship; a national shipment (i.e. about 500 km) is provided by railways and, finally, proximity transportation (about 150 km) could be carried out by lorry.
- *Scenario 2*: feedstock replenishment could only provided by freight ship; the estimated geographical distance is about 8.000 km.
- *Scenario 3*: feedstock replenishment could be carried out by freight ship (the distance is about 4000 km) followed by lorry (about 300 km).

The quantitative data for these scenarios are presented in Table 3.

Emissions have been estimated for a round trip, e.g. if the geographical distance is 4000 km, total emissions are evaluated for 8000 km. Logistics indices were estimated for the three scenarios; LI and NLI values are presented in Table 4. As a unique fuel was considered, the LI index comparison directly supplies information about the most effective scenario. The results show scenario 1, in which intermodal transportation was applied, to be the optimal GSCM strategy. The LI value estimated for scenario 1 provides a reduction in LI values of about 9% and 5%, respectively, in comparison with scenarios 3 and 2.

Although the energy company had no information about the industrial processes used by the raw materials supplier, an analysis of farming procedures and oil extraction processes was conducted by a review of the literature. According to the model hypothesis reported in Table 1, emissions derived from the farming and processing (i.e. oil extraction process) phases were analysed: thus, SCI indices were estimated for the three logistics scenarios. Finally, the NRI index was also evaluated using the proposed hypothesis for the whole SC, i.e. the contribution of all stages has been evaluated. All estimated NRI values show a slight positive CO_2 contribution, if impacts of the whole SCs were analysed, as reported in Table 4. Thus, the analysed SC is not ‘carbon neutral’ even if the total percentage of CO_2 emitted in the whole life cycle is quite low. It has to be noted that results are not characterised by a general validity, but they are specific for this case study.

Table 3. Quantitative data regarding the three logistics alternatives.

Transport alternative*	Unitary resource consumption** [kg $CO_2 \times$ tonne $\times$ km]	Description
Rail freight	0.03740	European railways
Lorry	0.1470	The lorry capacity is 16–32 tonne. The vehicle type is euro 5
Freight ship	0.0104	Transoceanic freight ship

Source*: Ecoinvent Database v.2. * Source*: Ecoindicator99. Reference unit represents the standard unit for the transportation activities.

Table 4. Main index estimation for the three logistics scenarios.

Transportation alternative	Unit	Scenario 1	Scenario 2	Scenario 3
Railways	km	400	0	0
	kg CO_2	5655	0	0
Lorry	km	150	0	300
	kg CO_2	8335	0	16,670
Ship	km	4.000	8.000	4.000
	kg CO_2	15,725	31,449	15,725
Total	kg CO_2	29,715	31,449	32,395
LI calculation		0.0557	0.0589	0.0607
NLI calculation		0.0564	0.0596	0.0614
SCI calculation		0.1094	0.1126	0.1144
NRI calculation		0.0974	0.1006	0.1024

Conclusions

Strategic planning for the management of renewable energy production chains is currently a complex activity: several factors have to be evaluated in order to assess actual environmental sustainability according to both logistic issues and technological choices. A strategic approach based on a set of synthetic environmental performance indicators is proposed in order to compare strategies for GSCM in biomass SCs. The approach represents a quick but effective tool for energy companies for the evaluation of strategies and policies for improving (or controlling) the sustainability level, characterising their whole SC. By comparison with the traditional method for LCA, the model proposes a simplified analysis, as only CO_2 emissions were considered for environmental sustainability analysis. On the other hand, a complete LCA could require information not yet available in the design phase of the biomass SC. Moreover, the high computational effort required for a complete LCA study could be unnecessary at this strategic decision stage; thus, the proposed tool could support a preliminary quantitative analysis that represents the basis for further elaboration.

The results from the model provide quantitative information for comparing the alternative GSCM strategies. Furthermore, the approach could highlight those critical processes in a biomass SC that could represent trigger points for improving the whole SC performance. The approach has been tested in a case study regarding a specific bioenergy SC located in southern Italy. The results have supplied effective information to an energy company in the design phase of its own SC.

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