ASSESSMENT OF SUSTAINABILITY BASED ON LCA – CASE OF WOODY BIOMASS

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Biomass represents both the dominant source of feedstock for biotechnological processes and the renewable foreseeable sustainable source of organic fuels, chemicals, and other materials. In particular, woody biomass is one of the most efficient sources for renewable energy on a large scale. Converting biomass to fuels, pulp and paper, chemicals, power, and/or feed is essential to be analyzed in terms of economic viability, as well as environmental friendliness. The benefits of using biomass as feedstock for bioenergy may include: the reduction of the use of non-renewable fuels, less dependence on foreign fuels, stabilization of income in rural areas, and reduced carbon dioxide emissions into the atmosphere.

Taking into account the current data in the literature and some Romanian practices, an analysis was developed considering woody biomass use. The paper discusses some stages of the biomass life cycle: extraction of forestry biomass–transport–biomass valorization. The way the Life Cycle Assessment (LCA) approach was further applied to assess the environmental impacts associated with the production of electricity and biofuels, starting from resource extraction until the end-of-life, is addressed. LCA has been discussed in relation to the estimation of biomass distribution on the land together with an evaluation of different chains, including harvesting, biomass transport, and final utilization through combustion and biorefining. System boundaries address cradle-to-gate, gate-to-gate and cradle-to-grave approaches.

The results of the analysis based on LCA allowed for the identification of some environmental indicators that make sustainability criteria measurable, and also the assessment of the potential for sustainable valorization of biomass, together with benefits and drawbacks from the economic, environmental and managerial points of view. The most relevant indicator analyzed was the climate change potential, in terms of greenhouse gas (GHG) emissions. It was found that woody biomass can often be associated with positive environmental impacts, since CO_2 emissions have biogenic character.

Keywords: biomass, bioelectricity, biofuel, life cycle assessment, sustainability indicators

INTRODUCTION

The biomass resource base includes a wide variety of forestry and agricultural resources, industrial processing residues, and municipal and urban solid wood residues (Fig. 1).[1-4] Parrish[5] considers that "primary sources of forest- and agriculture-derived biomass, such as logging residues, fuel thinning treatment, crop residues, and perennially grown grasses and woody crops, have the greatest potential to supply large, sustainable quantities of biomass".

Wood is one of the most plentiful feedstock capital accessible for the production of various materials, bioenergy and biofuels, being at the same time a highly complex material.[1,6] Wood plant species can grow in almost every part of the world, being harvested to produce solid, liquid or gaseous energy. The forest resources also include residues produced during the harvesting of forest products, fuel wood extracted from forestlands, residues generated at primary forest product processing mills, and forest resources that could become accessible by reducing fire hazards and improving forest vigor.[7,8] An evaluation of the quantity of forest-derived biomass should be based on an analysis of the existing resources, as well as considering all the trends in the requirement for forest products.[7] It is also noteworthy that living biomass plays an important role in the fight against climatic changes and for the enrichment of renewable energy sources.[8] Therefore, it is essential that any enhancement in biomass use should go hand in hand with the

requirement for the conservation of biodiversity and environmental protection.[9] If the sustainability principles are considered, then all products deriving from wood – including solid fuels resulted from the maintenance of wooded areas and the waste from cutting operations – must come from carefully managed wooded areas, avoiding deforestation and ecological imbalances.[8]

The substitution of fossil fuels by biomass for energy production usually results in a net reduction in greenhouse gas emissions.[9,10] However, the natural decomposition of biomass produces methane, which is about twenty times more active as a greenhouse gas than carbon dioxide.[10] Also, additional greenhouse gas emissions appear in burning biogas, landfill gas and biomass residues. Biomass fuels have negligible sulfur content and, therefore, do not contribute to sulfur dioxide emissions, which generate acid rains. The combustion of biomass could produce less ash than coal combustion, while the ash produced can be used as a soil additive on farm targets.[11,12]

The sustainability of biomass production usually depends on several factors, such as land use change and its further consequences, possible changes in the carbon stocks of the soil, changes in the biomass production capacity of a certain area, energy consumption related to the biomass supply chain, the efficiency of biomass conversion to various energy carriers, heat or electricity.[13-18] The biomass availability and supply chain emissions also depend very much on the local transportation potential.[7,15,16]

Therefore, some issues can be associated with the sustainability of biomass production and use for energy, of which the most relevant appear to be:[13,18-20]

- the costs of producing biomass;
- the need for environmental sustainability;
- the relationship between biomass production, social and cultural issues.

Consequently, in order to ensure sustainability in the exploitation of woody biomass, the economic, environmental and socio-cultural concerns should be integrated with the management and use of the forest as a valuable renewable alternative to finite fossil-based energy sources.[3,16,18,20] In this context, the focus of bioenergy initiatives should address the use of forests for energy in efficient, economic and environmentally sustainable ways.[21,22] Bioenergy is becoming more and more attractive and imperative for stakeholders, policy and decision makers, motivated by the increasing price of the fossil-derived energy coupled with some concerns over nuclear energy. Moreover, the environmental concerns and social requirements promote the use of alternative and renewable sources of energy, particularly in developed countries.

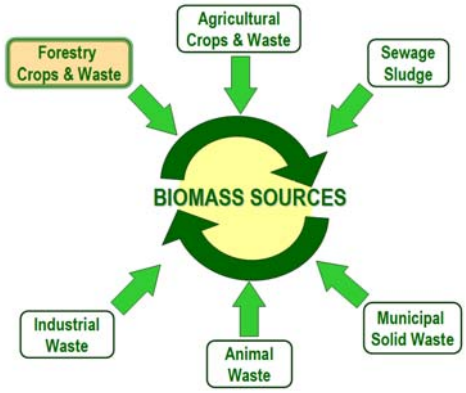

Figure 1: The most relevant sources of biomass (adapted from[2,3,4])

On a global level, the importance of bioenergy has been strengthened by the international legal instruments of intergovernmental mechanisms. They include the United Nations Framework Convention on Climate Change (UNFCC, 1992), which refers to the precautionary measures necessary to be taken so as to anticipate, prevent or minimize the cause of climate changes.[21] Also, the Kyoto Protocol recognizes explicitly the importance of renewable energy in the actions devoted to the mitigation of climate changes in the energy, transport, industrial sectors.[23-25]

SUSTAINABLE USE OF WOODY BIOMASS ALONG THE LIFE CYCLE

The United States Department of Agriculture[26] refers to the woody biomass as *"the by-product of management, restoration and hazardous fuel reduction treatments, including trees and woody plants"*. The same entity[26] defines the utilization of woody biomass as *"the harvest, sale, offer, trade and/or use of woody biomass"*. It is obvious that woody biomass valorization results in a large range of woody products, biobased chemicals, bioenergy.[3,7,20,26] Some ecological factors have to be considered when deciding wood biomass utilization, associated with the soil quality, nutrient and hydrological cycling wildlife habitat.

About 55% of the 4 billion m^3 of wood used annually by the world's population, mainly in developing countries, is used directly as fuel wood or charcoal to meet daily energy needs for heating and cooking. Bioenergy systems often use biomass that would otherwise be unmerchantable and the conversion of biomass may involve biochemical, thermochemical, or physical/chemical processes.[23]

Therefore, the most relevant end-products of biomass valorization consist in transportation fuels (ethanol and biodiesel), heat and electrical power.[27] Different resources and products generated by biomass conversion are shown in Fig. 2.

Wood as energy source

As mentioned above, woody biomass is largely associated with heating and electricity generation, since biomass provides about 10% of the world's primary energy. It can be converted into three main categories of energy/products: electrical/heat energy, transport fuel, chemical feedstock.[27,28]

The sustainability indicators associated with this source (growing conditions on the land, depletion of nutrients, local infrastructure and technology) are correlated with transportation, fuel form (pellet cord wood), storage, waste management (ash and other residues), the effect on other industries, costs.[2,17,29] At the European Union level, the figures show an ascending dynamics of the usage of woody biomass for power plants, where the liquid biofuel usage remains low (Table 1) (http://www.profmarkferris.com/wp-content/uploads/2012/05/Conversion-of-Bio-mass-1.pdf).

It is obvious that the conversion of woody biomass to energy (heat and/or industrial electrical production) induces some impacts on the environment, along the whole process, starting with wood harvesting to power generation and use, as shown in Fig. 3.[28] Some emissions resulted during heat generation are illustrated comparatively in Table 2 for various fuel sources (http://www.mahoosucinfo.org/mah_bioenergy_final.pdf).

The carbon that is emitted to the atmosphere during wood usage as fuels is absorbed by photosynthesis in new growth. Therefore, carbon is constantly used and regenerated in the growth cycle.

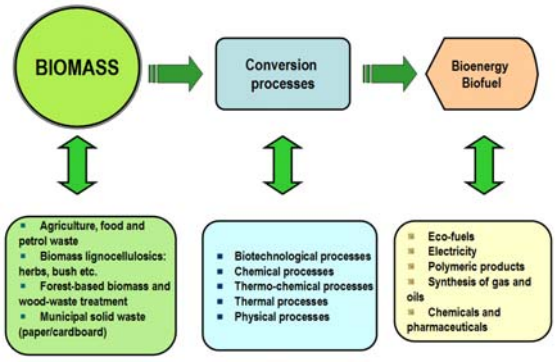

Figure 2: Different resources and products generated by biomass conversion (adapted from[27])

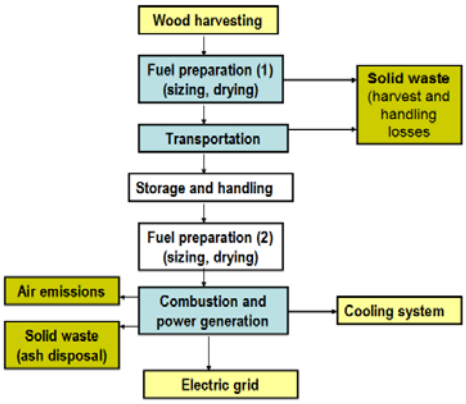

Figure 3: Diagram of energy production from woody biomass and associated impacts (adapted from[28])

Table 1
Dynamics of wood usage for energy, by consumer (adapted from http://ec.europa.eu/energy/renewables/studies/doc/bioenergy/euwood_final_report.pdf)

Wood usage for energy (Mm^3)	Year				
	2010	2015	2020	2025	2030
Household (pellets)	25	40	70	75	80
Household (other solid forms)	151	160	165	160	150
Internal use in the forest sector	85	95	100	110	120
Liquid biofuels	~4	~5	~6	15	30

Table 2
Efficiency and emissions during heat generation using various sources (adapted from http://www.mahoosucinfo.org/mah_bioenergy_final.pdf)

Energy source in boiler	Average efficiency (%)	Pollutant (mg per kWh)			
		PM10	CO	NO_x	SO_2
Wood pellets	22-25	n/a	0.789	0.421	n/a
Wood chips		0.155	1.130	0.255	0.127
Oil	38	0.027	0.054	0.221	0.774
Coal	35	0.064	0.435	1.407	1.586
Propane	n/a	0.062	0.033	0.238	0.025
Natural gas	45	0.011	0.1124	0.139	0.0008

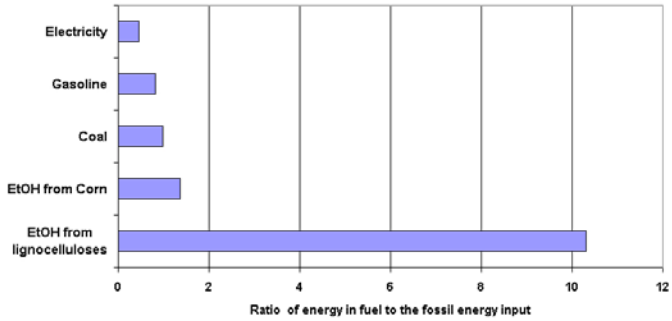

Figure 4: Ratio of the energy in various fuels to the fossil energy input (adapted from[28])

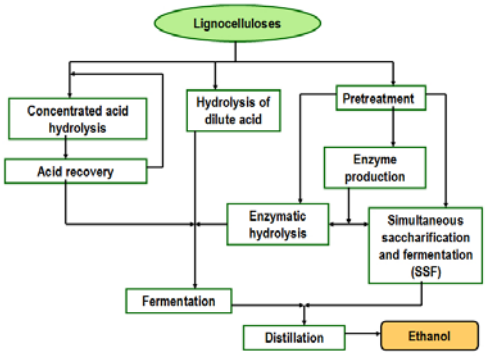

Figure 5: Schematic flowsheet of ethanol production from lignocellulosic materials (adapted from[28,33])

Wood as a source of liquid fuels

The fuels possible to be produced using wood as a source of lignocellulosic biomass (lignin, cellulose and hemicellulose) are ethanol, methanol and biodisel.[28,30] It has been proven that, when added directly to gasoline, EtOH improves combustion and contributes to the diminishing of CO_2 and hydrocarbon emissions (Fig. 4).[28] Since cellulosic ethanol is more energy-efficient and environmentally friendly than other proposed energy sources, a wide range of methods to produce ethanol from wood were developed and improved.[28] For example, the simultaneous saccharification and fermentation (SFF), which integrate two steps in only one, efficient in terms of yields and costs, is advantageous when producing ethanol directly from pretreated lignocellulose[28,31] (Fig. 5). Moreover, the presence of ethanol in the culture liquid medium diminishes the vulnerability against other microorganisms, other than those useful for the SFF process.[31-33] However, the main challenge is to elaborate and apply technologies that can currently collect and convert the under-utilized woody biomass into products with higher value.[34-36]

According to some opinions, producing only ethanol from lignocelluloses displays poor economics, so that biorefining technologies, which can make cellulosic fractions highly susceptible to enzymatic hydrolysis with very high yields of glucose (> 90% in 24 h) are proposed.[37,38] Also, using an integrated process, the lignin from the *organosolv* step is sent to well-established unit operations, so as to recover various by-products (lignin, furfural, xylose, acetic acid, lipophylic extractives fractions).[37] Moreover, wastewater containing low biodegradable organic compounds (measured as BOD_5) is suitable for overall system process closure. Benefits are attained in terms of greenhouse gas emission reduction.[37-39]

Some factors that influence the selection of the conversion process refer to the type and quantity of biomass feedstock, the desired form of energy, i.e. end-use requirements, environmental standards, economic conditions, and project specific factors. In many situations, the form in which the energy is required determines the process route followed by the available types and quantities of biomass.[40,41]

Some of the advantages of using biomass as energy source are the following:[42-44]

- biomass is far more widely available than fossil fuels and, with good management practices, can be produced renewably;
- modernized biomass energy can provide a basis for rural development and employment in developing countries, thereby helping curb urban migration;
- in developing countries, growing biomass for energy on deforested and otherwise degraded lands might provide a mechanism for financing the restoration of these lands;
- in industrialized countries, growing biomass for energy on excess croplands can provide a new livelihood for farmers who might otherwise abandon farming because of food crop overproduction;
- if biomass is grown sustainably, its production and use lead to net zero buildup of CO_2 in the atmosphere, because the CO_2 released in combustion is offset by the CO_2 extracted from the atmosphere during photosynthesis.

However, some questions could arise, for example, concerning the manner an expanding bioenergy sector would interact with other land uses (food production, biodiversity, nature conservation, carbon sequestration).[44] Also, only a few technologies are economically competitive under the existing conditions, while employment effects of using biofuels are small, but positive.[45]

Considering sustainability indicators, they prioritize the operations in terms of what issues are of foremost importance and where care needs to be taken to ensure sustainability. They can provide concrete and measurable information.

Sustainability indicators and criteria for woody biomass use

In spite of the opportunity of using forest-based energy feedstock with a significant role in the development and use of bioenergetical technologies, there are some concerns regarding the sustainability of long-term use of woody biomass.[46]

Because of the complexities of sustainability, it is difficult to define sustainability as a rule. Instead of a definition, general criteria and indicators are developed so that a range of forest activities can be assessed and their management adapted to the location. Environmental criteria are designed to evaluate health, productive capacity, biodiversity, soil, water, nutrient and carbon budgets.[25] Economic criteria involve levels of employment, price of wood and other forest products and social criteria. Creating new woody biomass markets can have positive economic benefits, such as creating markets for biomass wastes, improving economic viability of thinning operations, promoting new crops to farmers who have marginal or unused farm land, creating employment in biomass production, harvesting, transport and conversion to useful energy, and providing a saleable energy product.[25,47]

Sustainability indicators for woody biomass harvesting

Biomass harvesting for energy requires the accomplishment of some conditions, which mainly refer to *individual site quality and management objectives*.[46,48,49] Janowiak and Webster[46] provided some indicators for ensuring long-term sustainability during woody biomass harvesting (Fig. 6). They address the harvested components, which can include forest floor, dead down wood, standing dead trees, live trees (stern, branches and foliage, stump and roots), according to various levels of concern: high, medium and low. The increase of forested land is seen as a sustainable way to produce ecological benefits, so

as to provide more forestland for production of wood products and/or energy.[46,50] Dead down wood offers an appropriate habitat and structure for sustaining biodiversity and growing of trees and plant species.[46]

A sustainable forest management system should lead to a minimal environmental impact. Bioenergy harvest may be appropriate and sustainable as a part of a silvicultural plan and to mitigate impacts.[46,51] Indicators for many issues, such as those for indirect land use change effects need much more research: consequently indicators developed for these are suggestive in nature. IEA[25] provided a list of sustainability indicators, which can be combined to allow the assessment of sustainability (Fig. 7). Therefore, biomass for energy is a by-product of forest which can be monitored using criteria and indicators to ensure the sustainability of woody biomass use in terms of conservation and maintenance of soil and water resources, maintenance of forest ecosystem health and vitality, maintenance of productive capacity of forest ecosystems, conservation of biological diversity, maintenance and enhancement of long-term multiple socio-economic benefits to meet the needs of societies, legal, institutional and economic framework for conservation and sustainable management.[19,20,25]

Sustainability indicators for woody biomass as energy source

Energy crops are considered as being typically low-value products, whose effectiveness is based on low production costs.[25,46] The reliability of the fuel source depends on the growing conditions and how mass-tree-farming affects the land.[28,46] Commonly aspects to be considered in evaluating the sustainable quantity of wood as a fuel include:[49]

- dependability of fuel source;
- depletion of soil nutrients;
- local infrastructure and technology;
- transportation;
- fuel form (i.e. pellet, cord wood etc.);
- storage;
- waste management (ash and other residues, such as tar);
- the effect on other industries;
- costs.

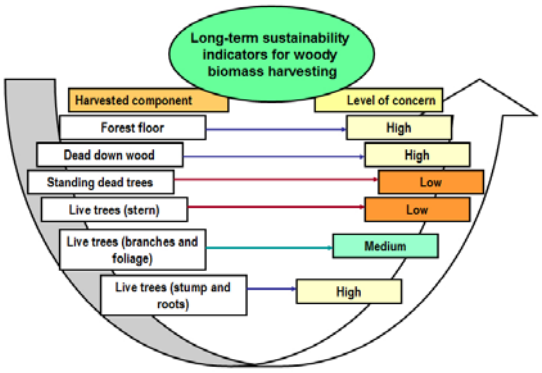

Figure 6: Long-term sustainability indicators for woody biomass harvesting and their relevance (adapted from[46])

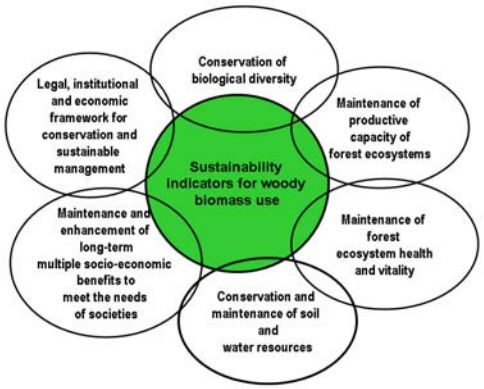

Figure 7: The most relevant sustainability indicators for woody biomass use (adapted from[25])

Most of these factors will apply to both small-scale and large-scale use of wood, but may vary slightly depending on the specific use. Additionally, cost is intertwined with every consideration. It is possible that initially the land will produce large quantities of wood; however, over time, without any renewal of the nutrients in the soil, the production will decrease as the fertility of the land decreases. Transportation is an important problem for sustainability assessment, since trees are particularly heavy and dense.[28] The difficulties in the advancement of woody biomass as an energy source are associated with the cost incurred in harvesting and transporting.

Some criteria and indicators of sustainability for the generation of renewable energy from biomass discussed within various energy working groups, in an attempt to contextualize and deepen the national and international debate about future initiatives, in a participatory and engaged manner are presented in Table 3.[20,49,52,53] It is evident that biomass energy developments will be strongly

influenced by policies and incentives in society to stimulate a reduction in greenhouse gas emissions. These frameworks need to ensure a positive climate for investment in biomass energy and the protection of the environment during the production of biomass to achieve social sustainability.

SUSTAINABILITY ANALYSIS: LIFE CYCLE ASSESSMENT (LCA), A TOOL FOR ENVIRONMENTAL IMPACT ASSESSMENT OF WOODY BIOMASS USAGE

Life Cycle Assessment of sustainable use of woody biomass

The concept of "life cycle" refers to the major activities developed during the lifespan of a product, process or service, starting with raw materials extraction, transport, manufacture, use, and maintenance, to the final disposal.[54-56] Life Cycle Assessment (LCA) is already known as a systematic tool, developed based on the principles of material and energy balances, which describes the full resource usage and environmental impacts associated with supply chains delivering products or services. The essence of LCA is that it considers all material and energy flows from the *cradle* of primary resources to the *grave* of final disposal.[57,58]

The LCA framework should incorporate the following phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Fig. 8).[59,60] By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection.[61] By accounting all the measurable raw material and energy inputs, product and co-product outputs, as well as emissions into the air, water and land, the assessment includes an inventory (*Life Cycle Inventory, LCI*). It can be focused on two main environmental assessments: energy requirements and emissions to the environment for the extraction, production, and transportation of resources for the manufacturing[62] (Fig. 9). Therefore, LCA is a useful instrument in the evaluation of the consequences addressing the decisions to select a product or process for manufacturing and/or implementing.[54,62] Fig. 9 illustrates the possible life cycle stages in woody biomass use, that can be considered in an LCA and the typical inputs/outputs measured.[63,64]

There are three ways of using the biomass resources, which belong to the bioenergy sector:[20,65,66]

- biomass for heating purposes (*bioheating*);
- biomass for electricity production (*bioelectricity*);
- biomass for transport fuels (*transportation biofuels*).

With increasing use of biomass for energy, questions arise about the validity of bioenergy as a means to reduce greenhouse gas emissions and dependence on fossil fuels. Life Cycle Assessment (LCA) is a methodology able to reveal these environmental and energy performances, but results may differ even for apparently similar bioenergy systems.[67] Differences are due to several reasons: type and management of raw materials, conversion technologies, end-use technologies, system boundaries and reference energy system with which the bioenergy chain is compared.

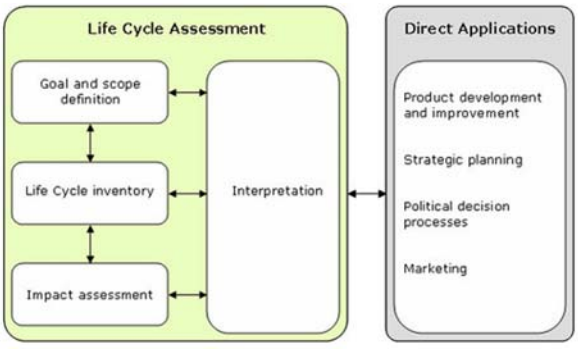

Figure 8: Life cycle assessment framework as recommended in (ISO 14040:1997) (adapted from[59,60])

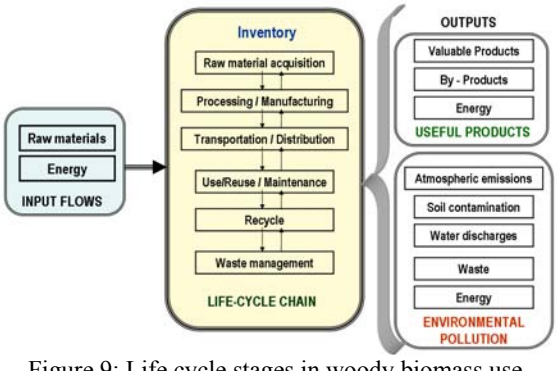

Figure 9: Life cycle stages in woody biomass use, associated with environmental impacts (adapted from[63,64])

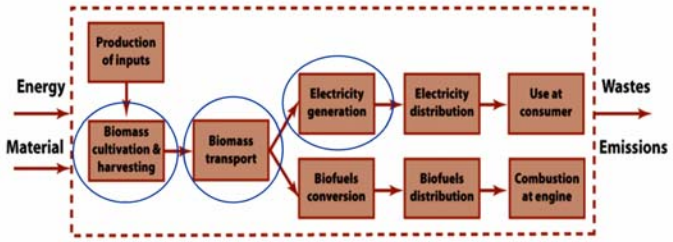

Figure 10: Electricity and biofuel generated from biomass (adapted from[70])

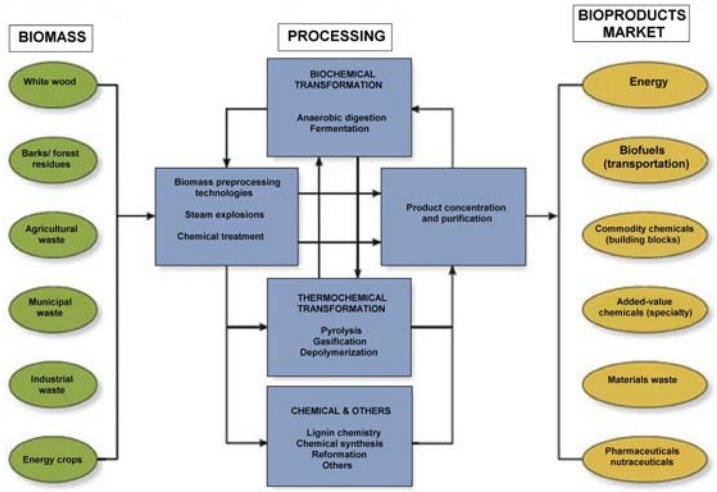

Figure 11: The chain of biomass harvesting conversion and use as bioproduct (adapted from[71])

GHG (greenhouse gas emissions) accounting with an LCA can be performed at each phase: biomass cultivation and harvest, biomass transport, electricity generation, electricity transmission and distribution, and electricity end-use.[68,69] The first three phases (cultivation and harvest, transport, and electricity generation) in the schematic represented in Fig. 10 are where the bulk of GHG emissions occur. GHG flux during the first three phases is site- and operation-specific, and depends on many factors, including the biomass type and management strategies.[70]

Environmental impacts of biomass conversion

As specified above, woody biomass can be converted both into useful forms of energy (solid, liquid or gaseous fuels) and useful biorefinery products (char, acids, pellets, bioplastics) based on technologies, which include chemical, thermochemical (gasification, pyrolysis) or/and biochemical pathways,[71] shown in Fig. 11. All these pathways of woody biomass use (biochemical transformation by fermentation, anaerobic digestion; thermochemical transformation by pyrolysis, gasification, depolymerization; chemical transformation by lignin reactions, chemical synthesis, reformation etc.) induce environmental impacts, social and economic costs and performance, which can be evaluated by using Life Cycle Assessment tools.[20,72]

For the case of woody biomass, environmental impacts of associated technologies, such as production of electricity or biofuels, are of important concern. To assess theses impacts, all the steps in the entire flowsheet should be considered. For example, biomass collecting and harvesting, wood pellets production (raw material processing), transportation, combustion or biorefinery (Figs. 11, 12). Fig. 12 indicates some of the process steps that should be included in LCA calculation of woody biomass, the emissions or energy requirement associated with each process step.[72] In addition, very different impacts are likely to arise depending on which category of biomass feedstock is used and which technologies are used to convert the biomass to useful energy.[73]

The inventory steps of LCA is therefore of great importance, since it should generate a complete list of all inputs and outputs involved in LCA, such as material and energy resource use, waste, emissions to air, soil, water.[74,75] A diagram

of emissions breakdown for heat and power production, necessary for the analysis of bioenergy chain should be associated to the whole life cycle (Fig. 13).[20,72] This diagram highlights the presence of biomass and non-biomass sources of impacts. Therefore, a particular problem in LCA of the woody biomass initialization is the presence of collateral contaminants, even in very small quantities. These contaminants can lead to measurable toxic emissions and health hazards, but they have to be taken into account, even though complicating the LCA process.

LCA can lead to information on the positive impacts of woody biomass on the environment, since the development of biomass resources and the conservation of biodiversity and local environments can go hand in hand.[76] These advantages in terms of environmental impacts include, but are not limited to:[74,75,77]

- increasing and maintaining biodiversity;
- substitution of fossil fuel with a less CO_2 emitting alternative;
- reduction in the emission of other atmospheric pollutants (SO_2, NO_x, for example);
- woodfuel could be one of the drivers in encouraging new native woodland planting;
- during the harvesting process, the poorer quality trees are removed;
- saving in GHG emissions, since a large part of the lifecycle CO_2 emissions are biogenic.

A relevant issue in environmental impact assessment is the greenhouse gas emission, since it is an "easy-to-estimate" global indicator.[75,77-79]

CO_2 emission is an important variable to be analyzed in the light of international concerns over greenhouse gas emissions.[79] Based on data from US Life Cycle Inventory database and the U.S. EPA's TRACI impact method, Howe *et al*.[62] made a comparison of the emissions, in terms of GHG emissions of wood–fired electric generation to coal and natural gas (per MJ of electricity). It was found that a woody biomass plant produces only 4% of the emissions generated by a bituminous coal plant (Fig. 14).[62]

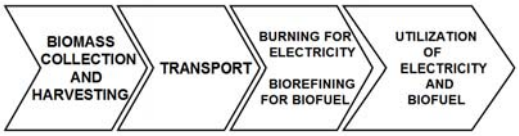

Figure 12: The main steps in the woody biomass utilizations, along the life cycle, from harvesting to combustion for electricity generation or biorefining (adapted from[72])

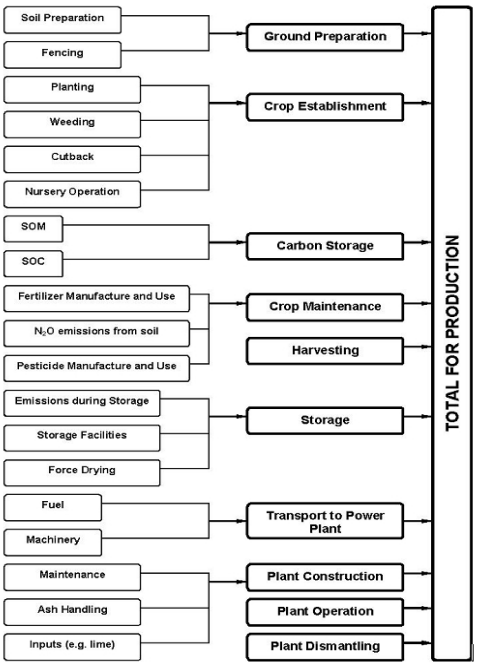

Figure 13: Diagram of emissions breakdown for heat and power production, necessary for each bioenergy chain (adapted from[20, 72])

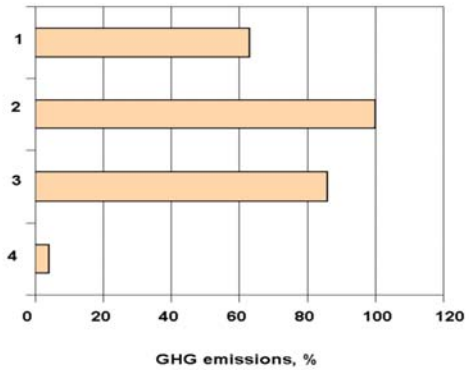

Figure 14: Green house gas (GHG) emissions associated with various electric power plants: 1-natural gas; 2-bituminos coal; 3-biomass (according to EPA rule with bioemissions); 4-biomass (based on life cycle with CO_2 uptake) (adapted from[62])

This diagram also shows a large difference in emissions calculated with the two methods (according to EPA rule with bioemissions and based on life cycle with CO_2 uptake).[62]

Parties from all sectors of society are increasingly becoming aware of the relationship between CO_2 emissions and global warming. Therefore, future development of energy facilities should minimize risk by demonstrating concern for this growing problem. In this context, biomass energy systems are basically CO_2 neutral from the perspective that the CO_2 emissions from biomass fuel are reabsorbed by the growth of sustainable biomass plantations.[80] Lots of LCA studies on woody biomass conversion for fuels and electricity often assume that CO_2 emissions could be considered as zero during combustion since this emission is a part of the biogenic CO_2 life cycle and the vegetation (in particular trees) will sequester the release CO_2 during the growing process.[75,77] It is considered that bioenergy systems which use woody waste and residues provide large GHG savings and do not induce relevant land-use changes.[75,81-83]

On the other hand, fossil fuel use in the production of biomass contributes to the fossil CO_2 emissions.[71] Fig. 15 gives an image of the combined effects of CO_2 emissions from biomass harvesting and burning with the savings resulted due to the replacement of fossil fuels in an European managed forest (with additional felling). However, some analyses and research showed that, under certain conditions, the production of bioenergy can induce significant environmental impacts since, with any increase in the use of biomass for energy, problems appear concerning the validity of bioenergy as a sustainable way to reduce GHG emissions and the dependence on fossil fuel.[75,84,85] Therefore, the use of GHG emissions as an indicator in life cycle analysis can induce a higher degree of divergence in the study, so that numerous approaches consider opportune to apply methodological standards for calculating the *carbon footprint* of a product or process.[85,86] In such a situation, LCA is able to highlight and compare the environmental impacts and energetical performances of bioenergy from woody biomass to that generated from fossil fuel.[84,85] Cherubini *et al*.[84] discussed some differences in environmental and energy performances, which could appear even in producing bioenergy from various biomass categories, as a result of variations in the "type and management of raw materials, conversion technologies, end-use technologies, system boundaries and reference energy systems with which the bioenergy chain is compared". Moreover, the use of different input data, reference systems, functional units, allocation methods can complicate LCA bioenergy studies.[85] For example, various categories of biomass or biomass-derived fuel types have chemical and physical properties that deviate significantly from the properties of coal. The key differences include:[87-89]

- the very high moisture contents of some biomass, which needs dewatering or drying prior to combustion;
- the lower ash contents of biomass than that of most coals; in addition, the ash recovered at biomass power facilities can be dispersed as fertilizer back on the biomass growing area to help in recycling the nutrients removed from the site during harvesting;
- the content free of toxic metals and other trace contaminants;

- high volatile matter content of biomass compared to those of most coals, so that biomass is more reactive to combustion processes than are most coals (easier to ignite, produce a smaller quantity of char and the char particles are more reactive then coal chars);
- significantly lower nitrogen contents of biomass than most coals (NO_x emission levels from biomass combustion tend to be lower than from coal combustion);
- the low energy density of harvested biomass and the dispersed nature of biomass production, which allow a large dispersion of biomass energy facilities, so as to avoid high transportation costs;
- lower sulfur content of biomass than that of coal (coal can contain 0.5 to 5 percent S by weight, compared to biomass feedstock, with S ranging from 0.01 to 0.1 percent). Therefore, biomass energy systems help alleviate acidification.[90]

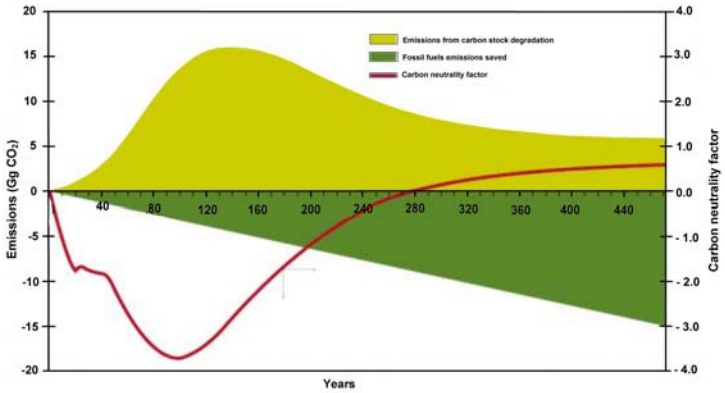

Figure 15: Interplay of emissions from harvesting and burning biomass *vs* savings from fossil fuel replacement (the red line shows the variation of the carbon neutrality factor: negative values mean net emissions, while positive values mean net savings; in the emission - green - graph, positive values mean emissions, while negative mean emission savings) (adapted from[71])

Emissions of other gases, such as NO_x, SO_x, CO, and particles are low on the whole and compared to fossil fuels.[91] However, during the impact assessment, impact categories are considered and various key values are assigned according to a ranking relative to a specific compound in the category.[74,75,81,85] In this context, Sunde *et al*.[74] gave the example of N_2O, which contributes 296 times more to global warming that CO_2, so that the characterization factor for global warming granted to NO_2 will be 296 times higher than for CO_2. Fig. 16 gives a comparison of atmospheric emissions from various woody biomass during the burning process of one ton of biomass.[63,91]

Biomass is also much more reactive than coal, being a very attractive feedstock for gasification and the subsequent power generation, leading to higher efficiency and cost-effective modest-scale biomass power facilities.[80,92-94] The economic analysis associated to LCA for woody biomass conversion to bioenergy shows that the most critical stages are forestry harvesting and transportation, since the costs associated with forest management are very high, and the environmental impacts are significant. Moreover, constructing energy recovery plants implies a large economic investment, depending on the scale and type of the plant.[95]

An important part of LCA is associated with the use of woody biomass products, in particular, but not limited to biofuel. Nowadays, a continuous improvement in the conventional biofuel process (sugar and starch based ethanol, conventional biodiesel, biogas) occurs in terms of efficiency and economics. At the same time, advanced conversion pathways became known to the demonstration stage (cellulosic ethanol, advanced biodiesel, other biomass sugar based biofuels). The stage of the development of various biofuel technologies and use was analyzed by the International Energy Agency in 2011, in a framework addressing sustainability in biomass use and current trends in energy supply.[96] IEA roadmap includes a special focus on biofuel from biomass, which provides about 2% of total transport fuel, but the new technologies can offer the possibility to enlarge the biofuel market and use, as shown in Fig. 16.[96,97] Also, IEA[96] highlights the important role of biofuels in

reducing GHG emissions against fossil fuels, by comparing these emissions based on LCA studies (Fig. 18). The assessment made by IEA[96] is based on UNEP and IEA review of 60 LCA studies originating from various sources.[98-100]

Environmental impact of woody biomass freight transport

One of the most relevant steps in woody biomass use, in terms of environmental impacts is the transport of biomass feedstock and biofuels. This issue should necessarily include the academic literature, since policy reports lack an in-depth analysis of biomass supply chain impacts (externalities) on transport. To accurately measure carbon savings of biofuels, it is necessary to account for CO_2 emissions of biomass feedstock or of biofuel transport.[71,92,96]

Cockeril and Martin[92] asserted that "true GHG abatement costs of biofuel incentives remain difficult to evaluate with any accuracy, as different production methods used for the same feedstock have a large impact." This is because the efficiency of biomass (60%-80%) is greater than that of biofuels (30%). The report argues that the energy and GHG emissions of biomass transportation will be a fraction of all the pathways (entire supply chain of biomass).[52]

More recently, the reduction in GHG emissions associated to the transport sector has become an important driving force for the development of biofuels.[96] Since the transport phase of raw materials is a defining element in LCA study, some data from the literature based on case studies have been analyzed and interpreted. The analysis involves some relevant issues:

- assessing the size of road freight vehicles for biomass transport;
- assessing vehicle emission rates for non-CO_2 and CO_2 emissions;
- assessing the most appropriate biomass mix and energy density;
- estimating distance traveled by vehicle for the entire trip.

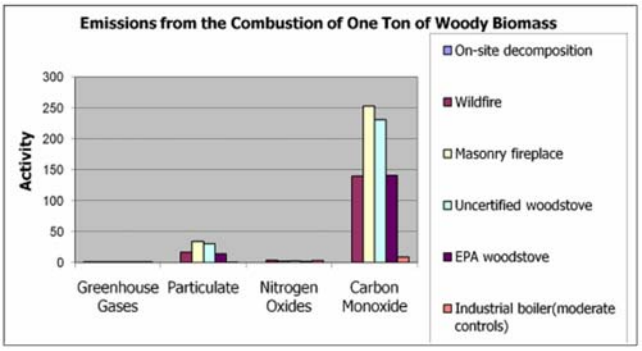

Figure 16: Emisssions from the combustion of one ton of woody biomass adapted from[20,30])

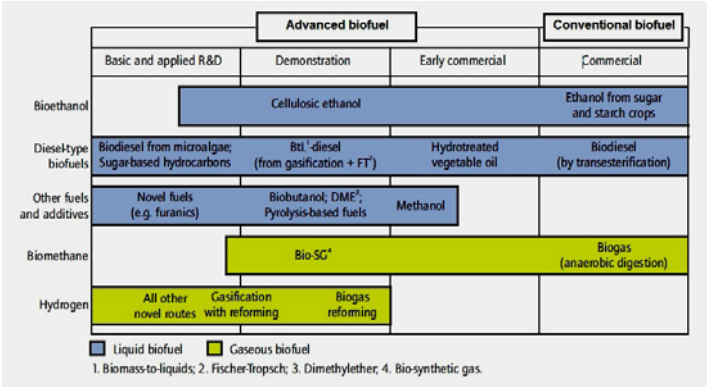

Figure 17: The relation among biofuel types and the status of the most applied biofuel technologies (adapted from[96,97])

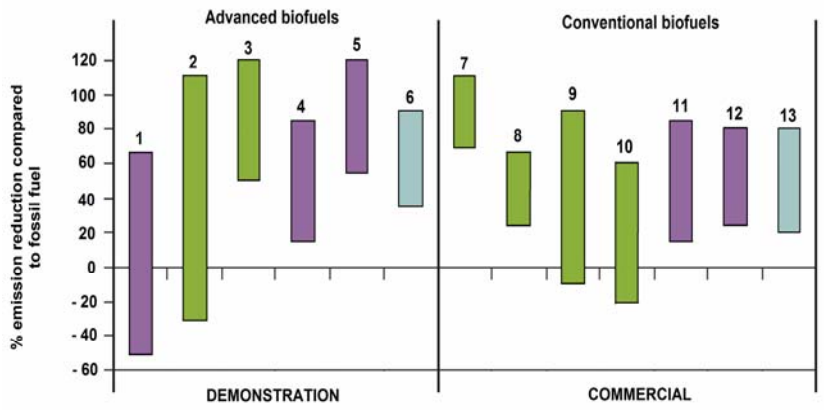

Figure 18: Life-cycle balance of GHGs emitted by different advanced biofuels in relation with current state of technology (1-algabiodiesel; 2-bioethanol; 3-cellulosic ethanol; 4-hydro-treated vegetable oil (HVO); 5-biomass-to-liquid (BtL)-diesel, 6-bio-synthetic gas (Bio-SG); 7-sugarcane ethanol; 8-sugarbeet-ethanol; 9-wheat-ethanol; 10-corn-ethanol; 11-rapeseed-fatty acid methyl esters (FAME); 12-palm oil – FAME; 13-biogas (2,3,7,8,9,10 – gasoline replacement; 1,4,5,11,12 – diesel replacement; 6,13 – natural gas replacement) (adapted from[96,97])

The reduction in transport emissions accounts for 23% (10 Gt CO_2 equivalent) of total energy-related emissions reduction, by 2050.[99,101] Emissions from vehicles are influenced by a large number of factors. One is the type of biofuel used in processing (Fig. 19). There are some factors that are sometimes omitted from analysis, such as infrastructure inputs.[74,102] Biomass to Liquid (BTL) fuels have shown some benefits concerning tailpipe emissions over fossil fuel, mainly due to low contents of sulfur and aromatics.[74,103] Cellulosic ethanol shows only 10% GHG emissions from gasoline emissions (Fig. 19).

INTEGRATED SUPPLY CHAIN OF WOODY BIOMASS TOWARDS SUSTAINABILITY

Some policy recommendations include the need to carefully select sitting and spatial factors when designing large-scale deployment of bio-energy and of biofuels. Designing an energy policy based on biomass brings new challenges since biomass may itself be freight transport intensive.[91]

The amount of greenhouse gases associated with a particular feedstock depends on what is emitted, when it is burned and on the energy used in growing, harvesting and processing. Coordination of all aspects of woody biomass supply chain is a relevant condition for sustainability achievement in the area of woody biomass use, as demonstrated by LCA.[104,105] Chaabane *et al*.[106] focused their studies on sustainable supply chain in the context of life cycle analysis. A similar approach has been applied by other scientists.[107,108-111] According to these studies a successful sustainable integrated supply chain should include individual dimensions: technical, societal, business/economic and environmental.

The economic and environmental performance of woody biomass energy are of major concern along the entire supply chain, from biomass harvesting to products use.[104,109] Johnson[104] considers that "there are several environmental dimensions that must be considered by stakeholders and actors in the supply chain to support the success of biomass based biofuels industry". Fig. 20 includes these dimensions, showing that sustainable bioenergy systems should address efficiency issues throughout the entire life cycle, mainly by reducing GHG emissions.[15,20,41,104,110,111]

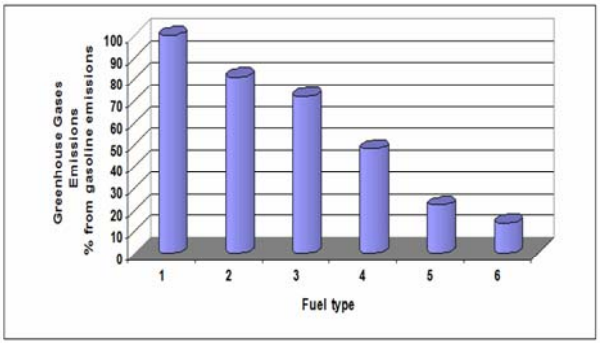

Figure 19: Greenhouse gas emissions by transportation fuel and type of energy used in processing: 1- gasoline from petroleum; 2-4: ethanol from corn (reduction against: 2-current average; 3-natural gas; 4-biomass); 5-sugarecane ethanol (biomass); 6-cellulosic ethanol (adapted from[30,74])

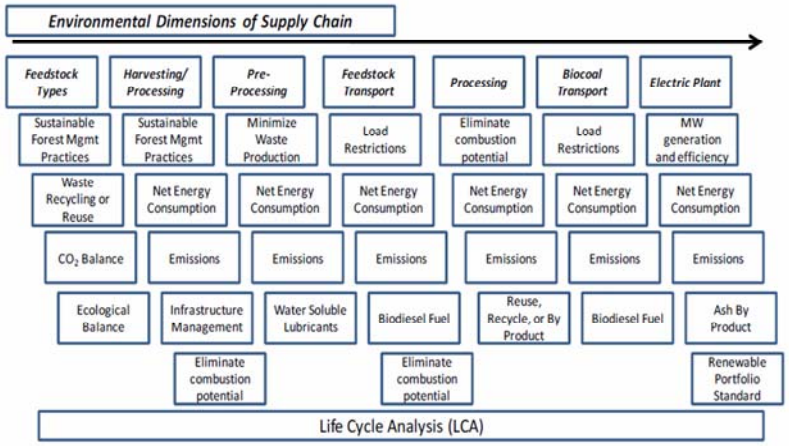

Figure 20: Environmental dimensions of woody biomass supply chain (adapted from[104])

Table 3
Criteria and indicators for sustainability (adapted from[20, 49, 52, 53])

Criteria	Indicators
Economic	
Use of bioenergy	Rates of reduction of consumption Increased end-use conservation Capacity for reduction, reuse and recycling of inputs in the final activities for which the energy is destined Inclusion of demand management in the project planning horizon
Technology	Relation between local workers and outsiders involved in project maintenance Application of clean technologies Technological innovation Capacity of reproduction of technology used Origin of equipment Existence of technology licenses Need for international technical support Changes in use of sustainable energy Cogeneration
Organization of production/labor relations	Sharing of profits from biofuels production chain by family farmers Level of satisfaction with existing contracts
Financing	Programs and lines of credit Conditions for government financing

Social	
Social accountability	Participation of local population and national socio-environmental organizations in projects design
Participation in decision making	Number, sites, nature and types of consultations, form of publicity, access to information, language and accessibility of material used
Type of management	Organizational structures and forms of decision-making, number of participants/decision makers, involvement of organizations representing local workers, participation of women
Job creation and income generation	Number of jobs per unit of energy (production chain, implementation and operation), profit sharing, generation of new local opportunities and sources of income, relation between local jobs before and after the project, indexes of increase in acquisitive power of the local population
Social inclusion	Number of families previously without access to energy who benefit from the project Measures of quality and compliance with accepted standards of the involuntary resettlements, when necessary and accepted Impact on quality life of the communities Social programmes, especially for health and education Epidemiological assessment and monitoring Contribution to access to services and infrastructure on the part of local populations to education, energy, waste and sewage services
Gender equality	Existence of programs and policies for women and youth
Environment	
Environmental management	Monoculture area Soil loss Atmospheric emissions and effluents into water bodies
Land use	Decentralization and diversification of production system in an area/region Sizes of continuous areas of monocultures Distance from energy source to consumer Distance traveled and time spent by workers to project area Time necessary to manage crops

CONCLUSION

Life Cycle Analysis (LCA) is a significant assessment tool for the sustainability of products/processes in terms of environmental impacts as well as economical efficiency. According to the LCA method, the energy and raw materials, various emission types and other relevant factors related to a specific process/product can be measured over the entire life cycle, mainly from an environmental point of view.

Forests and woody crops are recognized as significant sources of energy and products in the course of conversion of biomass into solid, liquid or gaseous fuels, as well as biorefinery products. Therefore, woody biomass can make a substantial contribution to supplying energy demands in a sustainable way being a renewable resource. Also, it is acknowledged that woody biomass can generate a positive environmental impact in terms of greenhouse gas (GHG) emissions. Woody biomass is able to ensure opportunities for economic and social development in specific communities, also reducing waste disposal problems and improving the scale and degree of the use of resources.

Sustainability of woody biomass as a natural, renewable and CO_2-neutral resource combines economic, environmental and social/cultural considerations.

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