Biofuels: A Survey on Pros and Cons

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A survey of research findings focusing on issues related to the pros and cons of using biofuels to substitute conventional fuels, namely, fossil fuels is presented in this paper. This controversial topic has attracted great political, economic, and social attention because it is touching interests of world significance during recent years. The paper presents the main biofuel types that are used today or can be used in the future, their properties and characteristics, and their production technologies and focuses on the evaluation and main economic, environmental, and social impacts of biofuels, measuring the pros and cons of their use in energy production. The future of biofuels is also discussed. The paper is concluded with a discussion, some conclusions, and suggestions for further research.

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1. Introduction

Although a considerable volume of research work during recent years has been directed toward biofuels and their impacts, to the best of the authors knowledge attempts to summarize research findings from different perspectives have been rather rare. However, it would be particularly interesting to survey these findings focusing on issues that are of great significance to practice and, what is most important, to the future of the planet. Such an issue is related to the pros and cons of using biofuels to substitute conventional fuels, namely, fossil fuels. This paper makes an attempt to address this issue.

The global virgin biomass potential is summarized in Table 1. Thus, the cultivated land corresponds to 2.7% of the global biomass production area (9% of the continental area) and produces 4.1 Gt of C yearly, whereas the cultivated "standing biomass" corresponds to 6.3 Gt of C. "Standing biomass" carbon is that contained in biomass on the surface of the earth and does not include the carbon stored underground.

Forest biomass is produced on only 9.5% of the earth's surface but contributes more than any other source. It corresponds to 89% of the total standing biomass (33.26 Gt). The yearly production of this biomass could cover approximately 2 times the 1993 global energy demand, which was 314 EJ. This demand corresponds to 16.9 Gt of dry biomass, which in turn is less than 1% of the total standing biomass on earth.[1] Forest biomass also is the largest contributor to standing carbon reserves. However, the process of deforestation tends to become a major problem. Deforestation is used for the increase of cultivated areas or for felling. According to satellite observations, the deforestation rate in Brazil's tropical forest is 80×10^3 km^2/year. This area corresponds to 0.16% of the global forests.[1]

Other sources of renewable biomass are the residues and more specifically:

- Municipal solid wastes (MSW)
- Municipal biosolids (sewage)
- Industrial wastes
- Animals' manures
- Agricultural crop and forestry residues.

The residues and other waste's potential in the U.S.A. and their use fraction appears in Table 2.

In this paper, starting with questions such as "what are the main biofuel types that are used today or can be used in the future?", "what are their properties and characteristics?", and "what production technologies, including the supply systems, are used?", the paper focuses on the main economic, environmental, and social impacts of biofuels, measuring the pros and cons of their use in energy production.

In addition, in this paper, a primary qualitative evaluation of the basic biofuels' types is performed. A conclusion is that biofuels, such as biodiesel and bioethanol, seem to be harmful because they come into conflict of interest with food production. In contrast, the main impacts of some other biofuels, such as agricultural or forest residues, are good enough because they can contribute to regional development in a sustainable way.

Another basic conclusion is related to the validity of the biofuels' life cycle impact assessment (LCIA) results appearing in relevant literature. These results are very often characterized by considerable uncertainty. Also, these LCIA studies rarely include biofuels' performance in all environmental impact categories. In addition, the environmental, economic, and social impacts are not combined in an overall performance index. Consequently, the decision making process for the biofuels is not an easy job and produces questionable results.

The rest of the paper is structured as follows: Sections 2 and 3 present the different categories of biofuels and their production technologies, respectively. Sections 4 and 5, dealing the former with biofuels evaluation and the latter with their economic, social, and environmental impacts, are the core of the paper. Some notes on the future of biofuels are the subject of section 6. The paper is concluded with a discussion, some conclusions, and suggestions for further research.

2. Categories of Biofuels

Either virgin or waste biomass can be used as raw material for the production of biofuels. In general, biofuels can be

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(1) Klass, D. L. *Biomass for Renewable Energy Fuels, and Chemicals*; Academic Press: New York, 1998.

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Table 1. Global Potential of Virgin Biomass[a]

	forests	savannahs	swamp and marsh	cultivated land	remaining terrestrial	marine
area (10^6 km^2)	48.5	24.0	2.0	14	74.5	361
%	9.5	4.7	0.4	2.7	14.6	70.8
carbon production (Gt/year)	33.26	8.51	2.70	4.10	8.40	24.62
%	42.9	11.0	3.5	5.2	10.8	31.8
standing biomass carbon (Gt)	744	33.5	14.0	6.3	37.5	4.5
%	89.3	4.0	1.7	0.7	4.5	0.5

[a] From ref 1.

Table 2. Residues and Other Waste's Potential in the U.S.A. (2000)[a]

source	potential (EJ/year)	use fraction (EJ/year)	percentage of use (%)
forestry residues	26.4	11.0	42
MSW	3.2	2.1	66
agricultural wastes	15.8	1.1	7
industrial wastes	2.2	0.2	9
other wastes	10.3	1.0	10
total	57.9	15.4	26

[a] From ref 1.

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classified as solid, liquid, and gaseous biofuels. Their properties, characteristics, and production technologies are presented in the following.

2.1. Solid Biofuels. Solid biofuels are the most common and ancient type of fuels in human history.

The main solid biofuels used are the following:

• *Refuse-Derived Fuel (RDF).* It is the fraction produced from MSW after mechanical and thermal treatment. It contains mainly paper and plastic residues. The thermal value of RDF is relatively low, approximately 9200 kJ/kg.[2] RDF is mainly used in industrial applications (cement works, etc.) as a fuel.

• *Briquettes.* They are produced from virgin biomass through a thermo-mechanical process. Their form is mainly cylindrical or rectangular. They contain moisture at a level of 5% (w/w). Their thermal value is approximately 19 000 kJ/kg. Briquettes are used as a fuel in industrial combustion applications (such as drying, steam or hot water production, etc.) and in central heating systems.

• *Pellets.* They are produced with compaction of finely chopped biomass (mainly forestry or agricultural residues). They contain about 5−10% moisture, and their heating value ranges from 10 000 to 20 000 kJ/kg. Their main difference from briquettes is their small size. Pellets and briquettes have the same applications. Their energy content is high in relation to the biomass, of which they originate. Their production is based on thermo-mechanical or physicochemical process of compaction of finely chopped lignocellulosic biomass.

• *Wood.* This category includes not only the wood that is produced from forests but the agricultural and forestry residues as well. Its water content ranges from 40 to 70% (w/w). This value depends upon the biomass harvest timing. Its typical heating value is approximately 18 600 kJ/kg (on a dry basis) but varies considerably depending upon the biomass' chemical composition (lignin, cellulose, etc.). Wood and woody residues are mainly used in power generation and co-generation, industrial heating applications (cement works, etc.), and central heating systems.[3]

• *Sewage.* It is produced from the municipal or industrial sewage cleaning process. Its heating value is approximately 19 000 kJ/kg. It is used in power generation applications.

• *Industrial Wastes.* They are byproducts of various industrial processes. Typical examples are residues of wood industry, cotton industry residues (gins), etc. Their properties, such as content energy, content moisture, etc., vary significantly. They are used mainly in industrial heating systems and power generation or co-generation applications.

2.2. Liquid Biofuels. Liquid biofuels can be classified in

- Natural biochemical liquefaction biofuels. This class includes biodiesel.
- Synthetic oxygenated liquid fuels. This class includes bioethanol, biomethanol, and methyl tertiary butyl ether (MTBE).

Properties and characteristics of biodiesel and bioethanol (which are the main liquid biofuels) are presented in the following.

Biodiesel. It is defined as monoalkyl esters of long-chain fatty acids derived from renewable feedstocks, such as vegetable oils and animal fats, or other triglyceride-bearing biomass, such as microalgae, for use in compression ignition engines. Biodiesel can be used in such a machine with or without modifications, in blends with diesel or as a neat fuel. The higher and lower heating values of biodiesel are 40 500 and 37 300 kJ/kg, respectively.

Bioethanol. It is produced through distillation of a liquid product coming from fermentation of sugars or lignocelluloses containing biomass. Sugar-containing biomass includes sugar canes, sugar beets, sorghum, molasses, and corn, whereas lignocellulosic biomass includes straw, cotton stalks, corn stalks, etc. The type of biomass that is used as raw material affects the yield ratio of each production process. Bioethanol can be used in internal combustion motors, as a neat fuel or in blends. It can also be used as a fuel for electric power generation, in fuel cells (thermo-chemical action) and in power co-generation systems, and as a raw material in the chemical industry. Its higher and lower heating values (at 20 °C) are 29 800 kJ/kg and 21 090 kJ/L, respectively.[1]

2.3. Gaseous Biofuels. They are the least used biofuels. Gaseous biofuels are produced through the biomass gasification process that is a thermal or a microbial degradation of biomass' substances. The main technologies used for commercial gasification are the thermal gasification process (pyrolysis) and the microbial gasification process (digestion). A mixture that contains one or more of the following gases is produced during the process of gasification:

- Methane (CH_4)
- Hydrogen (H_2)
- Carbon monoxide (CO)
- Carbon dioxide (CO_2).

The thermal value of biogas depends upon its composition, which in turn depends upon the biomass type and the technology used. In general, the thermal value of biogas varies between

(2) Scordilis, A. *Introduction to Municipal Solid Waste Treatment*; Technical Chamber of Greece: Athens, Greece, 1990.

(3) Petrou, E.; Mihiotis, A. Design of a factories' supply system with biomass in order to be used as an alternative fuel—A case study. *Energy Fuels* **2007**, *21*, 3718–3722.

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Table 3. Amounts of Energy Produced and Substituted by 1 ton of RDF[a]

burned in a	produce	and substitute
brown coal power plant	1500 kW h	1230 kg of brown coal
hard coal power plant	1500 kW h	550 kg of hard coal
cement kiln	4080 kg clinker	550 kg of hard coal
MSW incinerator	520 kW h	equivalent amount by public power generation

[a] From ref 4.

10 000 and 20 000 kJ/kg. Wood, forest, and agricultural residues and wastes and manure as well are used as raw materials in gasification. Biogas is produced to be used as

- A fuel in power and thermal co-generation
- An industrial fuel (e.g., cement works)
- A raw material for ammonia (NH_4) production
- A raw material in the chemical industry.

3. Biofuels Production Technologies

3.1. Solid Biofuels Production. *RDF.* A typical flow sheet of RDF's production includes size reduction, separation, drying, and sieving stages. This technology is called mechanical biological treatment (MBTP). In another RDF production technology (dry stabilization), municipal wastes (apart from iron containing) are dried and stabilized through a composting process, and they produce a fuel with a high thermal value proper for combustion. Pellets and briquettes can be produced from RDF as well. RDF production's yield depends upon the municipal wastes composition and the collection and production system's technology as well. In Europe, production yields that commonly range from 23 to 50% (% w RDF/w MSW) have been reported, while an 85% yield has once been achieved.[4]

Briquettes−Pellets. The basic process's stages in pellets or briquettes production are the biomass size reduction followed by its compaction through extruders. In some cases, a binder is added in the material through the compaction stage. This is not always necessary because lignin contained in the biomass is a natural binder. Pellets and briquettes are products of high thermal density and low water content. The total energy consumption (apart from the energy consumed for the biomass transportation) for the briquettes−pellets production is about 980 000 kcal/ton. The production cost ranges from 60 to 110 euros/ton of product.[5] Cost depends upon biomass water content (which affects the drying cost) and the market price of biomass used as raw material.

3.2. Liquid Biofuels Production. *Biodiesel.* Biodiesel's production includes the transesterification stage that is followed by separation and evaporation stages. Any material that contains triglycerides can be used as raw material for this production. The basic chemical reaction for this production is the following:

$$R_1COOCH_2CH(R_2CHCOO)CH_2COOR_3 + 3CH_3OH \xrightarrow{\text{catalyst}}$$

$$OHCH_2CHOHCH_2OH + R_1CO_2CH_3 + R_2CO_2CH_3 + R_3CO_2CH_3$$

The catalyst can be either a chemical acid or a base. The reaction temperature must be greater than 60 °C. The production occurs in batches. In a standard biodiesel production process, 1 ton of raw material, containing 2.5% fatty acids and 135 kg of methanol produce 946 kg of methyl esters, 89 kg of glycerine, and 23 kg of fatty acids. Byproducts, such as glycerine and animal feed, are exploitable and can add to the system's significant incomes.

Bioethanol. Bioethanol is produced through the fermentation of material containing sugars or cellulose. The fermentation stage is followed by distillation and separation stages. The basic chemical reactions during biomass fermentation are the following:

$$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6$$

$$nC_6H_{12}O_6 \rightarrow 2nCH_3CH_2OH + 2nCO_2$$

Various yeasts are used in the fermentation stage, but the most common is *Saccharomyces cerevisiae*. Recently, genetic modified microorganisms have become the subject of an intensive research, especially in the U.S.A., about their use as yeasts in bioethanol production.

Gaseous Biofuels. Gaseous biofuels are mainly produced through thermal or microbial gasification. In thermal gasification, various techniques are used for the degradation of the complicated organic substances that are contained in the raw material. Such techniques are pyrolysis, partial oxidation, steam oxidation, and hydrogen gasification. Differences between these techniques are related to process parameters and special stages used for the separation of the biogas and gaseous byproduct. The products of a thermal gasification process are simple hydrocarbons and others (mainly methane and hydrogen). Microorganisms that can degrade the biomass are used in microbial gasification. These microorganisms have a type of selectivity and lead the reaction toward methane or hydrogen. Methane production occurs in the absence of air, and the microorganisms used in this case are anaerobic. For hydrogen production, the following three basic methods are used:[1]

- Fermentation with certain species of heterotrophic anaerobes
- Biophotolysis in which photosynthetic organisms are used
- A method in which cell-free chloroplast ferrodoxin and hydrogenase components are used.

Hydrogen production through these methods is not yet commercial, but methane fermentation is used worldwide either alone or in combination with other processes.

4. Biofuels Evaluation

Generally, the biofuels' (which is a renewable source of energy) ability to substitute fossil fuels (nonrenewable) is their main advantage. Their environmental performance is better than that corresponding to fossil fuels only in a few cases. In addition, in most cases, their high overall (production and supply) cost makes their use nonattractive.

In the following, the main advantages (pros) and disadvantages (cons) of the biofuels that have been listed in this paper are presented. These pros and cons are related to environmental, social, and economics impacts.

4.1. Solid Biofuels. *RDF.* As has already been mentioned, RDF can be used as a fuel in electric power generation (or co-generation) and in cement works. In these applications, RDF can substitute coal, pet-coke, oil, or natural gas. According to the European Commission (Directorate General Environment), the savings from fossil fuels' substitution by RDF depend upon the combustion technology system used. More specifically, 1 ton of RDF (produced through the dry stabilization method) produces and substitutes the amounts of energy appearing in Table 3.

(4) European Commission−Directorate General Environment. Refuse derived fuel. Current practice of production and use of waste derived fuels. Final Report, July 2003.
(5) European Biomass Industry Association. www.eubia.com.

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Table 4. RDF Performance in Various Environmental Impact Categories[a]

	power station with brown coal		power station with hard coal		cement works		MSW incinerator for power production	
impact category	RDF	brown coal	RDF	hard coal	RDF	hard coal	RDF	fossil fuels
GWP (kg of CO_2 equiv)	4.85×10^2	1.72×10^3	4.91×10^2	1.62×10^3	2.48×10^3	4.09×10^3	4.91×10^2	3.44×10^2
summer smog (NCPCP) (kg of NO_x-corrected photo-oxidantial creation potential)	4.22×10^{-1}	1.79×10^{-1}	4.05×10^{-1}	2.97×10^{-1}	1.03×10^0	7.89×10^{-1}	3.69×10^{-1}	6.47×10^{-2}
acidification (AP) (kg of SO_2 equiv)	2.23×10^0	3.35×10^0	2.38×10^0	2.45×10^0	5.96×10^0	6.07×10^0	1.57×10^0	6.00×10^{-1}
nutrification (NP) (kg of PO_4^{-3} equiv)	2.32×10^{-1}	2.21×10^{-1}	1.84×10^{-1}	1.69×10^{-1}	9.11×10^{-1}	9.38×10^{-1}	1.71×10^{-1}	6.20×10^{-2}
human toxicity [carcinogenic risk potential (CRP)] (kg of As equiv)	1.53×10^{-4}	5.07×10^{-5}	5.52×10^{-5}	5.65×10^{-5}	3.42×10^{-5}	5.81×10^{-5}	9.41×10^{-6}	8.26×10^{-6}
Hg (kg)	4.63×10^{-4}	6.53×10^{-5}	3.31×10^{-4}	5.96×10^{-5}	7.24×10^{-4}	3.03×10^{-4}	1.08×10^{-4}	7.63×10^{-6}
Pb (kg)	2.30×10^{-3}	1.41×10^{-5}	8.97×10^{-4}	8.23×10^{-5}	5.81×10^{-6}	1.68×10^{-6}	6.21×10^{-5}	8.43×10^{-6}

[a] From ref 4.

Table 5. Environmental Impacts of Power Production from Hard Coal and Biomass Mix[a]

	hard coal combustion	combustion of a mix (90% hard coal/10% straw)	combustion of a mix (90% hard coal/10% wood)
nonrenewable sources of energy consumption (MW h/MW h_{power})	2514	130	119
CO_2 equiv (ton MW^{-1} h_{power}^{-1})	931	37	35
SO_2 equiv (kg MW^{-1} h_{power}^{-1})	1515	692	286

[a] From ref 7.

In Table 4, RDF's performance with regard to various environmental impact categories and a comparison to the coal's corresponding performance are presented. The RDF performance in global warming potential (GWP) is better than that corresponding to coal. An exception is observed in the incineration, in which its GWP performance is worse than the equivalent amount of the fossil fuel used in the public power generation system. In addition, RDF's performance in NO_x, Hg, and Pb emissions is also bad. Another serious problem with RDF is related to its significant concentration in Cd, Cu, and Zn.

The European Commission's main conclusions on the RDF production and use are that none of the options is globally advantageous. On the one hand, because of the effective substitution of primary fossil fuels by RFD use in coal power plants and cement works, these options show a large number of ecological advantages when they are compared to the alternative combustion in a MSW incinerator. On the other hand, this general statement has, however, to be qualified by the tendency of industrial plants to cause higher emission rates (especially of mercury) than a modern MSW incinerator. The benefit of using RFD as a fossil fuel substitute at industrial plants must be secured by adequate controls on emissions and the quality of input materials.[4]

Briquettes−Pellets−Virgin Biomass. Briquettes and pellets are of high energy density value, and this is their main advantage. They return 10−20 times the energy amount used for their production.

Their production cost depends upon the used biomass' price and, of course, the biomass' transportation cost from the fields to the production site. In general, briquettes and pellets can contribute to CO_2 emissions reduction, because they are produced from a renewable raw material. However, unfortunately, volatile organic compounds (VOCs) are emitted during their production processes and contribute in this way to environmental pollution. It must be noted that CO_2 emissions reduction are of a global significance, while VOC emissions are of a local one.

Virgin biomass and solids fuels produced from biomass are materials containing Cl. Because of this fact, these materials can form dioxins (PCDD/F) during their combustion. Dioxins (polychlorinated dibenzofurans) are formed at high oxygen concentrations on the surface of unburned fly ash particles in a temperature range between 180 and 500 °C. In addition to Cl, carbon, oxygen and catalysts (Cu) are necessary for PCDD/F formation. According to some researchers,[6] emission-related problems are expected for materials with a Cl concentration above 0.3 wt % (on a dry basis) and can therefore be of relevance for herbaceous biofuels.

Table 6. Uncertainty in Energy Consumption in Biodiesel Production[a]

researcher (year)	energy consumption (MJ/L biodiesel)	relative uncertainty (±%)
International Energy Agency (IEA) (1999)	22	35
Joint Research Centre of the European Commission (2003)	12	10
Levington (2000)	15	25

[a] From ref 8.

The partial substitution of hard coal in power generation systems for virgin biomass has been studied for its environmental performance.[7] An LCA has been realized for each of the following three power generation systems:

- Hard coal system
- Hard coal (90%) and straw (10%) system
- Hard coal (90%) and wood (10%) system.

The results of this LCA are presented in Table 5, which shows that the biomass' performance in the depletion of nonrenewable sources of energy is very good as it is in CO_2 and SO_2 emissions.

A disadvantage of these biofuels is the system needed for the biomass collection. These collection systems are very complicated and of a high cost because of:

- the biomass sources' high dispersion
- the relatively low bulk density of the biomass
- the biomass' high water content.

The above factors impose a high transportation cost because of the big number of the itineraries needed and a high cost of the biomass deposit.[3]

4.2. Liquid Biofuels. *Biodiesel.* Several studies have been conducted concerning the energy balance of the biodiesel production process. The results of these studies are accompanied very often with some degree of uncertainty and are almost always quite different. This is because of the following reasons:

- In some cases, byproducts come out from the process, while in some other cases, they do not. Because of this, the byproduct's energy content has been taken into account in some cases, while in some other cases, it has not.

(6) Obernberger, I.; Brunner, T.; Barnthaler, G. Chemical properties of solid biofuels−Significance and impact. *Biomass Bioenergy* **2006**, *30*, 973–982.

(7) Hartmann, D.; Kaltschmitt, M. Electricity generation from solid biomass via co-combustion with coal. Energy and emission balances from a German case study. *Biomass Bioenergy* **1999**, *16* (6), 397–406.

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Table 7. Biodiesel Production from Mustard and Used Olive Oil: Cost and Incomes[a]

biodiesel from mustard			biodiesel from used olive oil		
cost factor	cost (euros/kg)	incomes (euros/kg)	cost factor	cost (euros/kg)	incomes (euros/kg)
mustard procurement and oil extraction	0.47		olive oil procurement	0.15	
oil cake		0.17	filtration stage	0.03	
transesterification chemicals	0.16		transesterification chemicals	0.13	
power and water supply	0.01		power and water supply	0.01	
biodiesel cleaning stage	0.04		biodiesel cleaning stage	0.04	
glycerine		0.04	glycerine		0.07
labor	0.01		labor	0.01	
partial production cost	0.48		partial production cost	0.30	
taxes	0.08		taxes	0.05	
distribution	0.10		distribution	0.06	
total cost	0.66		total cost	0.41	

[a] From ref 9.

Table 8. Reduced Cost of Diesel and Biodiesel in Spain (Euros/MJ)[a]

fuel	cost (euros/kg)	net thermal value (MJ/kg)	reduced cost (euros/MJ)
diesel	0.82−0.86[b]	38.97	0.021−0.022
biodiesel from used olive oil	0.41	36.79	0.011
biodiesel from mustard	0.66	37.25	0.018

[a] From ref 9. [b] Average market price in Spain (2004). Today (July 2008), this price is almost double (1.56 euros/kg).

- A big range of biomass types is used for biodiesel production. Each of these types has different property values (e.g., energy content, bulk density, crops' yield, etc.); therefore, the performance of each production system is quite different.
- Different cultivation methods (such as fertilization, tilling, collecting, etc.) are used in each biodiesel production system; therefore, the energy amount demanded for the biomass cultivation varies significantly.

Results from various studies concerning the amounts of energy consumed in biodiesel production systems are presented in Table 6.

Given that biodiesel's net thermal value is 32.3 MJ/L, it is concluded that its extra energy (above the energy consumed in its production process) ranges between 45 and 166%. It should be noted that, in one certain case (IEA 1999), a likely outcome of the consumed energy amount is 30 MJ/L, which is slightly smaller than the energy amount produced (32.3 MJ/L).

Taking into account that

- the energy needed for the biodiesel's production process originates from transportation fossil fuels
- the energy content of the fossil diesel equivalent to 1 L of biodiesel is 32.3 MJ
- the fossil energy input required for transport and refinement is roughly 16% of the energy content of fossil diesel

it is obvious that, if diesel is substituted with biodiesel, roughly $^2/_3$ of fossil energy is saved. This makes biodiesel not a perfect substitute of conventional diesel.[8] From the above, it is clear that biodiesel's energy performance is arguable.

Much research has been realized about biodiesel's economics as well. Raw material is the biggest cost element of biodiesel production. For this reason, biodiesel enterprises prefer to use cheap biomass.

The production cost and respective incomes from biodiesel production from mustard or used olive oil in Europe (Spain) is shown in Table 7.

At a first sight and taking into account the reduced cost of diesel in Spain (that is given in Table 8), it seems that biodiesel produced from mustard or olive oil can be an efficient substitute of fossil diesel.

Table 9. Taxes Excemption in the European Biodiesel Market[a]

country	tax exception (euros/L of biodiesel)
Germany	0.53
France	0.37
Italy	0.33
Czech Republic	0.11
Spain	0.33
U.K.	0.32

[a] From ref 8.

Table 10. Biodiesel Pros and Cons[a]

category	biodiesel pros	biodiesel cons
resources	it is saving fossil fuels	biomass collection needs fossil fuels
GHG	lower GHG emissions in relation to fossil fuels	
acidification		bigger contribution to acidification in relation to fossil fuels
stratospheric ozone layer depletion		higher NO_2 emissions in relation to fossil fuels
eutrophication		higher NO_x emissions in relation to fossil fuels
human eco-toxicity	lower suspended matter and SO_2 emissions in relation to fossil fuels	surface water pollution with pesticides

[a] From ref 8.

Taxes are not included in the above biodiesel's cost, whereas in diesel's price, they are. Tax exceptions for biodiesel in EU countries are shown in Table 9.

From the above, it follows that the real biodiesel's price (including taxes) in Spain ranges from 0.74 to 0.99 euros/L. This makes the use of biodiesel nonfeasible in general, except in the case of its production from used olive oil. It must be noted that used olive oil has a relatively small market; therefore, it cannot be used in industrial scale for biodiesel production.

Some other researchers (e.g., refs 10 and 11) have shown that biodiesel use is not feasible, except in cases where it is subsidized or in the case of the absence of fossil fuel. Therefore, direct or indirect biodiesel's subsidy could be acceptable only if it had exceptional environment performance. However, this is not the case, as shown in Table 10.

Biofuels' subsidization has driven an intensive demand for arable land to be used for biodiesel or bioethanol production. For instance, the EU's decision for the substitution of 5.75% of fossil transportation fuels used in EU countries until 2010 corresponds to the occupation of 9.0 million ha of arable land for biodiesel's production and 2.2 million ha for bioethanol's production. Furthermore, this needed acreage corresponds to 13.6% of the total EU 25 arable land.[8] This arable land was

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Table 11. EU Arable Land for the Main Agricultural Products[a]

	average arable land for the period 2002−2006 (×1000 ha)	arable land for 2006 (×1000 ha)	arable land for 2007 (×1000 ha)
cereals (excluding rice)	59368	57010	57870
common wheat	22302	21953	22102
durum wheat	3739	3021	3031
barley	13908	13780	13691
sugar beet	2254	2030	1970
subtotal	101571	97794	98664
rape	4605	5333	6057

[a] From ref 13.

used until now mostly for food production. In other countries, the increased demand for arable land can drive to extreme deforestation phenomena as in the cases of the Amazon's tropical forest or Malaysia's ancient forests.

In any case, the pressure in food market prices is a reality, which is well-explained by the offer and demand balance law. According to some other researchers, biomass cultivation in large scale to be used for biodiesel's production can improve rural development especially in EU countries or the U.S.A., where big imports of agricultural products take place from Third World countries.

Specifically, biodiesel promoters advocate that subsidizing (or detaxing) biofuels can support the agricultural sector and, in this way, regulate food overproduction. In addition, they consider that biofuels' subsidy compensates food subsidy because the latter can cause food overproduction and unfair competition to Southern countries. This can happen because food overproduction, as a result of subsidization, results in reduction in food market prices and in farmers' income as well; therefore, they cannot afford to be farmers and give up.[12]

What biodiesel promoters suggest is the substitution of food subsidization with biofuels' subsidization. However, the question is raised of how food subsidization results in agricultural abandonment, while biofuels subsidizing can reverse this situation. This question becomes harder when it is taken into account that the global food demand is enormous in relation to the biofuels' demand.

Besides, as shown from the examination of the EU agricultural population's and arable land's evolution, both of them are decreasing, although a subsidizing system is taking place in recent years. According to Eurostat, in 1990, the EU-15 agricultural holdings were 7 370 400, while in 2005, they were only 5 843 050. Additionally, the arable land used for the cultivation of the main food products is becoming lower as Table 11 shows.

As we can see, the reduction of the arable land used for some basic products cultivation, such as wheat, barley, cereals, etc. (101 571 000 − 98 664 000 = 2 907 000 ha), is not compensated from the increase of the arable land used for rape cultivation (6 057 000 − 4 605 000 = 1 452 000 ha).

Table 12. Bioethanol's Net Energy Ratio Obtained from Various Research[a]

research body	year	NER
USDA	2004	1.42
Argonne	1999	1.37
ORNL	1990	1.25
UC Berkeley A	2006	1.22
UC Berkeley B	2006	1.10
Amoco	1989	0.95
Iowa State	1992	0.90
Pimentel	2005	0.77
MIT	2006	1.12

[a] From ref 14.

Table 13. Breakdown of Bioethanol's Cost in Two Typical Cases in EU[a]

	wheat			sugar beet		
	euros/L	euros/GJ	euros/toe	euros/L	euros/GJ	euros/toe
feedstock	0.40	18.9	790	0.26	12.3	513
co-product credit	0.15	7.1	296	0.03	1.4	59
subtotal feedstock cost	0.25	11.8	493	0.23	10.9	454
conversion costs	0.28	13.3	553	0.22	10.4	434
subtotal production cost	0.53	25	946	0.45	21.3	888
blending costs (including adaptation of gasoline)	0.05	2.4	99	0.05	2.4	99
distribution costs	0.01	0.5	20	0.1	4.7	197
total cost at the petrol station	0.59	27.9	1165	0.6	28.4	1184

[a] From ref 5.

Bioethanol. Bioethanol's life cycle analysis has recently become a very popular research field. However, the results obtained conflict with each other, even regarding the energy performance of bioethanol's production. A common measure for this performance is the net energy ratio (NER), which is the ratio of the produced bioethanol's energy content per energy amount consumed during its production. Some of the NER values reported until 2006 from various LCA studies concerning ethanol's production from corn are presented in Table 12.

It is clear from the above that NER in three cases is lower than 1 (0.77−0.95). This means that bioethanol's production in these cases is nonfeasible from an energy point of view. In the rest of the cases, the NER is bigger than 1 but varies significantly. This big range of NER values is probably due to

- Different corn cultivation yields. This yield varies reasonably from one geographical area to another (different soils, different climate, etc).
- Different cultivation techniques. It is reasonable for these techniques to vary from area to area because of the different climate or economic conditions.
- Different production system yields. Different production technologies have different yields.

According to the European Biomass Industry Association (EUBIA), ethanol's production from materials containing sugar or starch is a mature technology and small or nonprogress is expected for its yields and cost. The supply cost of ethanol produced from wheat and sugar beets in EU 27 and its breakdown into the partial cost factors is presented in the following Table 13.

(8) Frondel, M.; Peters, J. Biodiesel: A new Oildorado? *Energy Policy* **2007**, *35* (3), 1675–1684.

(9) Dorado, M. P.; Cruz, F.; Palomar, J. M.; López, F. J. An approach to the economics of two vegetable oil-based biofuels in Spain. *Renewable Energy* **2006**, *31* (8), 1231–1237.

(10) Peterson, C. L. Vegetable oil as a diesel fuel: Status and research priorities. *Trans. ASAE* **1986**, *29* (5), 1413–1422.

(11) Bender, M. Economic feasibility review for community-scale farmer cooperatives for biodiesel. *Bioresour. Technol.* **1999**, *70* (1), 81–87.

(12) Russi, D. An integrated assessment of a large-scale biodiesel production in Italy: Killing several birds with one stone. *Energy Policy* **2008**, *36* (3), 1169–1180.

(13) Eurostat. www.epp.eurostat.ec.europa.eu.

(14) Johnson, J. J. Technology assessment of biomass ethanol: A multiobjective life cycle approach under uncertainty. Ph.D. Thesis. Massachusetts Institute of Technology (MIT), Cambridge, MA, June 2006.

(15) Sassner, P.; Galbe, M.; Zacchi, G. Techno-economic evaluation of bioethanol production from three different lignocellulosic materials. *Biomass Bioenergy* **2008**, *32* (5), 422–430.

(16) Kim, S.; Dale, B. E. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy* **2004**, *26* (4), 361–375.

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Table 14. Ethanol's Production Cost from Some Lignocellulosic Materials[a]

raw material	base case (euros/L)	pentose-fermenting case (euros/L)
salix	0.58	0.48
corn stover	0.58	0.46
spruce	0.46	0.44

[a] From ref 15.

According to ref 5, the ethanol's production cost is

- 0.42 euros/L (20 euros/GJ) for ethanol produced from corn in the U.S.
- 0.32−0.53 euros/L (15−20 euros/GJ) for ethanol produced from sugar beets in northwest Europe.

It is clear from the above that, in these particular cases, the feedstock cost ranges approximately between 50 and 80% of the total ethanol's cost.

It must also be noted that, according to EUBIA, ethanol's production from lignocellulosic materials is a field open for research and development. The production cost for this technology is not studied enough yet.

Ethanol may also be produced from salix, corn stover, and spruce through two different technologies: the base case (classical saccharification and fermentation process) and the pentose-fermenting case (a process using the hemicellulosic pentose fraction to obtain good process economy). The production cost of these two cases is shown in Table 14.

The feedstock cost is about 40% of the total ethanol's cost in all six cases.

It is clear that in all of ethanol's production systems, the feedstock cost ranges from 40 to 80% of its final price. This fact makes ethanol's price vulnerable to the raw materials market prices.

According to EUBIA, ethanol's production from lignocellulosic materials offers some particular advantages because of the following reasons:

- Lignocellulosic materials are abundant and cheaper than agricultural food products. Also, their global potential corresponds to the production of 442 GL of ethanol/year. In addition to this, the agricultural wastes' potential corresponds to the production of 49.1 GL of ethanol/year; therefore, the total potential is 491.1 GL/year.[16]
- The ethanol production technologies from such materials have better energy performance.
- Ethanol produced from these materials can save up to 90% of CO_2 emissions in relation to fossil fuels.

Many LCIA studies have been realized until now about bioethanol. The results of these studies vary considerably, as shown in Table 15. The table 15 shows, in particular, that all studies in general agree that bioethanol has positive impacts in nonrenewable resource depletion, global warming effect, and CO_2 emissions.

On the other hand, bioethanol's production and use has negative impacts in SO_x emissions and acidification, while its impacts in other categories are not studied enough yet or are ambiguous. In some cases, these negative impacts could be reduced should bioethanol's production be combined with some power generation.

The ambiguity of the results of the above studies is probably due to

- different raw materials used for ethanol's production
- different cultivation techniques used
- different production technologies used
- different production system limits set by researchers.

4.3. Gaseous Biofuels. The environmental impacts of biogas produced in a power co-generation system, which uses agricultural wastes as a fuel and produces 86 kW electric power and 148 kW thermal energy as well, is the subject of a recent study.[18] In this study, the environmental impacts of this system have also been compared to other conventional power generation systems' impacts.

The environmental impacts of this co-generation system (in its limits, the transportation of the used biomass from a 60 km distance to the power station is included) and the results of the above comparison are presented in Table 16.

As it emerges from Table 16, the biogas co-generation system's impacts concerning the climate change and the resource depletion are particularly promising. However, its impacts in the acidification and eutrophication categories are worse than those corresponding to the conventional cases. This is probably due to high NO_x emissions in the biogas co-generation case. However, the total environmental performance of this production method based on eco-indicators (hierarchy method) is better than the three other conventional methods. Their performances are listed in Table 17.

The case of an integrated biomass gasification system combined with power generation and capture of the emitted gases (IBGCC−de-CO_2), in which biomass with low thermal energy (18 000 kJ/kg) is used, has been the subject of another study.[19] After the biogas production, the CO_2 contained in it is removed through its capturing in a diethanolamine/methyldiethanolamine solution. The remaining gas is burned in a combined thermodynamic cycle (Brayton/Hirn) to produce power and heat. The biomass is produced in fields about 75 km in distance from the production unit and is transferred toward it by trucks.

In this study, a LCIA has been implemented to determine the various environmental impacts and the overall environmental performance (through eco-indicator 95) and to compare these results to those corresponding to conventional coal gasification systems with CO_2 capturing (ICGCC−de-CO_2). The results are shown in Table 18. The functional unit is 1 MJ.

It is obvious that the IBGCC−de-CO_2 has worse performance than the ICGCC−de-CO_2 in a series of impacts, such as eutrophication, ozone layer depletion, carcinogenic substances, etc. However, the overall environmental performance of IBGCC−de-CO_2 is better than that corresponding to ICGCC−de-CO_2. This is probably due to its much better (negative) impact in the greenhouse effect.

The gasification of biomass has widely been implemented in developing countries for power generation, particularly in the nongrid areas. A unit [biomass gasification based power plant (BGBPP)] in an India area (Chottomollakhali Island) is such a case.[20] In this area, before the unit establishment, power was generated through small diesel generators. The unit produces 400 kW on average. It is fed with biomass (400 kg/day) at a price of $0.02/kg. A spare small-power diesel generator is also available. The power of the unit is used to supply 1 industrial unit, 150 commercials, and 74 households.

(17) von Blottnitz, H.; Curan, M. A. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J. Cleaner Prod.* **2007**, *15* (7), 607–619.

(18) Chevalier, C.; Meunier, F. Environmental assessment of biogas co- or tri-generation units by life cycle analysis methodology. *Appl. Therm. Eng.* **2005**, *25* (17−18), 3025–3041.

(19) Carpentieri, M.; Corti, A.; Lombardi, L. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal. *Energy Convers. Manage.* **2005**, *46* (11−12), 1790–1808.

(20) Mukhopadhyay, K. An assessment of a biomass gasification based power plant in the Sunderbans. *Biomass Bioenergy* **2004**, *27* (3), 253–264.

Table 15. Common LCI Categories and Inventory Releases for Bioethanol Compared to Conventional Fuel from a Review of the Literature[a]

	agricultural feedstock				waste feedstock		
	researcher						
	Kaltshmit 1997, sugar beet, wheat, potato Germany	Puppan 2001, sugar beet, winter wheat, potato Germany	Reinhardt 2002, sugar beet, wheat, potato Europe	Hu 2004, cassava China	Kadam 2002, waste bagasse India	Sheehan 2004, corn stover U.S.A.	Tan and Culuba 2002, agricultural cellulosic waste Philippines
resource depletion	+	+	+	+	+	+	+
global warming	+	+	+	NA	+	+	+
CO_2	NA	NA	+	+	NA	NA	NA
acidification	0	0	−	NA	+	−	−
SO_x	−	NA	−	NA	NA	NA	NA
NO_x	+	NA	−	−	NA	NA	NA
eutrophication	NA	NA	−	NA	+	NA	−
human toxicity	NA	0	NA	NA	+	NA	−
CO	NA	NA	−	+	NA	NA	NA
PM	NA	NA	−	+	NA	NA	NA
eco-toxicity	NA	0	NA	NA	NA	NA	NA
photochemical smog	NA	NA	+	NA	NA	−	+
HC	NA	NA	+	+	NA	NA	NA
solid waste	NA	NA	NA	NA	+	NA	NA
land use	NA	NA	NA	NA	NA	0	NA
water use	NA	NA	NA	NA	0	NA	NA
ozone depletion	−	−	NA	NA	NA	+	NA
odor	NA	NA	NA	NA	+	NA	NA

[a] From ref 17. +, Increased impact for bioethanol; −, decreased impact for bioethanol; NA, not assessed; 0, no significant change.

Table 16. Comparison of the Impacts Because of Power Production by the Biogas Co-generation Unit Case (Including Transport) and Conventional Means[a]

category technology	resource depletion (MJ equivalent fossil fuels)	climate change (equivalent g of CO_2)	acidification (equivalent mg of SO_2)	eutrophication (equivalent mg of NO_x)
conventional case (power by the grid/Germany)	4.72	281	1170	539
conventional case (power by the grid/Austria)	3.24	193	604	328
conventional case (power by the grid/France)	2.52	142	350	249
biogas co-generation	0.23	−112	515	838

[a] From ref 18.

Table 17. Comparison between the Impacts of the Biogas Co-generation Unit Case (Including Transport) and Conventional Means (EI_99 Approach)[a]

technology	eco-indicator 99
conventional case (power by the grid/Germany)	0.013
conventional case (power by the grid/Austria)	0.010
conventional case (power by the grid/France)	0.009
biogas co-generation	0.0025

[a] From ref 18.

The power prices in the various categories of consumers are listed in Table 19.

The above prices compared to the power production cost of the diesel generators ($0.49/unit of consumption) are significantly smaller. In Table 20, the savings of each consumer category are presented.

5. Impacts of Biofuels

5.1. Positive Impacts.

- According to many researchers, the most common positive impact of biofuels is the reduction of the emissions of gases producing the greenhouse effect, particularly CO_2 emissions. This is because organisms (that biomass comes from) during their lives absorb CO_2 equal to the amount emitted when biomass (or biofuel produced from it) is burned. However, this consideration presumes that

(21) United Nations Environment Programme. GEF ID 1361. Project Executive Summary. www.unjobs.org.

Table 18. Comparison between the IBGCC LCA and the ICGCC Indicators[a]

	IBGCC−de-CO_2 eco-indicator 99	ICGCC−de-CO_2 eco-indicator 99
greenhouse effect (kg of CO equiv/MJ)	−0.165	0.1
ozone layer depletion (kg/MJ)	3.26×10^{-8}	1×10^{-8}
acidification (kg/MJ)	0.00251	0.0022
eutrophication (kg/MJ)	4.62×10^{-4}	4.9×10^{-4}
heavy metals (kg/MJ)	1.54×10^{-7}	6×10^{-8}
carcinogenic substances (kg/MJ)	4.89×10^{-5}	0.00×10^{00}
pesticides (kg/MJ)	1.17×10^{-6}	
energy (MJ)	0.296	4
eco-indicator 95	0.00026	0.0025

[a] From ref 19.

○ Biomass used is 100% renewed. That is, in the same period, the biomass use rate must be equal to the new biomass cultivation rate.

○ Cut and renewed biomass must absorb equal amounts of CO_2.

The fulfilment of the above presumptions seems to be ignored silently (or its importance diminished) by most researchers when they determine the impacts of biofuels on the greenhouse effect.

On the other hand, mass production of biofuels (such as biodiesel and bioethanol) can lead to the increase of gases contributing to the greenhouse effect. This is due to

○ The use of fossil transportation fuels in the complicated logistics needed for biomass collection and transportation and in biofuels distribution.

○ The deforestation or clearing of grasslands to be used for biomass cultivation. This leads to emission of CO_2 captured in biomass and the soil into the atmosphere.

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Table 19. Electricity Tariff Structure in a Power Generation System from Domestic Biomass in India[a]

customer	tariff rate (\$/unit of consumption)
industry	0.1
commercials	0.09
households	0.08

[a] From ref 20.

Table 20. Benefits for the Various Consumers from the BGBPP Operation[a]

commercials		households	
savings per month (\$)	percent of consumers (%)	savings per month (\$)	percent of consumers (%)
0.02−1.02	18	0.02−1.02	0
1.02−2.04	20	1.02−2.04	32
2.04−3.07	30	2.04−3.07	36
3.07−4.09	18	3.07−4.09	22
4.09 and above	14	4.09 and above	10

[a] From ref 20.

Table 21. Corn Price in the U.S. (Period 2000−2008)[a]

year	price (\$/bushel)
2000−2001	1.82
2001−2002	1.85
2002−2003	1.97
2003−2004	2.32
2004−2005	2.42
2005−2006	2.06
2006−2007	2.00
2007−2008	3.04

[a] From ref 22.

- Probably positive is biofuels' impact on SO_2 emissions. This is due to the low content of biomass (plants) in sulfur. However, in a complicated supply system of biofuels production, this advantage may be eliminated because of fossil fuels usage in these systems (for biomass cultivation, harvesting, and transportation stages).
- Biofuels' contribution to the nonrenewable sources (fossil fuels mainly) depletion depends upon the net energy ratio of each of them. NER is equal to "biofuel energy content/energy consumed for its production and distribution". In most of the biofuel production cases, NER is greater than 1. However, in some cases,[14] NER is lower than 1, which means that these production systems are unacceptable from an energy point of view. Of course, NER depends upon the boundaries of the system and various other parameters, such as cultivation techniques, production methods, etc.
- In some cases, biofuels can contribute positively to regional development and sustainability, as in the case of co-generation power systems through biogas combustion. Two indicative cases are the power generation systems in India[20] and Cuba (Isla de Juventud).[21] These units are operated with local biomass and contribute to the local communities power supply systems and, furthermore, to their development. Used biomass substitutes fossil fuels, such as kerosene and diesel. As shown in the research in the India case, 80% of users declared an economic benefit from the system greater than \$1/month, while 40% of the population of this area has a monthly income of \$20. In any case, biofuels' contribution to local development and sustainability depends upon the type of biomass used (residues or biomass from energy cultivation).

5.2. Negative Impacts.

- Today the most serious problem arising from biofuels' use is the increase of food market prices. This is explained, to some extent, if the decrease on food production because of the increased use of cultivation land for biomass' production is taken into account. In addition, the agricultural commodities trading in the future market push their prices to rise in an unpredictable way.
- At the same time, the global demand for food (agricultural food products) is enormous and only partially satisfied. Subsiding biofuels also contributes in the same way, causing food prices to rise because farmers prefer to produce products with certain prices. A characteristic example of the problem of food prices is the corn price in the U.S.A. Corn in the U.S.A. is used extenively for ethanol production. Its prices during the period 2000−2008 have evolved as shown in Table 21. Thus, a scale up in corn's price is observed in 2003−2004, which is the year of a big expansion in the commercial use of corn as a raw material for ethanol production. After this year, the rise of corn prices is almost continuous. Of course, the influence of bad weather conditions on corn production and price should not be ignored. It must also be noted that the above prices are those given to the farmers and, of course, end-users prices are greater than these. Another example of the continuous rise of prices of agricultural products comes from Europe (Greece). In 2006−2007, chicken egg producers in Greece bought soy for 180 euros/ton and corn for 170 euros/ton. Next year (2007−2008), these prices had risen at the level of 300 and 270 euros/ton, respectively, which is approximately a 60% rise, with obvious consequences in egg's price.
- A similar rise is also observed in the prices of nonfood biomass used as a fuel or as a raw material for biofuels production. In this case, the mechanism is the CO_2 rights trading system established in the framework of the Kyoto agreement and aiming at the reduction of global CO_2 emissions. It was predicted that, through this system, enterprises would want to substitute fossil fuels with biomass considered as CO_2 neutral to sell their CO_2 rights in the market and obtain, in this way, an additional income. This market's behavior leads to an increased demand for biomass, which is traditionally used as a raw material in various industrial sectors, such as paper and wood industry, and causes a consequent rise in its price. Enterprises that are not members of the CO_2-trading system undergo an extreme competition that can lead them to increase of their products prices, change of their technological systems, or decrease of their profits. A study on the influence of the CO_2-trading system in the wooden biomass market in Finland has been realized.[23]
- In this study, the CO_2 breakeven prices, i.e., prices at which the biomass producers prefer to supply enterprises that are members of the CO_2-trading system (as opposed to those which are not), have been determined. These breakeven prices for some of Finland's basic industrial sectors are shown in Table 22. The CO_2-trading system did not have the predicted and desirable effect on the reduction of CO_2 emissions during the 2005−2007 period. The CO_2 right price in early 2005 was 30 euros/ton, while at the end of 2007, it was sunk at the level of 0.02 euros/ton. Overof-

(22) United States Department of Agriculture. http://ers.usda.gov/amberwaves.
(23) Ranta, T.; Lahtinenb, P.; Elo, J.; Laitila, J. The effect of CO_2 emission trade on the wood fuel market in Finland. *Biomass Bioenergy* **2007**, *31* (8), 535–542.
(24) Biofuelreview. http://www.biofuelreview.com/content/view/1439/5/.
(25) National Renewable Energy Laboratory. http://www.nrel.gov/biomass/biorefinery.html.

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Table 22. Breakeven CO_2 Prices in Finland[a]

industrial sector	breakeven CO_2 price (euros/ton of CO_2)
chipboard industry	5
paper pulp industry (from wood)	15
paper pulp industry (from chipped wood)	20

[a] From ref 23.

fering of CO_2 rights, because of bad estimation of each country's or companies' initial rights, or nonsatisfactory verification systems may be the reasons for this excessive cutback.

- Negative impacts from biofuels are also observed in a series of environmental impact categories, such as ozone layer depletion and acidification. More specifically, in some cases, these impacts are worse than those corresponding to fossil fuels. These impacts vary from study to study and depend upon the definition of limits of each system, the cultivation and production methods, etc.
- Another negative impact concerning the supply chain of solid biofuels production is heavy metal (Pb, Hg, etc.) and dioxin emissions. This problem is mainly related with RDFs use as a fuel (but even with virgin biomass under certain conditions) and constitutes a conflict of interest between the various stakeholders.
- Energy plants are cultivated in an intensive way, in which many pesticides and fertilizers are used. This causes the contamination of surface waters and, as a consequence, problems such as eutrophication and eco-toxicity.

5.3. Biofuels' Risks. The main risks related with the biofuels' production and use are the following:

- Use of extremely large cultivated land for biomass production to be used as a raw material for biofuels' production. This large land's usage can result in shortages in basic foods, such as corn, cereals, soy, etc., because these are the cultivations most often replaced. The aforementioned risk will be decreased or eliminated only if certain limitations will be set in land use for biofuels' production.
- Use of genetically modified organisms (GMOs) in biomass cultivation (genetically modified corn, or soy for example) and in biofuels' production (as in the case of ethanol production with genetically modified enzymes). This usage can result in the spread of GMOs in natural habitats, certain species extinction, human mutations, etc. The extent of these risks, which have been studied only in the literature, will be practically verified only in the real world (*in vivo*), and unfortunately, then it will be late. Here, it should be noted that, in the European Union, the GMOs usage is under certain restrictions, but attempts to break them by import companies have been recently uncovered.
- The development of a large economic sector dealing with biofuels production and distribution, including biomass cultivation, can lead the world into a no return condition. This means that, if the negative impacts of biofuels override in fact the positive ones, the results will be of a disastrous global importance. In addition, the existence of such a giant economic sector will affect global economics and businesses in an unpredictable way.

6. The Future

Biofuels' use is firmly related to the evolution of recent research in their production technology. This research's directions are as follows:

- The use of GMOs in biomass cultivation and in biofuels' production is a recently developed technology. The aim of the GMO use is the increase of cultivated land's yield (biomass production quantity or quality) and the increase of the various production methods' yields. An advance in GMOs use regarding some microbes' genetical modification, which allows them to transform CO_2 into octane, may be very close.[24] Such an advance would obviously represent a breakthrough, which potentially may give a good solution to the global warming effect problem. What remains is the confirmation of this achievement and relevant LCIA studies. In any case, a risk assessment analysis should precede the implementation of such a GMO technology.
- Another direction is attempts to increase biofuels' production yields. This direction focuses on finding better raw materials and optimizing production parameters and equipment.
- Biorefineries are the subject of advanced research. They constitute the field of a coordinate research project of the National Renewable Energy Laboratory (NREL) of the U.S.A.[25] Biorefineries are industrial units in which solid, liquid, and gaseous biofuels, electric power, thermal energy, and various chemicals can be produced as in a standard refinery. NREL's research is directed in two main platforms: the "sugars platform", which is based on biochemical transformation of sugars extracted from biomass, and the "syngas platform", which is based on the thermochemical transformation of biomass.
- Biodiesel's production from alga is another promising technology. Alga can be cultivated in farms absorbing CO_2 from the air. They contain oils that can be used as raw material for biodiesel production. They have the advantage that they do not conflict with food production. In addition, they have the potential to cover the global demand for transportation fuels.[26] At the same time, they have some negative environmental impacts, such as ozone layer depletion, methane production, etc. Today, some semi-commercial units (pilot plans) of diesel production from alga are in operation, particularly in the U.S.

7. Discussion and Conclusions

From the preceding discussion, it is clear that biofuels have advantages and disadvantages and also positive or negative impacts on human and natural systems, while they pose some risks. The decision for biofuels' introduction into human systems should be connected with the satisfaction of certain criteria regarding these impacts and risks.

Conflicts of interest are common between the stakeholders (enterprises, local communities, consumers, etc.), but rarely all of them are involved in the decision-making process. For example, final consumers who bear a high cost for biofuels and food (directly or indirectly through biofuels' subsidising) have the right to take part in the decision making, but they are rarely called to do this. On the contrary, biofuels' enterprises that have big profits (directly or indirectly through subsidising) have assured their sales via mechanisms, such as the establishment of a minimum biofuels' quantity consumed by a country or a region in a certain period. For example, the European Union's 2010 target for this minimum quantity corresponds to 5.7% of the total consumed transportation fuels, while the 2020 target is 10%.

(26) Chisti, Y. Biodiesel from microalgae beats bioethanol. *Trends Biotechnol.* **2008**, *26* (3), 126–131.

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The conflicts of interest between the stakeholders are obvious and becoming bigger as biofuels' environmental impacts in some cases, such as biodiesel and bioethanol produced from energy cultivations, are at least doubtable. The EU's commission officer for environmental issues has conceded that biofuels' negative impacts outnumber the expected ones and that the EU should review the 2020 target of 10%.[27]

It should also be noted that decisions including biofuels' use in combination with other measures, such as the limitation of private cars population, sound logical and attractive from an environmental point of view, but they have no chance to be applied within the limits of modern societies, which are based on an ever-increasing consumption model.

The following basic conclusions may be drawn from the preceding discussion:

- The forest and agricultural residues seem to be a very attractive source for biofuel's production or power generation. They have a big potential, and in addition, they have no adverse effect on food production. Furthermore, if they are not used, they degrade in CO_2, thus contributing to the global warming effect. The use of residues biomass (agricultural or forest) for biofuels production has probably the least negative impacts (economic, environmental, and social) to human systems compared to energy plant cultivations. Certainly, its collection and transportation needs energy and relevant sources, which incur some negative impacts. However, these negative impacts are fewer than those corresponding to biofuels produced from energy cultivation biomass.
- The more integrated a technological system of biofuels production (that is, the more products and byproduct are produced), the less the environmental, economic, and social impacts incured. This happens because the overall impact is subdivided and distributed to partial impacts for each product or byproduct. In addition, some researchers (e.g., ref 28) have shown that biofuels' production is more feasible if the operation occurs through small cooperative enterprises of biomass producers (as for example in the case of small cooperative schemes of soy producers). This is because these cooperative enterprises can easily use all of the byproduct quantities (e.g., for animal feed).
- Measurement of the environmental and other impacts by various researchers is characterized by considerable differences and uncertainty. Differences are due to
  - the different way that each system's limits are set
  - the different biomass cultivation techniques
  - the different biofuels' production methods and techniques
  - differences in local economic conditions (market prices, wages, etc.)
  - differences in local climate (for example, temperature and humidity conditions that affect the quality of the combustion in engines but also the needs for irrigation of cultivated fields, etc.). It follows that the determination of the impacts is a multiparametric issue and is accompanied with big uncertainty. For this reason, decision making related to biofuels is not easy.
- Another fact that causes problems in decision making is that the majority of the researchers make partial LCI analysis; that is, they determine biofuels' performance with respect to only one or some of the impact categories. In addition, the environmental, economic, and social impacts are not combined in an overall performance index. For example, some researchers evaluate a biofuel only from an environmental or economic point of view, or they give some scatter values and compare them to the corresponding values of fossil fuels to show whether or not biofuels prevail against fossil fuels. Thus, the biofuels' evaluation is one-tailed and biased or at least unreliable.
- The feasibility of biofuels' use depends upon the prices of fossil fuels to be substituted. The less the biofuel's supply cost (in relation to a certain fossil fuel's price), the more feasible the biofuel's business and, of course, the more the final consumers benefit incurred. Fossil fuels prices are very high recently in relation to the past. It is interesting to note that, at the time this paper was written (May 2008), the crude oil market price was \$130/barrel and that the first commercial implementations of biofuels started in 1990s when the crude oil price was in the range of \$50−60/barrel. On the other hand, high crude oil prices raise the biomass and biofuel transportation costs because fossil fuels (diesel and gasoline) are used in these operations.
- Power generation and co-generation through biomass gasification can be an environmentally and economically acceptable solution, contributing to regional development and sustainability. The environmental impacts of this technology are attractive and becoming more attractive when a de-CO_2 technology is implemented.
- Subsidization of agricultural cultivations for biofuels production counteracts food production. In addition, it does not contribute to regional development because it fails to keep farmers on their lands. The CO_2 emission rights trading system acts similarly. More specifically, it makes the cultivation of biomass used for biofuels' production more attractive to farmers than that corresponding to biomass used as a raw material for other products (paper, fiberboard, etc.). This farmers' preference can lead to increased market prices of such products.
- Biofuels' supply chain includes complicated logistics in many cases, particularly for biomass' transportation and storage. This is due to big fragmentation of the cultivated land and the short biomass collection period. In these systems, farming machines, tractors, and trucks are used, which have a negative impact in the system's overall environmental performance, because they operate with fossil transportation fuels. The question is whether these production systems have the potential to be sustainable. In other words, whether they can produce enough fuels to cover their energy consumption (based on fossil fuels) and to make the system economically feasible.
- It seems that biorefineries are a very promising technology. They can minimize the production cost and the environmental impacts because they are integrated systems. In these systems, large-scale savings can be realized. Also, biodiesel production from alga seems to be attractive as well. It is produced from a nonfood biomass; therefore, it may have less social impacts than other systems using food products as a raw material. However, there is a need for decreasing or eliminating its negative environmental impacts.

(27) Dimas, S. EU commission officer for environmental issues. Statement on BBC (Jan 14, 2008).

(28) Weber, J. A.; Van Dyne, D. L. Macroeconomic effects of a community-based biodiesel production system. *Bioresour. Technol.* **1996**, *56* (1), 1–6.

(29) Goldemberg, J.; Coelho, S. T.; Guardabassi, P. The sustainability of ethanol production from sugarcane. *Energy Policy* **2008**, *36* (6), 2086–2097.

(30) Feng, H.; Rubin, O. D.; Babcock, B. A. Greenhouse gas impacts of ethanol from Iowa corn: Life cycle analysis versus system-wide accounting. Working Paper 08-WP 461. Center for Agricultural and Rural Development, Iowa State University, Ames, IA, Feb 2008.

Concluding, the following topics need to be further investigated:

- Ranking of the main biofuels (biodiesel, bioethanol, syngas, etc.) based on their overall performance, which must combine their environmental, economic, and social impacts.
- Environmental and economic appraisal of biorefineries. Is this technology mature for producing fuels, products, and energy in a way economically efficient and environmentally friendly?
- Evolution of the energy plant cultivation (land, biomass quantity, etc.) in EU and developing countries and correlation with biomass and agricultural products prices' evolution.
- Effect of fossil transportation fuels price rise on biofuels' supply cost.
- Relation between CO_2 right prices and the evolution of market prices of biomass used as raw material (or fuel) in industries involved in the CO_2-trading system.
- Decision-making issues: Evaluation of biofuels' production systems with different criteria groups (business criteria, environmental criteria, mixed criteria). To which extent is a decision concerning such a system influenced by the type of criteria used?
- Determination of uncertainties related to environmental and economic impacts of biofuels and methods for their handling.

Finally, several more recent papers, which are generally in line with the main conclusions of this survey, may be cited for further reference. Notable among them are some papers referring to the impacts of bioethanol production and use,[29−31] biodiesel's impacts,[32,33] and biomass' impacts.[34]

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(31) Du, X.; Hayes, D. J.; Baker, M. L. A welfare analysis of the U.S. ethanol subsidy. Working Paper 08-WP 480. Center for Agricultural and Rural Development, Iowa State University, Ames, IA, Nov 2008.

(32) Bozbas, K. Biodiesel as an alternative motor fuel: Production and policies in the European Union. *Renewable Sustainable Energy Rev.* **2008**, *12* (4), 542–552.

(33) Hu, Z.; Tan, P.; Yan, X.; Lou, D. Life cycle energy, environment and economic assessment of soybean-based biodiesel as an alternative automotive fuel in China. *Energy* **2008**, *38* (11), 1654–1658.

(34) Rowe, R. L.; Street, N. R.; Taylor, G. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the U.K. *Renewable Sustainable Energy Rev.* **2009**, *13* (1), 271–290.

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