Comparing renewable energies: estimating area requirement for biodiesel and photovoltaic solar energy

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Abstract

This paper describes two kinds of renewable energy: photovoltaic (PV) solar energy installations connected to the Italian electrical grid system, and pure biodiesel (BD100) production by using sunflower oil. A comparison between them is proposed on the basis of: (A) greenhouse gas emissions (GHG) and (B) land requirement. Point (A) is related to the emissions from carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) deriving from energy production and use, which are calculated in terms of CO_2 equivalent by their global warming potentials (GWP); point (B) is related to the area (hectares of biomass plantations and m^2 of photovoltaic panels) necessary for energy production. The results will be compared to those resulting from the use of fossil fuels.
Keywords: biodiesel, sunflower, photovoltaic, GHG, CO_2 equivalent, land requirements, power generation systems.

1 Introduction

Energy from biomass and photovoltaic (PV) energy systems are two renewable methods to reduce GHG emission, and can contribute to sustainable development. Today about 2.54 x 10^{13} kg of CO_2 are added to the atmosphere annually [1] because 3 x 10^{20} joules per year of energy depends on coal, oil and natural gas [2]. Incoming solar radiation (5.6 x 10^{24} joules) is far larger than the total demand of energy; from this point of view renewable energies like PV-system and biomass plantations represent the way to intercept more incoming solar energy. There are two very important limits to the amount of energy that can be obtained from these sources. One is the technological limit due to the

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efficiencies of these energy-converting systems, and the other is connected to the land required to intercept solar radiation. This paper focuses on the second aspect, evaluating energy, CO_2 emission and space required for these two kinds of renewable energies with respect to fossil fuels. We compare data on the electricity production from biomass (sunflower production) and PV-system.

The assessment compares a lot of results from various case studies, in order to understand and quantify the environmental impacts.

The ultimate purpose is to evaluate to what extent it is possible to provide renewable energy and avoid emissions under certain conditions. In fact, the electrical power system is one of the most important producers of greenhouse gas (GHG); to reduce them, a strategic approach is:

a) reduce total consumption of energy
b) improve efficiency
c) increase the fraction of renewable energy

These aspects can be evaluated together with other important issues such as:

1) economic and social effects;
2) "ancillary" services required to assure electrical system stability, such as the maintenance of generation/load balance, because some forms of energy generation (photovoltaic and wind) are intermittent and therefore they require a reserve of energy (backup systems) like fossil fuels to compensate demand and supply.
3) The reliability of electrical supply and the size of plants

2 Methods

In order to analyse the system of biodiesel production and use, we calculate emission inventory of sunflower cultivation, oilseed transesterification, and its final combustion in engines for electrical power generation. Inventory refers to carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), that are converted into CO_2 equivalent by their GWP. We also evaluate the entire process from a point of view of land requirement and CO_2 equivalent emissions.

The simulation shows four possible steps:

- step ***a:*** we quantify the amount of fossil diesel used and the related emissions (industrial production and combustion) per hectare in typical Tuscan farm that produces sunflower;
- step ***b***: we calculate the amount of biodiesel necessary to substitute fossil diesel and the emissions related to its production (data per hectare);
- step ***c:*** we calculate the amount of biodiesel necessary to generate electricity in small-scale power generation system and, consequently, land requirement and related emission;
- step ***d:*** we calculate greenhouse gas emissions and land requirement of electricity production from biodiesel in tree different cases; the results are then compared with data published in international literature.

We take up different data set:

- diesel fuel quantities involved in sunflower production come from field data on diesel fuel for each field operation;
- emissions of diesel fuel industrial production are based on data from Danish Life Cycle Assessment (LCA) EDIP Database [3];
- emissions of diesel fuel combustion are calculated by the IPCC method, Energy module [4];
- emissions of biodiesel agricultural production are calculated using IPCC method, Agriculture module [4];
- emissions of biodiesel industrial production are calculated using data from the EU Biofit project [5];
- emissions of biodiesel combustion are calculated from data in the EPA Biodiesel Emissions Database [6].
- We compared our results with the international literature [7, 8].

The compared analysis between electrical power production from biodiesel and other generation systems, like photovoltaic, diesel, coal and natural gas is made by using data on CO_2 equivalent emissions and energy produced (kWh) for each system, from case studies based on life cycle assessment (LCA). The assessment of these data defines the range of values found in the following international literature:

- emissions per kWh of electricity produced from diesel, coal and natural gas [9, 10, 13];
- emissions per kWh of electricity generated from PV technology [11–14].

3 Results

3.1 Step A

To obtain input and output of energy we analyzed sunflower crop production with standards of Life Cycle Analysis methodology. Sunflower seed yield was estimated to vary between 1500 and 2500 kg ha^{-1}[16]; The yield of raw oil output in seeds crushing process is about 32-38% [17]. We calculate the yield of biodiesel production for two fixed values: a sunflower seed yield of 2000 kg ha^{-1} and an oilseed yield of 35%.

Sunflower cultivation phases, diesel consumption per phase and nitrogen fertilizers requirement are presented in table 1. These data are an average for a farm of 1000 hectares. The amount of biodiesel necessary to substitute diesel is calculated using the net calorific value of the two fuels, all reported in the same table.

The biodiesel production depends on sunflower oil-seed yield which is connecting to catalysts used for methanolysis during transesterification process. In this case we refer to the study conduced by Vicente *et al.* [15] who compared different basic catalysts like sodium hydroxide, potassium hydroxide, sodium methoxide, potassium methoxide and each of them has a specific yield of biodiesel in the transformation process. The average value among the four catalysts is 94.04%. The biodiesel yield of this plantation in this condition is estimated to be 658 kg ha^{-1} year $^{-1}$.

Table 2 shows GHG emissions related diesel fuel used per hectare of sunflower production, considering the total quantity of diesel produced and its combustion. Conversion into CO_2 equivalent figures by Global Warming Potential (GWP) are presented too.

Table 1: Fuel quantities and nitrogen fertilizers (kg ha^{-1} $year^{-1}$) for sunflower cultivation.

	Ploughing	Sowing	Fertilization	Pesticide	Harvesting	Transport	Total
Diesel	43	10	10	10	20	15	108
Biodiesel	49	11	11	11	23	17	124
Fertilizer			200				200

Table 2: Emissions (kg ha^{-1} $year^{-1}$) from diesel and fertilizers use. N_2O f is nitrous oxide from fertilizers used for sunflower cultivation, N_2O c is nitrous oxide from diesel fuel. CO_2 equivalent is calculated by GWP.

	CO_2	CH_4	N_2O^f	N_2O^c
Emissions from diesel production	49.6	0.463		0.001
Emissions from diesel combustion	343	0.023		0.003
Total GHG emissions	392.6	0.486	2.26	0.004
GWP	1	23	310	310
CO_2 eq.	392.6	11.2	700.6	1.3
Total CO_2 eq.	1105.7			

3.2 Step B

In Table 3 GHG emissions related to biodiesel fuel used per hectare of sunflower production and CO_2 equivalent emissions are reported.

Emissions from the industrial process of biodiesel production (transesterification), are based on the EU Biofit 2000 project, in which eight European countries and related research institutes (BLT, Austria; TUD, Denmark; INRA, France; IFEU, Germany; CRES, Greece; CTI, Italy; CLM, The Netherlands; FAT, Switzerland) analyzed production and use of biofuels by an LCA method; biodiesel emissions from combustion are based on the EPA Biodiesel Emissions Database which contains emission test cycles in different engine types. We selected data referred to pure biodiesel (BD100) and the values used in our calculations are average values. GHG emissions result from the production process of biodiesel (transesterification), while the net emission of CO_2 is considered zero when biodiesel is combusted.

Table 3: Emissions (kg ha^{-1} $year^{-1}$) from biodiesel and fertilizers use. N_2O^f is nitrous oxide from fertilizers used for sunflower cultivation, N_2O^c is nitrous oxide from diesel fuel. CO_2 equivalent is calculated by GWP.

	CO_2	CH_4	N_2O^f	N_2O^c
Emissions from Biodiesel production	21.72	0.18	2.26	0.00
Emissions from Biodiesel combustion	0.00	0.00	0.00	0.01
Total emissions from Biodiesel use	21.72	0.18	2.26	0.01
GWP	1	23	310	310
CO_2 eq.	21.72	4.17	700.6	2.76
Total CO_2 eq.	729.25			

3.3 Step C

The use of biodiesel is also possible in small-scale electricity power generation systems. Power plants from less than 11 kWel up to 1,4 MWel are commercialized in EU [18] and they are considered potentially important markets. Diesel engines are the main mature power technologies with a thermal efficiency between 32.4% and 36% [20] with specific-fuel consumption 278.8-218 g/kWh [17, 21], when operating on bio-fuels.

On the basis of the characteristics of the farm (1000 ha and 658 kg ha^{-1} $year^{-1}$) we assumed a power plant capacity of 350 kWel, with an average consumption of 245g/kWh using diesel and 265g/kWh using biodiesel. The quantity of energy production is about 2483 MWhel per year. In the first year fossil diesel fuel is necessary to start agriculture operations, but in the second year we can consider the farm system self-sufficient using only biodiesel, locally produced, for field operations. In this case (farm of 1000 ha), the amount of land requirements necessary to substitute diesel is calculated to be 188 ha. At the same time, CO_2 equivalent emissions from biodiesel-power plants are 739 g CO_2 eq./KWh for the first year, and 349 g CO_2 eq./KWh for the following years. These emissions are site specific and depend on the production yields. In other words, the amount of biodiesel per unit area can vary depending on different factors: kind of lands, latitude and use of fertilizers and pesticides.

Biodiesel systems generate emissions only the production phase. Fertilizers are the most important emission factors in sunflower production but they are related to agricultural productivity. This means that a reduction of fertilizers is not considered feasible because it would decrease production yields [17].

The results obtained in the analysis, are listed in table 4.

Table 4: Overview of electrical energy generation system using pure biodiesel product in Siena Province.

Biodiesel yield	kg ha^{-1} year^{-1}	658
Biofuel requirement per unit energy (BD100)	kg/kWel.	0.265
Efficiency	%	36
First year		
Diesel required for field operations	kg ha^{-1} year^{-1}	108
Land use	ha	1000
Electricity generation	MWh/year	2483
CO_2 equivalent from Diesel for field operation	ton	1105.7
CO_2 equivalent from Biodiesel production	ton	726.5
CO_2 equivalent from Biodiesel combustion	ton	2.8
Unit CO_2 equivalent	g/kWhel.	739
Direct land requirements	ha/MWhel.	0.403
Second year		
Biodiesel required for field operation	kg ha^{-1} year^{-1}	124
Land use	ha	1188
Electricity generation	MWh/year	2483
CO_2 equivalent from Biodiesel for field operation	ton	137
CO_2 equivalent from Biodiesel production	ton	726.5
CO_2 equivalent from Biodiesel combustion	ton	2.8
Unit CO_2 equivalent	g/kWhel.	349
Direct land requirements	ha/MWhel.	0.479

3.4 Step D

Five different kinds of power generation systems are examined: Solar photovoltaic, diesel (oil), coal, natural gas and biodiesel. Typical values of greenhouse gas emissions and land requirement to generate electricity from biodiesel are calculated and compared with data published in case studies; also typical values of fossil fuels and photovoltaic (in terms of emissions of CO_2 equivalent) reported by Gagnon et al. [9] are used for comparison. To evaluate land requirement necessary to PV systems installation, we assume that the annual total electricity generated in the central and southern regions of Italy is about 1200 kWh/KWp per year [22] and electrical energy output from 1 m^2 is about 76 kWh per year [23].

In this phase we supposed to produce electrical energy by biodiesel in tree different cases of inputs; for each case we calculate the amount of land use and CO_2 equivalent per MWh. Different inputs for sunflower cultivation for each case are reported:

1) The farm system is fed by diesel fuels and fertilizers (step a);
2) we consider the farm system partially self-sufficient with biodiesel fuel and fertilizers (step b);
3) In this case we suppose the farm system totally self-sufficient with biodiesel fuel and one hypothetical amount of natural fertilizers (zero emissions) as by-product of sunflower production. In this case, biodiesel yield is reduced and it is estimated at 428 kg ha^{-1} year $^{-1}$. Figure 1 show CO_2 equivalent requirement to generate energy per MWh.

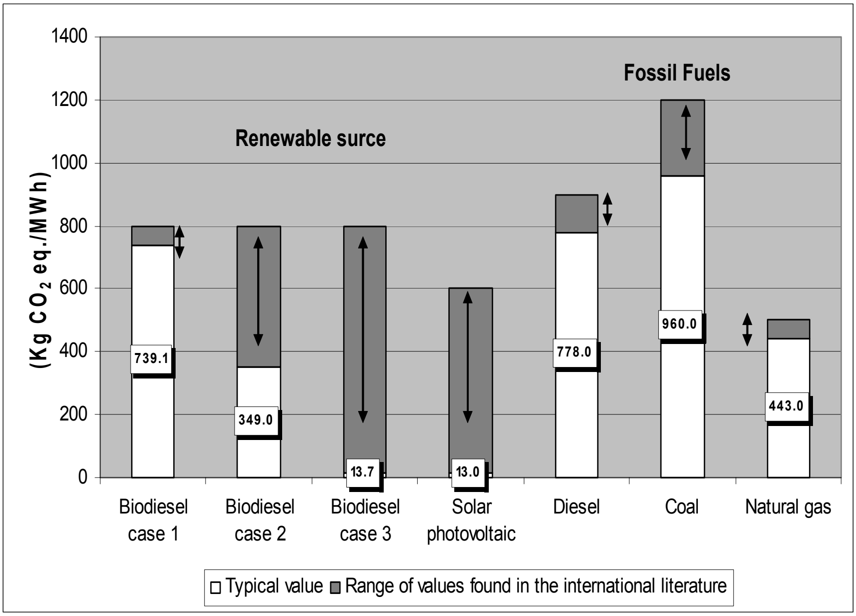

Figure 1: CO^2 eq./MWh for power generation systems.

Biodiesel CO_2 equivalent emissions could be reduced if input of fossil resources (diesel and fertilizers) are limited. The use of natural fertilizers come out from cattle, fed with residual products of sunflower crop, represents the best option to achieve the target. In this hypothetical condition (case 3) CO_2 eq. emissions from biodiesel power plant are 13.7 kg CO_2eq./MWh. In real conditions, emissions related to fertilizers reduce these benefits (case 2) in fact they are 349 kg CO_2eq./MWh. This level is low if compared with emissions from coal, diesel and natural gas, that are 960, 778 and 443 kg CO_2eq./MWh respectively.

Results indicate also (Figure 2) that biodiesel can supply low emissions to produce electrical energy, but it requires 30-40 times more land than photovoltaic system (PV 13 m^2/MWh per year; biodiesel 403-519 m^2/MWh per year). Furthermore, Tiezzi [2] expresses the necessity to consider the time of generation and use of resources. Two generations of man have practically depleted resources of coal, oil and natural gas which took thousands of years to accumulate. As shown in figure 2, the difference in petroleum diesel and biodiesel is the time of carbon dioxide fixation; in the case of fossil diesel the process occurred in geological time, while for biodiesel carbon dioxide released in atmosphere is fixed in recent years.

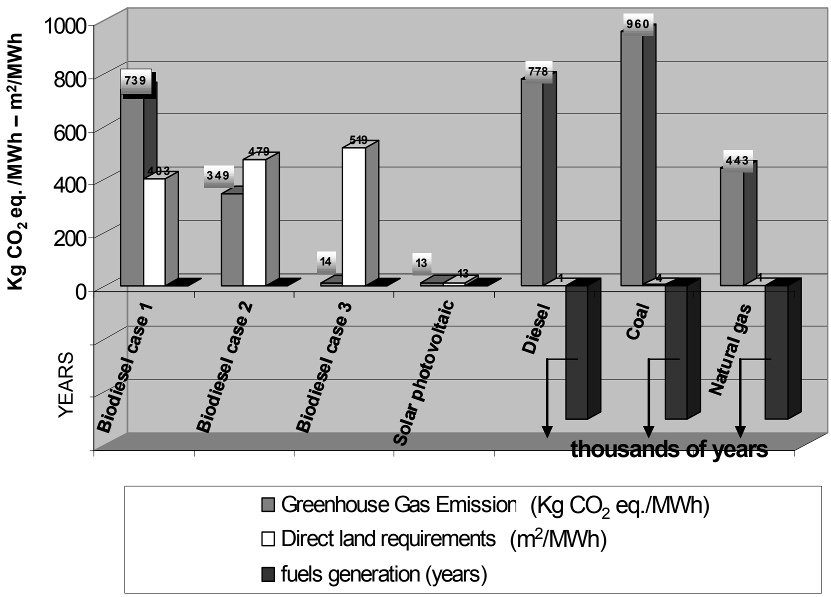

Figure 2: CO_2 eq./MWh, time and land requirement, necessary to generate energy.

4 Conclusions

Energy saving practices and renewable energies together remain the best way to reduce the dependence from fossil fuels, and they can potentially reduce greenhouse emissions. Biodiesel can supply low emissions to produce electrical energy, but it requires 30-40 times more land than photovoltaic system respect to the estimates yields used (cases 1,2,3). Results indicate also that the use of natural fertilizers come out from cattle, fed with residual products of sunflower crop, could represent the best option to reduce emissions and make totally self-sufficient the farm system.

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