*Spyros Foteinis, Victor Kouloumpis, Theocharis Tsoutsos, "Life cycle analysis for bioethanol production from sugar beet crops in Greece",* ***Energy Policy****, 39 (9), 4834-4841, September 2011*

*https://doi.org/10.1016/j.enpol.2011.06.036*

# Life cycle analysis for bioethanol production from sugar beet crops in Greece

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**Abstract**

The main aim of this study is to evaluate whether the potential transformation of the existing sugar plants of Northern Greece to modern bioethanol plants, using the existing cultivations of sugar beet, would be an environmental sustainable decision. Using Life Cycle Inventory and Impact Assessment, all processes for bioethanol production from sugar beets were analyzed, quantitative data were collected and the environmental loads of the final product (bioethanol) and of each process were estimated. The final results of the environmental impact assessment are encouraging since bioethanol production gives better results than sugar production for the use of the same quantity of sugar beets. If the old sugar plants were transformed into modern bioethanol plants, the total reduction of the environmental load would be, at least, 32,6 % and a reduction of more than 2 tons of $CO_2$-e/sugar beet of ha cultivation could be reached. Moreover bioethanol production was compared to conventional fuel (gasoline), as well as to other types of biofuels (biodiesel from Greek cultivations).

**Keywords:** Life cycle analysis; Biofuels; Bioethanol; Gasoline; Sugar beet; Environmental impacts

## 1. Introduction

Constantly growing energy demand, depletion of fossil fuels and negative environmental impacts derived from conventional fuel use (gasoline, diesel, etc.) has led to numerous policies supporting the use of transport biofuels (EC, 2003; Botha and von Blottnitz, 2006; Kondili et al, 2007; Tsoutsos et al, 2008; EC, 2009). The most famous example of bioethanol production is that from sugarcane in Brazil, which has raised a number of questions regarding its potential negative consequences and sustainability (Goldemberg et al, 2008).

Recently European Commission announced a Decision which focuses especially on the sustainability criteria for biofuels to implement the Renewable Energy Directive (EC, 2009; EC,2010). The main priorities are: Sustainable Biofuel Certificates based on "voluntary schemes"; protection of untouched nature; promotion of only biofuels with high greenhouse gas savings. Biofuels must deliver greenhouse gas savings of at least 35% compared to fossil fuels, rising to 50% in 2017 and to 60%, for biofuels from new plants, in 2018.

Currently (2011), although more than four biodiesel plants are cited in Greece, no bioethanol-for-transport production plant, for transport purposes, exists yet, noted also by Panoutsou (2008).

The use of sugar beets is essential for the Greek obligations within the 2009/28/EC Directive, especially taking into account the optimistic estimations of the National Renewable Energy Sources Plan for high rate of the use of biofuels in transport , i.e. from 0,11 Mtoe (2010) to 0,62 Mtoe (2020) (MEECE, 2010).

A possible scenario for Northern Greece is that the raw material for bioethanol production could come from existing sugar beet cultivations, so that the existing sugar plants in Northern Greece, which are facing crisis, could be transformed into modern bioethanol production facilities. In that way any further potential land use change may be avoided (Crutzen et al, 2007), especially in the case that sugar comes from a more environmental friendly and, in parallel, productive cultivation (e.g. from a land that needs less pesticides and fertilizers). This assumption could be further examined in future studies.

The main aim of this study is to evaluate whether the potential transformation of the existing sugar plants of Northern Greece to modern bioethanol plants, using the existing cultivations of sugar beets, would be an environmental sustainable decision. For this reason, the environmental impacts, which if proved similar or lower, could support the overall sustainability of bioethanol production, are assessed. This paper focuses on the environmental aspects of sustainability, although the overall sustainability includes social and economic aspects too, which potentially could also be improved because of lowering the fossil fuel imports and minimizing the probabilities of the farmers losing their jobs. Since, there are growing concerns about a variety of environmental issues expressed either by public opinion, political bodies or industry that accompany bioethanol production, a widely used assessment tool that takes into account all relevant processes used for the final product (bioethanol), like Life Cycle Assessment (LCA) is needed (Baumann and Tillman, 2004). As it is known there are additional sustainability assessment methods. The main difference is due to differences in the scope of assessment. LCA methods generally provide the most reliably complete quantification of net environmental impact from a macro perspective for specific products.

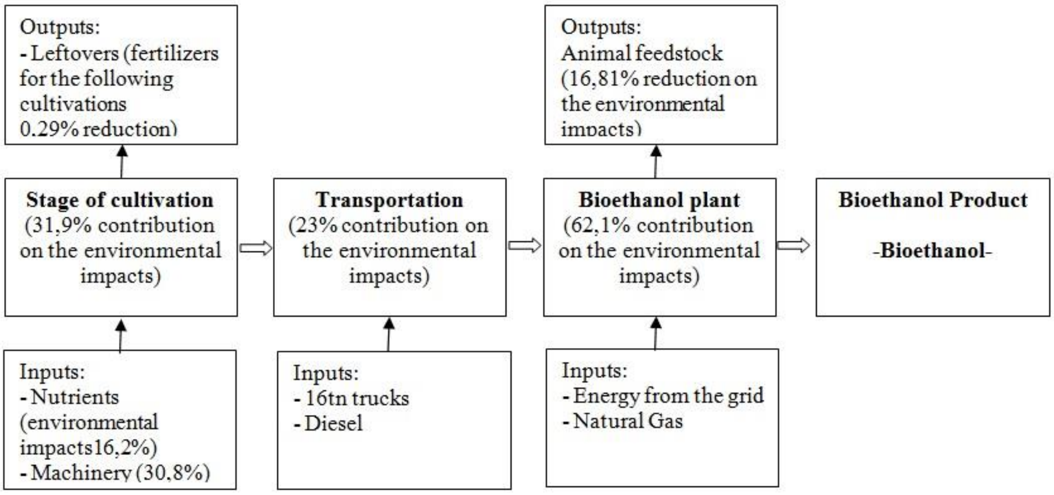
The whole process is divided into three main phases, which are the cultivation of sugar beets, transportation and the bioethanol plant. After a LCA is performed, it turns out that bioethanol plant has the highest environmental load reaching 62,1% followed by the cultivation of sugar beet with 31,9 %, the stage of transportation contributes 23 %, while the co-products (mainly animal feedstock) reduce the environmental load of the whole process by 17,1% . Then bioethanol production is compared to sugar production, using the same raw material (sugar beet), and also to conventional fuel (gasoline), as well as to other types of biodiesel from Greek cultivations (Halleux et al, 2008).

## 2. Methodology

SimaPro7.14 (an LCA tool widely used by professionals and researchers), has been selected for the construction of the bioethanol production model through its life cycle inventory and the life cycle impact assessment, due to its main advantages such as several available databases and the ability to produce and evaluate results. Results can be translated into a number of impact categories such, as acidification and climate change to demonstrate the environmental impacts or loads. LCA methodology is an effective way to introduce environmental considerations in the design, production, use and disposal of a product (ISO 14040:2006, ISO 14044:2006, ISO/TR 14047:2003, ISO/TS 14048:2002) (EPA, 1995; ISO, 2006).

After defining the boundaries of the life cycle under consideration as seen in fig.1 the functional unit of this LCA is set to be 35 Gcal or 146,4 GJ, equal to the energy content of 6.800 L or 5.440 kg of bioethanol (HSI, 2008) that can be produced from the 65 t of sugar beets which is the yield per ha. Then the inventory analysis includes the gathering of all necessary data for quantitative analysis of environmental in- and out- flows. Finally, the impact assessment aims at describing the environmental consequences of the environmental loads quantified in the inventory analysis (Bauman and Tillman, 2004) (fig.1). Both of these steps of the LCA methodology are presented in the following sections of this paper.

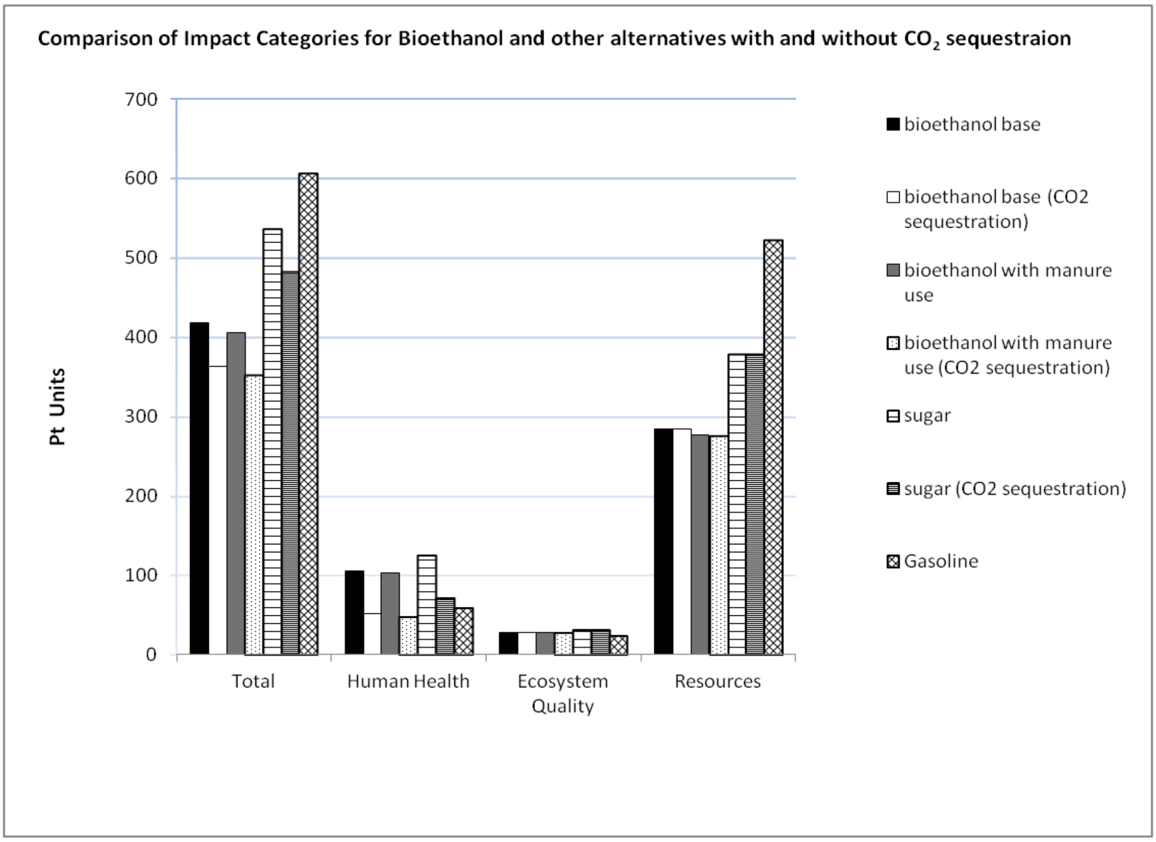
**Fig. 1** Flow chart of the life cycle stages and their environmental loads




In order to measure the total environmental impacts of the transformation, the method Eco-Indicator 99 was used, in where the loads are classified into 10 main categories: Carcinogens, Respiratory Organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrofication, Land use and Minerals. Then they are aggregated into 3 main damage categories **-** human health, ecosystem quality and resources – (fig. 2). Each environmental load is expressed in a different unit, but the aggregated impacts are measured in dimensionless Eco-indicator points (Pt). The Eco-indicator 99 methodology provides three “Archetypes” of perspectives: the “Hierarchist”, the “Individualistic” and the “Egalitarian” characterizing them according to the following three criteria: time perspective, manageability and required level of evidence. In this study the Egalitarian perspective has been used because on the contrary to the other two it used a very long time perspective, considers that problems can lead to catastrophe and considers all possible effects (Ministry of Housing, 2000), following the precautionary principle.

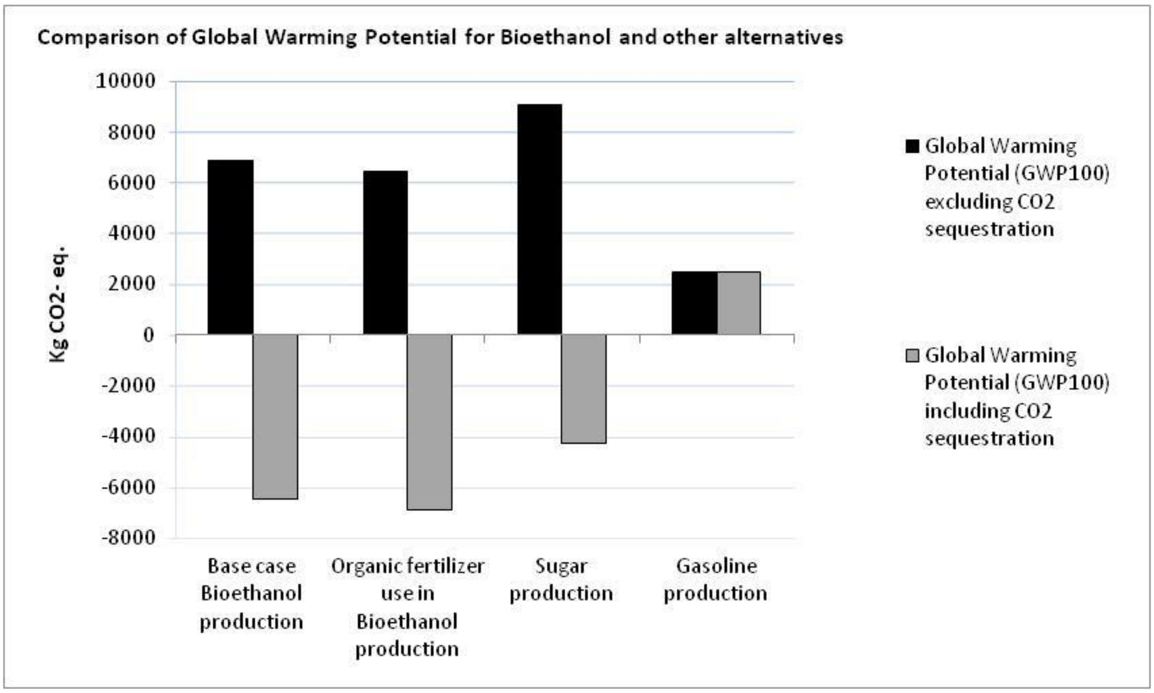
Apart from the above mentioned assessments of the total environmental impacts, a specific greenhouse gas emission assessment has been carried out. For this assessment, the CML 2 baseline method was used, which includes the impact category Global Warming Potential (GWP100), where the GHG emissions are measured in kg of $CO_2$ equivalent.

**Fig.2** Comparison of the production of Bioethanol, Bioethanol with organic fertilizer use, Sugar and Gasoline, according to the 3 damage categories




It has to be noted that during its life cycle, one ha of sugar beet cultivation has the ability to sequester a considerable amount of $CO_2$ lowering significantly the amount of the total greenhouse gas emissions making them negative and rendering the bioethanol a more environmental friendly fuel than gasoline (fig. 3). Based on the Eco-invent database for the production of 1kg of sugar beet approximately 0,32 kg $CO_2$ could be absorbed. This information has been used in the modeling and in the results both cases (including the $CO_2$ sequestration or not) have been taken into account.

**Fig.3** Comparison of greenhouse gas emissions of Bioethanol production, Bioethanol production using organic fertilizers, Sugar production and conventional fuel production (Gasoline)




## 3. Inventory analysis

For the production of bioethanol and sugar from sugar beets three main phases were considered: cultivation, transportation and plant processing (fig. 1). The first two phases are similar for both bioethanol and sugar production and the data for these stages were collected mostly from field surveys and interviewing employs and engineers that work for the existing sugar plants of northern Greece and farmers that cultivates sugar beets. For bioethanol plant processing, bibliographic data were used because until now there is no bioethanol-for-transport plant sited in Greece and hence the necessary data were not available.

### 3.1 Cultivation: nutrition and machinery

The phase of cultivation was subdivided into two basic processes: use of machinery and fertilizing. The data used for fertilizing and the equipment are average values for a typical Greek sugar beet field taking into account all field procedures. Examples include residues of the cultivation process (leaves or other parts left after harvesting), which could be used as a natural fertilizer. For the phase of fertilizing, data obtained by field studies show that residues of the sugar beet cultivation contribute less than 1% to the total nutritional needs of sugar beet crop. These residues are treated in our study as co-products of the LCA of bioethanol. For the production of bioethanol a number of co-products are produced (leftover in the field, pulp from sugar beet processing etc) and their use can reduce the total environmental load of final product (bioethanol). The remaining nutrition requirements are covered from a mixture of pesticides and fertilizers that is used, which was found during the inventory analysis. The most common mixtures for sugar beet cultivation in northern Greece are the N, $K_2O$ and $P_2O_5$ ones. The other main nutrient is irrigation water, which in the Greek case comes mainly from rivers. All the inputs used for the phase of fertilizing are showed in table 1.

**Table 1**

Nutrients and pesticides consumed per ha and 1 L of bioethanol

| **Nutrients** | **Quantity per ha** | **Quantity for the production of 1 L of bioethanol** | **Pesticides** | **Quantity per ha (kg)** | **Quantity for the production of 1 L of bioethanol (g)** |
|---|---|---|---|---|---|
| Water | 4.500 L | 0,662 L | Maneb | 10,000 | 1,471 |
| Fertilizers | | | Desmedipham | 0,233 | 0,034 |
| Nitrogen (N) | 120 kg | 0,018 kg | Phenmedipham | 0,233 | 0,034 |
| Potassium ($K_2O$) | 200 kg | 0,030 kg | Ethofusanate | 0,233 | 0,034 |
| Phosphorus ($P_2O_5$) | 100 kg | 0,015 kg | Metamitron | 2,470 | 0,363 |
| | | | Parafinic oil | 3,500 | 0,515 |
| | | | Haloxyphop | 0,133 | 0,020 |
| | | | Methidathion | 2,000 | 0,294 |

The machinery phase includes the use of all machinery equipment in the field, from planting to harvesting. The main procedures that take place in the field start with ploughing in autumn before the seeds are planted, then the field is irrigated and fertilized on standard basis followed by tillage in spring and harvesting is the last stage (table 2) (Stout, 1999; Hulsbergen et al, 2001; ISO, 2006).

**Table 2**

Energy used for the machinery in the stage of sugar beet cultivation

| **Agricultural process** | **Machinery used** | **times per ha** | **Minutes of tractor operation per ha** | **Diesel L /ha** | **Diesel energy per ha (MJ)** | **Energy needs for the production of 1 L of bioethanol (J)** |
|---|---|---|---|---|---|---|
| Ploughing | Tillage, ploughing | 1 | 40 | 6,0 | 231,6 | 34,1 |
| Planting | Planting | 1 | 50 | 6,7 | 258,6 | 38,03 |
| Irrigation | Irrigating | 1 | - | - | - | - |
| Fertilizing | Fertilizing, by broadcaster | 6 | 360 | 45,0 | 1.737,0 | 255,4 |
| Tillage | Tillage, harrowing, by spring tine harrow | 1 | 20 | 3,0 | 115,8 | 17,03 |
| Harvest | Harvesting, by complete harvester, beers | 1 | 100 | 13,8 | 532,7 | 78,3 |

In Greece, the tractor is the main machine used for the cultivation of the beets. The most energy demanding procedure is fertilizing, because it has to be replicated six (6) times and then harvested (table 2) (Stout, 1999). Approximately 65 t of beets are produced per ha using 2,5 kg of sugar beet seeds. Moreover about 8 t of animal food are co-produced and the rest sugar beet residues can cover partially the nutrition needs of the forthcoming cultivations in the same field.

### 3.2 Transportation

Sugar beets are transported from the field to the plant, by a diesel fuelled truck of 16 t capacity, which is the most common in Greece. The average distance from the field to the bioethanol plant is 65 km, so 130 km is the total distance from the field to the plant and back. Since the truck in the return trip is empty, it is assumed that the truck has an average load 50%.

### 3.3 Plant processing

#### 3.3.1 Bioethanol plant processing

Data for the first three stages of the bioethanol plant processes are provided from existing sugar beet plants in Northern Greece, and are applicable to a bioethanol plant, while data for the remaining stages were found in the literature (Thibault, 1988; Mortimer et al, 2004, HSI, 2008). These procedures are not available in Simapro libraries and the most feasible option was to use the amount of energy requirements of the installed machinery for each stage. The most prominent fuel to be used in a modern bioethanol facility in Greece is natural gas, a cleaner fuel than crude oil that is still used in some sugar factories in Northern Greece.

The process in the sugar beet- based bioethanol plant is divided into the following stages:

*(i) Sugar beet washing*

Sugar beet harvest cleaning is necessary to remove soil residuals and foreign bodies (stones, weeds, etc). The capacity of the typical beet washer is 8.000 beets/day and 325 MJ are necessary for the washing of the yield of 1 ha, which is 65 t sugar beets in this study. During the washing stage, 5,4% of the incoming load is removed mainly as soil and stones, the final weight of the cleaned beets is 62 t (HSI, 2008).

*(ii) Sugar beet slicing*

The second phase is the mechanical slicing of the sugar beets, during which long sliced beets called cossettes are produced. In this stage five slicing machines are necessary which consume a total of 163 MJ for the slicing of the 62 t of washed sugar beets (HSI, 2008; Grassi, 2009).

*(iii) Diffusion*

During the diffusion stage the sugar juice is extracted from the cossettes. The cossettes are conveyed to a continuous inclined screw diffuser, where hot water extracts sucrose. The water temperature in the diffuser is kept between 60 to 70 ºC and depends on several factors. The denaturisation temperature of the cossettes, the thermal behavior of the beet cell wall, the potential enzymatic reactions, the bacterial activity and pressability of the beet pulp are such factors. The sugar-enriched water extracted from the diffusers usually contains 12,92% of sugar content. The used cossettes, or pulp, exit the diffuser at about 95% moisture content and a lower sugar content (1,67%). Using screw presses, the wet pulp is then pressed down to 75% moisture. This recovers additional sucrose in the liquid which is pressed out of the pulp and reduces the energy needed to dry the pulp. The liquid pressed out of the pulp is combined with the raw juice is more often introduced into the diffuser at the appropriate point in the countercurrent process. The energy required for the processing of 62 t of sliced sugar beet is calculated to reach a total of 5,146  MJ (HSI, 2008).

*(iv) Purification of the extracted sugar juice*

The purification stage is necessary because the extracted sugar juice contains non-sugar impurities which should be removed before the fermentation process. The purification of sugar juice comprises the calcification and carbonation processes (Stout, 1999). The mixture is then filtered off leaving a cleaner, golden light brown sugar solution, called thin juice.

Due to the nature of this and the following three stages (fermentation, distillation and dehydration) no appropriate data were found for yeast in the inventory analysis. Therefore, based on literature (Stout, 1999), the total energy consumed in these four stages is approximately 61.000 MJ.

*(v)  Fermentation*

During batch fermentation the retention time of the mash is about 48 h; yeast converts simple sugars (primarily glucose) into ethanol, $CO_2$ and heat, as follows:

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 2ATP$ (Energy Released: 118 kJ/mol) (1)

It has to be noted that due to the nature of this process (biogenic) the $CO_2$ emissions could not be estimated and hence are not included in our study.

*(vi) Distillation*

In the distillation columns, ethanol is separated from the non-fermentable contents. Absolute bioethanol flows from the top of the final column and the residue mash, called tillage, is transferred from the base of the column to the co-product processing area.

*(vii) Dehydration*

The distilled ethanol solution is azeotropic (approximately 5% water). By adding a third liquid such as cyclohexane, the azeotropic point of the solution is moved in such a way that the ethanol can be rectified while the water or ethanol is entrained by the ternary fluid. An entrained recovery column then separates the binary mixture and recovers the entrained component. As stated above the energy used (natural gas) in the last four stages (purification, fermentation, distillation and dehydration) is approximately 61.000 MJ (Stot, 1999). From the processing of sugar beets some co-products are produced such as residues of sugar beets in the field, pulp from the used cossettes and yeast from the fermentation process. The pulp potentially co-produced in a bioethanol plant is similar to one in the existing sugar plants in Northern Greece, which is mainly used as animal food. Additionally the co-produced yeast could be used in farming as a single cell protein for animal food. These co-products are not treated as waste but as a tool to reduce the environmental impacts of the process. In this study residues in the fields (which contribute less than 1% of the total nutrition needs) and pulp were also treated as outputs (products) and were quantified. It was estimated that the use of these products (leftovers as fertilizer and pulp as animal feedstock) could reduce the environmental loads of bioethanol production about 17,1%. The yeast was not quantified and will be studied in the future.

## 4 Results

### 4.1 Environmental impact Assessment

The data that were collected during the inventory analysis were used as inputs in the model and the environmental loads and impacts were calculated using the eco-indicator 99 Egalitarian and CML 2 baseline methods, as mentioned before.

#### 4.1.1 Cultivation

The environmental loads of each process are indicated in table 3.

During the nutrition stage, which contributes with 11,98 % to the total environmental load, pesticides are used to increase the yield. The agricultural processes with the largest environmental impacts are pesticide use and field fertilizing using N, K fertilizers, and lead to significant quantities of greenhouse gases emissions, especially the production and application of fertilizers that use $HNO_3$ or $NH_4HCO_3$ which result in the emissions of NOx, $NH_3$

and $CO_2$. If organic fertilizers, like manure, were used to fertilize the fields, the environmental impacts would be minimized. For 1.000 kg of manure/ha the environmental impacts could be reduced by 3,57%.

**Table 3**

Environmental impacts of the different life cycle stages for the functional unit

| Impact category | Unit | Total | Cultivation | Transportation | Plant | Co-products |
|---|---|---|---|---|---|---|
| Total | Pt | 363,56 | 116,10 | 83,59 | 225,84 | -62 |
| Carcinogens | Pt | 2,83 | 2,72 | 0,199 | 0,34 | -0,43 |
| Respiratory organics | Pt | 0,20 | 0,048 | 0,150 | 0,035 | -0,03 |
| Respiratory inorganics | Pt | 74,05 | 46,76 | 32,40 | 8,26 | -13,37 |
| Climate change | Pt | -26,29 | -43,83 | 4,08 | 17,00 | -3,55 |
| Radiation | Pt | 0,32 | 0,31 | 0 | 0,006 | 0 |
| Ozone layer | Pt | 0,03 | 0,003 | 0,017 | 0,01 | -0,004 |
| Ecotoxicity | Pt | 7,70 | 11,98 | 0,51 | 0,35 | -5,07 |
| Acidification/ Eutrophication | Pt | 13,89. | 8,65 | 9,79 | 1,86 | -6,40 |
| Land use | Pt | 6,33 | 5,11 | 0 | 1,22 | 0 |
| Minerals | Pt | 4,59 | 4,28 | 0 | 0,30 | 0 |
| Fossil fuels | Pt | 279,90 | 80,14 | 36,44 | 196,46 | -33,14 |

### 4.1.2 Use of machineries

The use of machinery is an energy demanding process, since in Greece the machinery is usually old and not environmental friendly; the typical farmer usually owns small land parts and uses his own machinery, thus a large fleet of machines exists. At this stage, the environmental impacts are 20,92 % of the total environmental load, mainly due to harvesting and irrigation.

Harvesting of sugar beet could be a problematic and highly energy consuming procedure. Landowners irrigate their land with three different techniques (flood - furrow - irrigation, drip irrigation, spray irrigation) usually irrationally in terms of energy and water. Modern techniques, which are more efficient and environmentally friendly could be adopted (like drip irrigation). If the produced biofuels are more environmental friendly they could be used in these machines and could further decrease the environmental impacts.

### 4.1.3 Transportation

The environmental impacts refer mainly to the tracks used, the diesel burned and their road route, because in Greece the trucks are generally old and small, and the roads are narrow and, often, not asphalted the environmental impact of this stage is 23 % of total impact. With further improvements on the truck fleet and roads and the use of biofuels (biodiesel) the environmental burdens of this stage could be minimized.

#### 4.1.4 Bioethanol plant processing

The bioethanol plant contributes 62,1 % to the total environmental load mainly due to the fermentation/distillation/dehydration process. Washing and slicing of sugar beets have almost negligible environmental impact. For the minimization of these environmental impacts air filters and ‘cleaner’ fuel techniques could be used.

#### 4.1.5 Summary

The processes and their contribution to the total environmental loads for the production of bioethanol from sugar beet crops are indicated in fig.1 (base scenario). From the three main phases (bioethanol plant, transportation of sugar beet crops and cultivation of sugar beet) the contribution of bioethanol plant has the highest environmental load reaching 62,1%, while the cultivation of sugar beet contributes 31,9% and transportation with 23% to the total process. It should be noted that a part of the environmental impacts of the whole process is reduced by the production of useful byproducts (8.000 kg of animal feedstocks per ha) that reduce the environmental impacts of bioethanol production by 17,1%.

### 4.2. Comparison of results

In order to evaluate whether the potential transformation of the existing sugar plants of Northern Greece to bioethanol plants would be an environmental friendly decision, the environmental impacts of the existing sugar plants are compared to those that the potential transformation could produce. Moreover, possible improvements of the stage of cultivation and the resources used are taken into account, in order to study feasible environmental friendly scenarios. Finally, a comparison with conventional (gasoline) and alternative fuels (biodiesel) was performed.

*(i) Differentiation in bioethanol production*

The use of organic fertilizer (manure) was tested so as to examine if the bioethanol production that has been studied so far, could become more environmental friendly. The composition of Greek origin (organic fertilizer) manure is approximately 4% N, 6% $P_2O_5$ and 4% $K_2O$ (the remaining 86% consists of organic material that helps the further soil improvement) (Tsoutsos et al, 2008). For the cultivation of 1 ha 1.000 kg of manure should be used and this could lead to a 3,57% reduction of the environmental impacts and to 420,7 kg CO2e/ ha of sugar beet. Furthermore, the estimated environmental impacts from bioethanol production and bioethanol production using organic fertilizer were compared to other joint products (sugar and gasoline) which are analyzed in the following paragraphs and shown below (table 4).

**Table 4**

Environmental impacts using eco-Indicator 99 for production of Bioethanol, Bioethanol using organic fertilizer, Sugar and Gasoline

| Impact category | Bioethanol Base | Bioethanol base (CO2 sequestration) | Bioethanol with organic fertilizers | Bioethanol using organic fertilizers (CO2 sequestration) | Sugar | Sugar (CO2 sequestration) | Gasoline |
|---|---|---|---|---|---|---|---|
| Total | 418,09 | 363,54 | 406,02 | 351,47 | 536,51 | 481,96 | 605,96 |
| Human Health | 105,68 | 51,13 | 102,40 | 47,86 | 125,87 | 71,33 | 59,72 |
| Ecosystem Quality | 27,92 | 27,92 | 27,31 | 27,31 | 31,81 | 31,81 | 23,56 |
| Resources | 284,48 | 284,48 | 276,30 | 276,30 | 378,82 | 378,82 | 522,67 |

*(ii) Comparison with the environmental impact of sugar plants in Northern Greece*

For the comparison of the environmental impacts of using the beet root cultivation for bioethanol or sugar production it has to be noted that the cultivation and transportation phases are exactly the same in both cases, but the sugar beet processing phase is different in its last stages. Therefore, the environmental impacts of both different cases are expected to have marginal differences. The average Greek sugar plant energy requirements for the same beet processing capacity like the studied bioethanol plant, are 2,214 t of crude oil (92,7 GJ of energy) for 62 t of beets; additionally 3,7143 t limestone and 290 kg coke are required (Stout, 1999). Comparing bioethanol to sugar production (the comparison was done using the yield of one ha, 65 t of sugar beet) showed that bioethanol production will have 32,6 % less environmental impacts and a gain of 2.214 kg of CO2e/hectare of sugar beet cultivation. Thus, the expected size of the impacts is almost the same with the already existing sugar plants. Consequently, we could assume that the sugar plants in Northern Greece could be converted into bioethanol plants without substantially increasing the global environmental impacts.

*(iii) Comparison with the environmental impact of conventional fuels used in Greece*

Considering the mean production of a European factory that uses gasoline, as is provided in Simapro, bioethanol and gasoline fuels, using the same energy content were compared. The comparison shows that bioethanol base scenario has 40 % and bioethanol with the use of organic fertilizer (manure) has 42% less environmental impacts than bioethanol production, rendering bioethanol a more environmentally friendly, renewable fuel. A comparison between bioethanol and gasoline combustion was not conducted because the internal combustion engines and the emissions are different for each fuel. However, this comparison could be examined in future studies.

*(iv) Comparison with biodiesel produced in Greece*

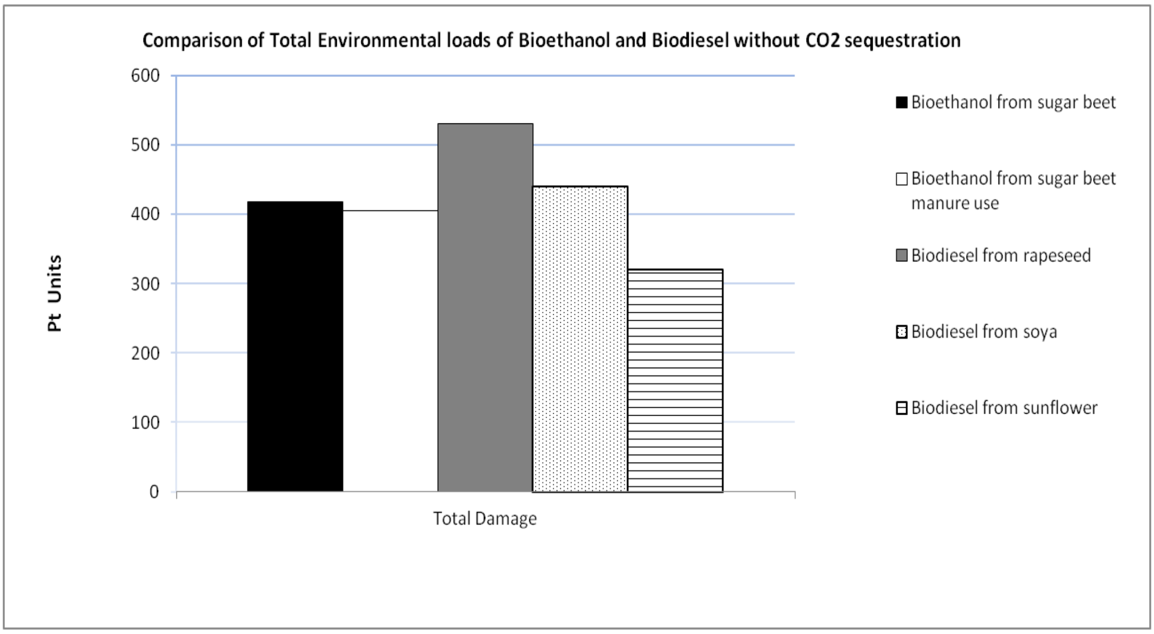
In order to evaluate the environmental impacts of bioethanol versus other biofuels a comparison of bioethanol versus biodiesel cultivated under Greek conditions (Tsoutsos et al, 2010) was conducted. Biodiesel can be produced from various raw materials and in Greece these are mainly soya, rapeseed and sunflower. Environmental impacts from biodiesel production under Greek conditions are already available. Hence, it is possible to compare the environmental impacts (Pt) using the same functional unit (MJ/L). This comparison (between the final results of the bioethanol LCA versus biodiesel LCA per litter produced) shows that biodiesel with the same energy content, has, in most of the cases, less environmental impacts than bioethanol. More specifically sunflower produce 30,33 % less environmental impacts, while soya has 4,92% and rapeseed 21,36 % more environmental impacts from bioethanol for the Greek scenario (table 5). Thus, biodiesel production from sunflower is more environmental friendly than bioethanol production (fig.4).

1

**Table 5**

Comparison of total environmental impacts for bioethanol and biodiesel of the same energy content

| Product | Environmental Impacts (Pt) |
|---|---|
| *Bioethanol production Base scenario* | 418,09 |
| *Bioethanol production Scenario 1 (manure)* | 406,02 |
| *Biodiesel Production from Rapeseed* | 531,64 |
| *Biodiesel Production from Soya* | 439,73 |
| *Biodiesel Production from Sunflower* | 320,79 |




## 5. Discussion and conclusion

Recently objections have been raised against the use of ethanol produced from agricultural products as a replacement for gasoline, despite some of their advantages such as being cleaner and to some extent renewable (Goldemberg and Guardabassi, 2009). Concerning the sugar beet cultivation, existing data has been adapted to the Greek agricultural conditions so the current analysis results are connected to the presented cases with adopted assumptions.

The environmental impacts of the bioethanol plant come from the amount of fossil fuel used, which has negative impacts on the climate change and on resources depletion. The main environmental impacts from cultivation phase are similar to these of beet transportation phase, and are mainly minerals, respiratory organics and ozone layer depletion. It has to be noted that during the stage of cultivation a big amount of CO2 is sequestrated, which has positive impacts on climate change (table 6). Minerals are necessary during cultivation phase. The use of machinery in the cultivation and trucks in transportation demands fossil fuels and results in GHG emission. Transportation plays an important role in ozone layer depletion (mostly because of the $NO_x$ emissions from the trucks) and in respiratory organics.

**Table 6**

Environmental impacts, using CML 2 baseline method, for the production of Bioethanol, Bioethanol using organic fertilizer, Sugar (with CO2 sequestration) and Gasoline.

| Impact category | Unit | sugar | bioethanol | bioethanol (organic fertilizers) | Gasoline |
|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 67,90883 | 50,70765 | 49,2175 | 88,41532 |
| Global warming (GWP100) | kg CO2 eq | -4279,03 | -6493,19 | -6913,93 | 2463,827 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 0,001494 | 0,001306 | 0,001306 | 0,001659 |
| Human toxicity | kg 1,4-DB eq | 1591,882 | 1549,335 | 1551,258 | 1415,081 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 118,7533 | 113,5573 | 113,9735 | 152,4196 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 358976,9 | 478054,2 | 478834,3 | 1246788 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 12,60511 | 12,21841 | 12,22798 | 9,526538 |
| photochemical oxidation | kg C2H4 | 1,007902 | 0,794355 | 0,793975 | 1,61087 |
| Acidification | kg SO2 eq | 22,19915 | 17,72349 | 17,2469 | 28,33281 |
| Eutrophication | kg PO4--- eq | 1,410345 | 0,751205 | 0,595576 | 2,315968 |

The consumption of already produced bioethanol in the three processes is feasible because adequate quantities of bioethanol can be produced. Moreover, the substitution of fossil fuel in the life cycle by bioethanol could further reduce the environmental impacts. Similar conclusions have also been referred in other life cycle assessment studies confirming, thus, the reliability of this study (Von Blottnitz et al, 2007). It has to be noted that the quantities of Greek sugar beets are adequate and could supply two bioethanol production facilities (in Larissa and Xanthi, Northern Greece), which are proposed to be converted from sugar plants into bioethanol plants. The environmental impacts of a modern bioethanol plant are less than a conventional Greek sugar plant, Thus, from environmental point of view, the conversion is proved to be feasible.

Besides, it is important to refer that, as it is shown in fig.2, the total environmental impacts from the bioethanol use versus gasoline are more than the 35%, if the parameter of CO2 sequestration will be taken into account, which is the first sustainability target for the EC policy.

An important issue for follow-up of this study could be the comparison with the second generation bioethanol (i.e. from lignocellulosics) as a long-term green liquid fuels policy. Although safe data is missing, in both cases there are obvious advantages in comparison with the current liquid fuel mix. It is essential to note that in most cases, sugar beets, as an already industrialized plant has organizational virtues, such as long-term contacts with the producers, well-known logistics, etc (HSI, 2008).

The comparison with other alternative fuels, which can be produced under the Greek climate conditions, like biodiesel, showed that bioethanol from sugar beets environmental impacts are similar to biodiesel from rapeseed and soy impacts and only bioethanol from sunflower has substantially less environmental impacts. Therefore, bioethanol from sugar beets can be considered as an equal environmentally alternative to biodiesel, especially in northern Greece, where sunflower cultivations yield is low.

In the future the exploitation of other sugar sources such as lignocellulosics, could increase the potential for sustainable fuel bioethanol production (Borjesson, 2009). Moreover, the complete energy utilization of all the co- products could make the production more sustainable. The above together with answering to a number of questions regarding its negative consequences and sustainability by using similar LCA studies could create similar famous examples like the bioethanol production from sugarcane in Brazil.

In conclusion, conversion of existing sugar plants to bioethanol production plants does not cause more environmental impacts, but follows the European Directives and supports the reduction of the greenhouse gases. Since the know-how and the infrastructure, suitable for bioethanol facility, already exist and its location is close to the fields, it is feasible to convert these sugar plants into bioethanol production facilities. Moreover, the rising gasoline prices and fossil fuel depletion render bioethanol a feasible, environmentally friendly fossil fuel for an independent way of producing energy, alternative to biodiesel.

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**Table 1** Nutrients and pesticides consumed per ha and 1 L of bioethanol

**Table 2** Energy used for the machinery in the stage of sugar beet cultivation

**Table 3** Environmental impacts of the different life cycle stages for the functional unit

**Table 4** Environmental damage for production of Bioethanol, Bioethanol using organic fertilizer, Sugar and Gasoline

**Table 5** Comparison of total environmental impacts for bioethanol and biodiesel of the same energy content

## Figure captures

**Fig. 1** Flow chart of the life cycle stages and their environmental loads

**Fig.2** Comparison of the production of Bioethanol, Bioethanol with organic fertilizer use, Sugar and Gasoline, according to the 3 damage categories

**Fig.3** Comparison of greenhouse gas emissions of Bioethanol production, Bioethanol production using organic fertilizers, Sugar production and conventional fuel production (Gasoline)

**Fig. 4** Comparison of Bioethanol and Biodiesel from 3 different types of Greek cultivations