# Environmental and economic integrated assessment of local energy crops production in southern europe

Carles Martínez Gasol

## Doctoral Thesis

**Dissertation supervisors:** *Dr. Xavier Gabarrell i Durany & Dr. Joan Rieradevall i Pons*

To obtain the Doctoral Degree in Environmental Sciences
Programa de Doctorat en Ciències Ambientals
Universitat Autònoma de Barcelona (UAB)
Institut de Ciència i Tecnologia Ambientals (ICTA)
Grup de recerca en Sostenibilitat i Prevenció Ambiental (SosteniPrA)

Bellaterra, May 2009

icta Institut de Ciència i Tecnologia Ambientals · UAB

UAB
Universitat Autònoma de Barcelona

Environmental and economic integrated assessment of local energy crops production in southern europe

Doctoral Thesis

*Carles Martínez Gasol*

icta

# Acknowledgements/ Agraïments/ Agradecimientos

The author thanks Spanish Ministry of Science and Technology for awarding his research scholarship (AP2005-2518).

Moltes gràcies a tots els grups d'amics que han col·laborat activament o passivament en aquesta experiència.

Als directors de tesis, professors i doctors amb els que he col·laborat, companys de feina i a la meva família.

Gràcies a tots.

Carles

# Index

## Section 1. General aspects

- **Chapter I. Introduction and objectives**

- **Chapter II. Methodologies**

## Section 2. Environmental assessment

- **Chapter III. Life Cycle Assessment of a Brassica carinata cropping system in southern Europe.**

- **Chapter IV. Life Cycle Assessment of Populus spp. bioenergy systeem compared withBrassica carinata energy crop and natural gas in local scenario.**

- **Chapter V. Comparative of winter rape (Brassica napus) cultivations as energy crop to produce Biodiesel in southern Europe.**

## Section **3**. Enconomic assessment

- **Chapter VI. Feasibility assessment of Populus spp. bioenergy system in the southern Europe.**

- **Chapter VII. Feasibility assessment of *Brassica carinata* bioenergy system in the southern Europe.**

## Section 4. Integrated assessment

- **Chapter VIII. Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale**

## Section **5**. Conclusions summarize and future research

### Chapter IX. General conclusions and future research

# List of tables

# List of figures

## Main Abbreviations

AP: Acidification Potential

ASTM: A Standard Test Method

A.D.P: Abiotic Depletion Potential

BUWAL: Bundesamt für Umwelt, Wald und Landschaft (Swiss Federal Agency for the Environment, Forests and Landscape).

CAP: Common Agricultural Policy

CERA: Cumulative Energy Requirement Analysis

CIEMAT: Centro de Investigaciones Energéticas y Medioambientales y Tecnológicas

CIRCE: Centro de Investigaciones de Recursos y Consumos Energéticos

CML: Centrum voor Milieukunde, Leiden (Centre for Environmental Science, Leiden University , The Netherlands.)

C.V: Horsepowers

D.B.: Dry Basis

E: Spain

EEA: Environmental European Agency

EIA: Environmental Impact Assessment

EP: Eutrofization Potential

EMPA: Eidg. Materialrüfungs – und Forschungsanstalt (Swiss Federal Laboratories for Material Testing and Research).

ERA: Environmental Risk Assessment

ETH: Eidgenössische Technische Hochschule

EU: European Union

FU: Functional Unit

FWAEP: Fresh Water Aquatic Ecotoxicity Potential

GJ: Giga Joule

GIS: Geographic Information System

GWP: Global Warming Potential

h: Hours

Ha: Hectare

HHV: High Heating Value

HTP: Human Toxicity Potential

HP: High Preassure

ICTA: Institut de Ciència i Tecnologia Ambientals

INIA: Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria

IOA: Input-Output Analysis

IRR: Internal Rate of Return

IRTA: Institut de Recerca Tecnologia Agroalimentarias

ISO: International Standard Organization

ITGA: Instituto Técnico de Gestión Agrícola

Kg: kilogram

kJ: kilo Joule

km: Kilometer

ktoe: Kilo Tones Oil Equivalent

kW: Kilowat

kWh: kilowat hour

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Inventory Assessment

LCC: Life Cycle Cost

LHV: Low Heating Value

MAEP: Marine Aquatic Ecotoxicity Potential

MFA: Material Flow Accounting

MIA: Material intensity Analysis

Mg: Megagram

mg: miligram

MJ: Mega Joule

MtOE: Million Tones Oil Equivalent

MWe: Mega Watt electric

NPV: Net Present Value

ODP: Ozone Depletion Potential

PSE: Proyecto Singular Estrategico

REP: Renewable Energy Plan

REPA: Resource and Environmental Profile Analysis

RES: Renewable Energy Source

SETAC: Society for Environmental Toxicology and Chemistry

SFA: Substance Flow Analysis

SosteniPrA: Sostenibilitat i Prevenció Ambiental, Grup de Recerca

SPOLD: Society for the Promotion of LCA Development

SPP: Simple Payback Period

SRC: Short Rotation Coppice

SRF: Short Rotation Forestry

Tep: Tonne Equivalent of Petrol

TEP: Terrestrial Ecotoxicity Potential

TJ: Tera Joule

TR: Technical Report

UCPTE: Union for the Co-ordination of Production and Transmission of Electricity

UdG: Universitat de Girona

UdS: Universidad de Sevilla

UPM: Universidad Politécnica de Madrid

URV: Universitat Rovira i Virgili de Tarragona

W.C.: Water Content

YR: Year

# Topic 1. General Aspects

# Chapter I. Introduction and objectives

*Contents of the section.*

This introductory chapter aims to explain to the reader the purpose and content of the thesis. First, in chapter I the concepts of bioenergy, biomass and energy crops are presented. Then the state of the art of biomass in Europe and Spain, and also in Catalonia, is introduced, followed by the objectives and structure of this thesis. In Chapter II the main methodologies applied in this thesis are described.

# I.1 Definitions and concepts: bioenergy, biomass, and energy crops

Bioenergy

Energy produced from biomass is called "**bioenergy**" [1]. Bioenergy can play an important role in combating climate change as well as improving the security of the world'senergy supply [1].

Biomass

"Biomass", in general terms, refers to any type of organic matter whose origin is the consequence of a biological process. The concept of "Biomass" includes products of vegetal and animal origin. The **"current definition of biomass"** has been accepted as a group of renewable energy products or subproducts and raw materials that originate from organic matter by biological way. Fossil fuels and their derivate organic products are excluded despite their biological origin [1]. Biomass is the world's fourth largest energy source, providing around 10% of the demand for energy worldwide. Most of it is used in developing countries for cooking and heating [1].

"Biomass" for energy applications includes a wide range of products and by-products of agriculture and forestry as well as municipal and industrial waste. It thus includes energy crops, short rotation forestry, trees, agricultural and forest residues, algae, biological sludge, manure, industrial by-products and the organic fraction of solid municipal waste. However, biomass is also used for a large number of purposes other than energy such as: providing human and animal food, clothing, paper, bioplastics and building materials.

Energy crops

"**Energy crops**", the study topic of this dissertation, can be defined as a plant grown and used to generate biomass that can be transformed into fuels, or directly exploited for its energy content. Any energy crops should produce a positive energy balance [2]. Energy crops can be organised into four main groups as shown in table I.1 [3].

Table I.1 Energy crops group's organization, examples and applications.

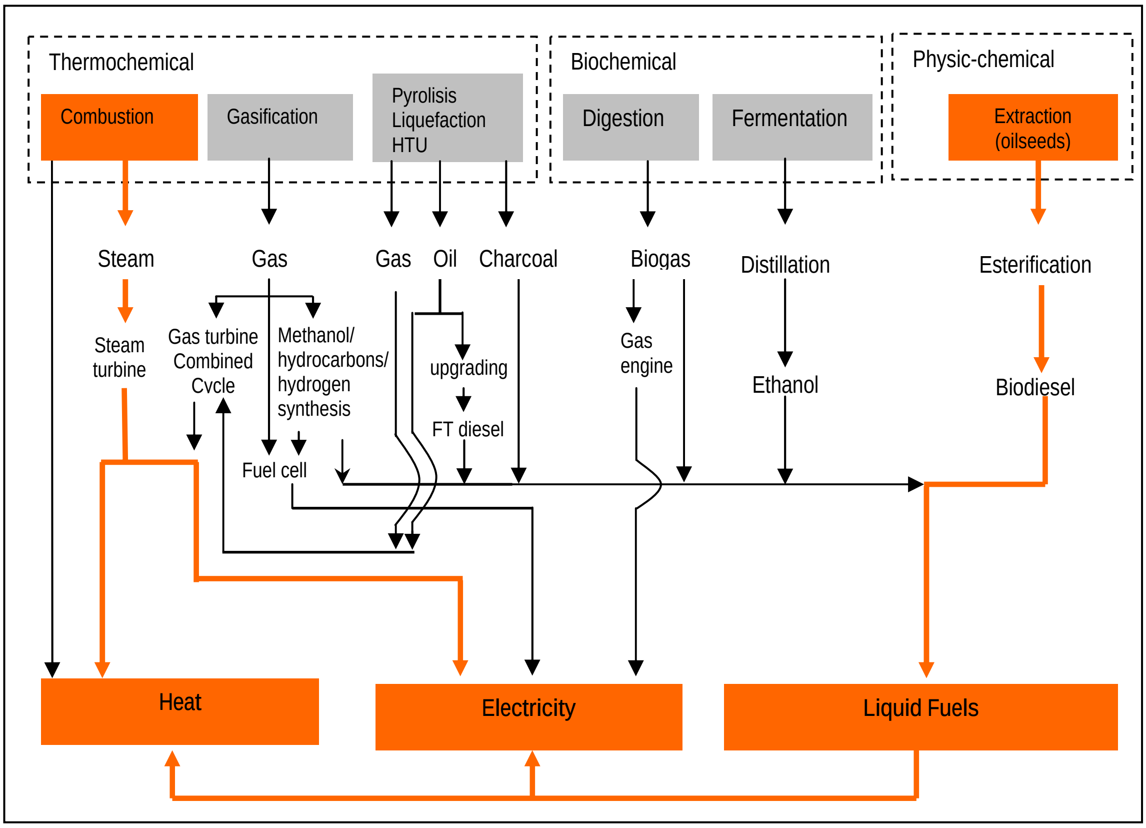
| Energy crops Groups | Examples | Main current energy applications |
|---|---|---|
| Wood Crops or<br>Short Rotation Forestry (SRF) | Poplar, Willow,<br>Acacia, Eucaliptus | Solid fuel: chips, pellet and packet of stems. |
| Herbaceous crops | Mischantus, Red Canary,<br>Cardoon, Triticale | Solid fuel: bales |
| Oilseed crops | Rapeseed, Sunflowers | Biofuels: Biodiesel |
| Sugar containing crops | Beet, Sorghum, Maize | Biofuels: Bioethanol |

Source: [3]

Energy Conversion Systems

Depending on the conversion technology and type of primary biomass applied different types of fuels and energy can be provided [4, 5]. See figure I.1. Energy conversion options analyzed in this dissertation are shown in orange.

Figure I.1 Main energy conversion options for biomass.

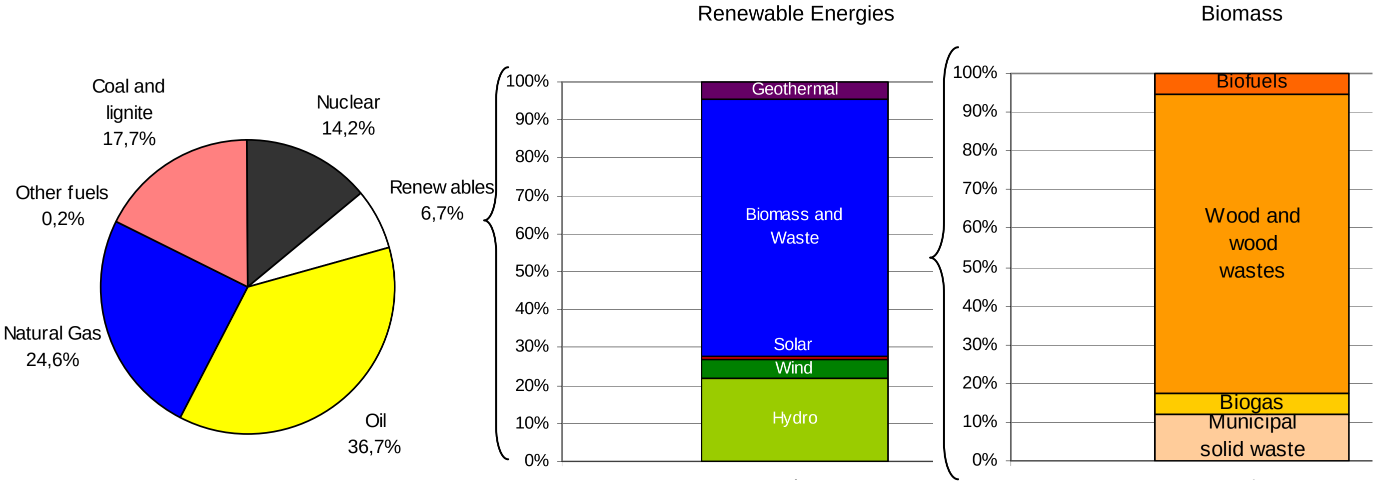


Source: [4,5]

## I.2 Bioenergy in the European Union

Bioenergy interest in the European Union began with the oil crisis of 1973 and fortified due to the second crisis of 1979. During the decades that followed, as the international price of petrol went down, bioenergy development programs in the EU entered a decline. Nowadays, the European Union (EU) is seeking to increase the use of renewable energy to substitute fossil fuels in order to limit climate change and enhance the security of the energy supply. The exploitation of renewable energy sources can help the EU meet many of the goals of its environmental and energy policies, including its obligation to reduce greenhouse gases under the Kyoto Protocol [6], and reduce dependency on energy imports [7,8]. The EU has thus set ambitious indicative targets for 2010 and 2020 for its share of renewable energy in terms of both total energy [9,10] and electricity consumption [11]. In addition, there is a specific target to increase the share of biofuels used in transport by 5.75% and 10% in 2010 and 2020 respectively [12-15]. In 2005, renewable energy accounted for 6.7% of the EU's gross energy consumption, of which two thirds were biomass and waste [1]. See figure I.2.

Figure I.2 Share of primary energy consumption by fuel type in 2005 for EU27.



Source: [1]

Around 4% (69 MtOE) of the EU's total primary energy consumption comes from biomass [16]. This makes biomass by far the most important renewable energy source. Nevertheless, compared to other renewable energy sources during the last five years, such as wind and solar power, biomass production has increased at a much slower rate [16]. Achieving the EU's target of a 10% or 20% share of renewable energy consumption in total energy consumption by 2010 or 2020 respectively will require a substantial increase in the use of biomass [17]. In December 2005, the European Commission published a Biomass Action Plan [12] followed by a communication on an EU strategy for Biofuels [13]. The biomass action plan aims to increase biomass use to 150 MtOE (in primary energy terms) by 2010 or soon after. In the longer term, a target of about a 20% share of renewables in total energy consumption in 2020 would require about 230-250 MtOE from primary biomass potential. Biomass from agriculture (agriculture waste and energy crops) could make a substantial contribution to reaching these objectives without underestimating the forest and waste sectors [18].

### *I.2.1 Current energy crops production patterns in EU*

Attempts have been made to cultivate many crops as energy crops over the last twenty years in Europe. Table I.2 shows the species of energy crops that have been cultivated a number of times as demonstration or experimental crops in Europe. These energy crops have been commercialized and their biomass has been applied as a renewable energy resource in power plants or for biofuel production in Europe.

Table I.2 Energy crops experiences in Europe during las 20 years.

| Latin Name | Common English name | Common Spanish name | Common Catalan name |
|---|---|---|---|
| • *Short Rotation Forestry* | | | |
| *Eucalyptus spp.* | Eucalypt | Eucalipto | Eucalipto |
| *Paulownia spp.* | Paulownia | Paulownia | Pawlonia |
| *Populus spp.* | Poplar | Chopo | Pollancre |
| *Robinia pseudoacacia* | Black locust | Acacia | Acàcia |
| *Salix spp.* | Willow | Sauce | Salze |
| • *Herbaceous crops* | | | |
| *Arundo donax* | Giant reed | Caña | Canya |
| *Brassica carinata* | Ethiopian mustard | Mostaza de Etiopia | Mostassa d'Etiopia |
| *Cannabis sativa* | Hemp | Cáñamo | Cànem |
| *Miscanthus spp.* | Mischantus | Mischantus | Mischantus |
| *Phalaris arundinacea* | Reed canary grass | Phalaris | Phalaris |
| *Phargmites australis* | Reed | Carrizo | Canyís |
| *Spartium junceum* | Spartina | Spartina | Spartina |
| *Triticosecale* | Triticale | Triticale | Triticale |
| • *Oilseed crops* | | | |
| *Brassica napus* | Oilseed rape seed | Colza | Colza |
| *Cynara cardunculus* | Cardoon | Cardo | Card |
| *Helianthus annuus* | Sunflower | Girasol | Girasol |
| *Jatropha curcas* | Barbados nut | Jatrofa | Pinyó de l'India |
| • *Sugar containing crops* | | | |
| *Beta vulgaris* | Sugar beet | Remolacha | Remolatxa |
| *Hordeum vulgare* | Spring barley | Cebada | Ordi |
| *Panicum vulgari* | Switchgrass | Mijo | Mill |
| *Secale cereale* | Winter rye | Centeno | Sègol |
| Sorghum bicolour | Sweet sorghum | Sorgo | Sorgo |
| *Triticum aestivum* | Winter wheat | Trigo otoñal | Blat de tardor |
| *Zea mays* | Maize | Maiz | Blat de moro |

Source: [3,19]

In 2005, an estimated 3.6 million hectares of agricultural land in the EU-25 was directly devoted to biomass production for energy use. The majority of this land (83%) was used for oil crops (used for biodiesel), and the remainder was devoted to ethanol crops (11%), biogas production (4%) and short rotation forestry (2%). The production of biodiesel from oilseed crops increased more than twentyfold in the 1994-2005 period, resulting in primary energy production of 3,000 ktoe per year, or 3.1% of total renewable energy production in 2005 [16].

In terms of oil crops, *Brassica spp.* has been the most cultivated species. In 2005, oilseed rape production for biodiesel or edible oil stood at a record 15.5 million tonnes, 28% more than the average for the preceding five years. In 2005, the area used for oilseed rape in the EU-25 for biodiesel production, edible oils, meal and other production was 4.8 million hectares (ha), 80% of which is concentrated in five countries: Germany (1.35 million ha), France (1.21 million ha), the United Kingdom (0.6 million ha), Poland (0.55 million ha) and the Czech Republic (0.27 million ha) [16].

Furthermore, European Biodiesel plants have a greater demand for oil than crops in the EU can produce. Poland and the Czech Republic are the only countries in which the cropped area still exceeds the potential demand of processing biodiesel plants or power plants, creating the possibility of exporting a large share of production [16]. All of this seems to indicate that increased areas of this crop and oil or oil seed importation will be required very shortly. Short rotation forestry crops such as poplar, willow and acacia have been predominantly cultivated in such countries as the United Kingdom, Italy, Ireland, Belgium, Austria, Germany, Sweden and the Netherlands [3,16-18].

## I.3 Biomass energy in Spain

In accordance with targets and biomass promotion by the EU, Spain has also updated its laws and published Royal Decree 2818/1998 [20] on the electricity sector and developed its Renewable Energy Plan (REP) 2000-2004 and its updated Renewable Energy Plan (REP) 2005-2010 [21] to promote renewable energies and biomass applications as renewable energy sources. According to Royal Decree 2818/1998 renewable energies should amount to 12.1 % of the total Spanish energy demand in 2010 [20,21]. Meanwhile, biofuels for transport should amount to 5.83% of petrol and diesel consumption in 2010 [21]. At the same time the Energy efficiency plan was also developed by the Spanish government with the aim of reducing Spanish energy consumption, external energy dependency and environmental impact [22]. The objectives of REP 2005-2010 foresee that primary energy production applying several sources of biomass (see table I.3) as renewable energy sources should be 5,040,300 tep in 2010 [21].

Table I.3 Energy targets of the REP for each resource and application in 2010.

| Biomass resources | Energy targets (tep) | Energy generation applying biomass (tep) | |
|---|---:|---|---:|
| Forest wastes | 462.000 | Heat generation | 582.514 |
| Lignocellulosic agricultural wastes | 670.000 | Electricity generation | 4.457.786 |
| Herbaceous agricultural wastes | 660.000 | Primary Energy (Total) | 5.040.300 |
| Industrial forest wastes | 670.000 | | |
| Industrial agricultural wastes | 670.000 | | |
| Energy Crops | 1.908.300 | | |
| Total | 5.040.300 | | |

Source: [21]

As can be observed in table I.3 and according to the Spanish REP 2005 - 2010 energy crops should represent 37.86% of primary energy production (heat or electricity) applying solid biomass [21]. In both REP documents, biomass from energy crops is the most important source to be considered in order to reach the energy targets for biomass as renewable energy. This demonstrates the importance of agriculture for energy purposes in solving the energy production challenges for 2010 in Spain [21].

Liquid biofuel production, pure vegetable oils also obtained from energy crops, is the option that should be developed most over the coming years, as shown in table I.4. It alone represents 51.82% of the liquid biofuel production for 2010 in Spain. The Spanish REP 2005-2010 does not mention whether this pure vegetable oil will be produced inside the national territory or imported from abroad. Although judging by the implementation of energy crop projects in Spain from 1999 to 2004 (see table I.5) it is obvious that the most of the Spanish biodiesel and bioethanol production that applies energy crops as a raw material, excluding biodiesel produced with used cooking oils, is achieved with importations of oil seed, or crops containing sugar .

Table I.4 Liquid biofuels targets for 2010 of the REP 2005-2010 for each type of renewable resource.

| Energy target 2010 (tep) | | | |
|---|---|---|---|
| Resources | | Applications | |
| Cereals and biomass | 550.000 | Bioetanol | 750.000 |
| Wine Alcohol | 200.000 | Biodiesel | 1.221.800 |
| Pure vegetables oils | 1.021.800 | Total Primary Energy | 1.971.800 |
| Used oils | 200.000 | | |

Source: [21]

According to the description in the Spanish REP 2005-2010, power generation (electricity and heat) targets and also liquid biofuel targets are mainly addressed at the development of energy crop projects [21]. But until 2004 the implementation of energy crops in the territory had had a minimum repercussion on the total energy production applying biomass as renewable energy, see table I.5

Table I.5 Comercial biomass projects applying biomass to generate electricity from 1999 to 2004.

| Fuel | Number of projects | Primary Energy (tep) |
|---|---|---|
| Forest wastes | 2 | 5.733 |
| Lignocellulosic agricultural wastes | 0 | 0 |
| Herbaceous agricultural wastes | 1 | 55.500 |
| Industrial forest wastes | 8 | 166.578 |
| Industrial agricultural wastes | 11 | 241.005 |
| Energy Crops | 1 | 0 |
| Total | 22 | 468.856 |

Source: [21]

The main barrier for developing energy crops had been the lack of legislation that provides economic support and coordination between different actors for developing energy crop projects from the point of view of farmers and energy producers [21].

In trying to overcome this barrier, and in the case of electricity and heat production, the Spanish government developed the 611/07 Royal Decree that promotes the generation of electricity applying biomass in power generation plants, valuing the cost per kWh at €0.14 [23]. Initially, this law should revitalize the sector by making it easier for all of the actors implied in the biomass chain (production, distribution and power generators) to obtain economic profits. Europe and Spain’s potential bioenergy production by applying energy crops is supported by European and Spanish laws and energy plans. There are many different sources of biomass and many different ways of using it for energy. It can be converted into electricity, heat or liquid biofuels for transport. (see figure I.1). This means that there will be competition for the significant, but finite, primary bioenergy feedstocks that can be produced in Spain and in Europe in general. It is important to use the available biomass as effectively as possible in terms of climate change and the energy supply perspective.

## I.4 Energy crops experiences in Spain

It has been shown that Spanish commercial experience with energy crops was inexistent from 1999 to 2004. On the other hand some research projects have been undertaken by research institutions such as: Institut de Recerca Tecnologia Agroalimentarias (IRTA), Instituto Técnico de Gestión Agrícola (ITGA), Universidad Politécnica de Madrid (UPM), Universidad de Sevilla (UdS), Centro de Investigaciones de Recursos y Consumos Energéticos (CIRCE), Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA) and Centro de Investigaciones Energéticas y Medioambientales y Tecnológicas (CIEMAT).

All these institutions have developed pioneer energy crop research projects focusing their efforts on improving biomass energy crop yields and technology development.

Another group of institutions has focalised their research on the environmental and economic performance of bioenergy systems, such as: Centro de Investigaciones Energéticas y Medioambientales y Tecnológicas (CIEMAT), Universitat de Girona (UdG), Universitat Rovira i Virgili de Tarragona (URV), Recerca Tecnologia Agroalimentarias (IRTA) and Institut de Ciència i Tecnologia Ambientals (ICTA) of Universitat Autònoma de Barcelona (UAB).

To try to coordinate and group this potential research for implementing energy crops in the national territory, a project called Proyecto Singular Estratégico (PSE) para el desarrollo de los cultivos energéticos coordinated by CIEMAT and funded by the Ministerio de Educación y Ciencia was set up in 2005 [24]. This project aims to promote energy generation by applying biomass of energy crops in Spain by means of the definition of optimal technical, economic and environmental conditions for their sustainable commercial implementation [24]. The expected results of this project have to provide a strategy for implementing energy crops on a national level. The energy crop cultivations carried out as part of the PSE project and pioneer projects are listed in table I.6.

Table I.6 Research experiences in Spain related to PSE and other pionner projects by regions and extensions (ha) between 2004-2008.

| | Vulgar name | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sorghum | Rapeseed | Cardoon | Ethiopian mustard | Poplar | Paulownia | Maize | Wheat | Barley |
| | Scientific name | | | | | | | | |
| Region | *Sorghum spp.* | *Brassica napus* | *Cynara Cardunculus* | *Brassica carinata* | *Populus spp.* | *Paulownia Spp.* | *Zea Mais* | *Triticum spp.* | *Hordeum vulgare* |
| Albacete | | 28.00 b | | | | | | | |
| Avila | | | | | | | | 1.50b | 1.50b |
| Badajoz | | 45.00b | | | | | | | |
| Burgos | | | | | | | | 4.50b | 1.50b |
| Caceres | | 50.00b | | | 1.00b | | | | |
| Córdoba | 45.92b | | | | | | | | |
| Ciudad Real | | 7.00b | | | | | | | |
| Cuenca | | 5.00b | | | | | | | |
| Girona | 1.00b.c | 10.00b.c<br>265.00 d | | | 1.00b.c | | | | |
| Granada | | | | | 4.00b<br>1.00c | 0.25c | | | |
| Leon | | | | | | | 8.40c | | |
| Madrid | | | 10.00c | | | | | | |
| Navarra | | 330.00b | | 100.00 a<br>20.00b | 4.00b<br>0.50c | 0.25c | | | |
| Palencia | | | 1.78b | | | | 2.00b<br>1.00c | 3.00b | 3.00b |
| Salamanca | | | | | | | 4.50b | 1.50b | 1.50b |
| Segovia | | | | | | | | 1.50b | 1.50b |
| Sevilla | 125.36b | | | | | | | | |
| Soria | | 75.00b | | 60.00a<br>3.00b<br>1.25c | 4.00b | 0.60c | | 1.50b | |
| Toledo | | 64.00b | | | 2.00b<br>1.00c | 0.25c | | | |
| Valladolid | | | | | | | 1.50b<br>1.00c | 1.50b | 3.00b |
| Zamora | | | | | | | 8.40b | | |
| Zaragoza | 10,00b | | | | | | | | |

a) Crops cultivated from 2004 to 2005. b) Crops cultivated from 2005 to 2006.
c) Crops cultivated from 2006 to 2007. d) Crops cultivated from 2007 to 2008.
Source: [24, 25]

The cultivations implemented and shown in table I.6 represent the greatest effort in terms of the research, implementation and demonstration of energy crops carried out in Spain on an agronomic level. However, there were previous and pioneer studies focused on the environmental and economic assessment of energy crops carried out specifically by SosteniPrA, see sections 1.4.1 and 1.4.2.

### *I.4.1 SosteniPrA (ICTA-IRTA) energy crops research projects*

SosteniPrA (ICTA-IRTA-Cabrils) SGR007/2005 is qualified as a high quality research group by the Generalitat de Catalunya.

SosteniPrA, in association with IRTA-Mas Badia, CIEMAT, Universitat de Girona (UdG), Universitat Rovira and Virgili (URV) have made advances in environmental research and the economic assessment of energy crops in Spain.

The projects carried out by SosteniPrA in collaboration with other institutions that have analysed the sustainability of bioenergy systems based on energy crops are:

- Evaluación de la sostenibilidad medio ambiental de cultivos energéticos mediante Análisis de Ciclo de Vida (AGROSOST CTM 2004-05800-c03-1/TECNO), 2003-2006

As a result of this multidisciplinary collaboration between research groups a project called "Evaluación de la Sostenibilidad de Cultivos Energéticos mediante Análisis de Ciclo de Vida (ACV) (AGROSOST) funded by the Ministerio de Educación y Ciencia was undertaken. This project aimed to analyse the environmental impact of the generation of energy by applying biomass in relation to two energy crops: Ethiopian mustard (*Brassica carinata*) and Poplar (*Populus spp*.). The experimental energy crop fields were coordinated by Phd. Juan Carrasco and Phd. Pilar Ciria of CIEMAT. Part of the results obtained by this project will be presented in the following chapters of this dissertation.

Figure I.3 Experimental parcels of *Brassica carinata* and *Populus spp.* in Soria, 2005.

*Photographies by Carles Martinez Gasol*

- Análisis integral de la producción para la producción de energía renovable a partir de cultivos agroenergéticos y residuos orgánicos (BIOENERGIA CTM2007-66948-CO2-01/TECNO)

This bioenergy project funded by the Ministerio de Educación y Ciencia was an annual project that made it possible to analyse the environmental impact of *Brassica napus* cultivation for biodiesel production purposes.

Furthermore, 1 hectare of *Populus spp.* was implemented with funding from SosteniPrA, URV and IRTA Mas Badia. The crop is cultivated in a high density plantation and a low density plantation. The aforementioned hectare is still available for future research focused on discovering the optimal agricultural technique for *Populus spp*. cultivation and its environmental consequences. The demonstration and experimental fields were managed by eng. Jordi Salvia of IRTA-Mas Badia. Part of the results obtained by this project will be presented in the following chapter of this dissertation.

Figure I.4 Experimental and demonstration fields of *Brassica napus* and *Populus spp*. in Caldes de Malavella and Tallada de l'Empordà (Girona), 2007.

*Photografies by Carles Martinez Gasol and Jordi Salvia*

- PSE. Erosion and Water Consumption Indicators 2007- in progress

SosteniPrA is carrying out a partial task related to the PSE project. It is focused on developing local indicators to evaluate the erosion and water consumption impact that a generalized implementation of energy crops in Spain can generate.

- "Mejora de la gestión y reutilización de residuos de Aceites domésticos y canales HORECA mediante el análisis de Exergia (MAcExe)", 2007.

Project funded by the Ministerio de Medio Ambiente that aimed to analyse the environmental impact of used cooking oils as a renewable energy source by applying exergy assessment methodology.

- La biomassa com a font d'energia de materies primers i energia: Estudi de viabilitat Montseny – Montnegre Corredor, 2004-2005.

Social, economic and environmental assessment of the feasibility of applying forest biomass as an energy resource in the case study area of Montseny and Corredor that was carried out mainly by SosteniPrA members and Dr. Jordi Bartroli, Dr. Jordi Bartroli Almera both of UAB and Dr. Miquel Rigola. This project was funded by the Fundacio Abertis.

### I.4.1.1 SosteniPrA’s publications in journals and conferences

From these projects and other one-off collaborations with chemical engineers from the UAB, Carles Martinez Gasol (SosteniPrA’s member) has been funded by Spanish Ministry of Science and Technology with a research scholarship (AP2005-2518). The following papers focused on energy crops and uses of biomass have been published during the last years:

Papers in international journals

- Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P., Solano Ml and Rieradevall J. Life cycle assessment of a Brassica carinata cropping system in souther Europe. Biomass & Bioenergy 31 (2007) 543-555.
- Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P. & Rieradevall J. LCA of poplar bioenergy system compared with Brassica carinata and natural gas in regional scenario.Biomas & Bioenergy 33 (2009) 119-129.
- Gasol C.M., Martinez S., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P. & Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable & Sustainable Energy Reviews 13 (2009) 801-812.
- Martinez S., Gasol C.M., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P. & Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable Energy (Accepted).
- Ruggieri L., Cadena E., Martínez-Blanco J., Gasol C.M., Rieradevall J., Gabarrell X. Gea T., Sort X. & Sánchez A. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyse of the composting process. Journal of Cleaner Production 17 (2009) 830 -838.
- Gasol C.M., Farreny R., Gabarrell X. & Rieradevall J. Life Cycle Assessment comparison among different reuse intensities for industrial wooden containers. Int. J. of Life Cycle Asses. (2008) 13 421-431

Participation in Conferences

- Carles Martínez Gasol, Dr. Xavier Gabarrell, Jordi Salvia, Dr. Juan Carrasco, Dr. Miquel Rigola, Sergi Martinez & Dr. Joan Rieradevall. Environmental Assessment of renewable energy production from integrated biomass sources (Oral Presentation). 16th European Biomass Conference. Valencia (Spain), June 2008
- Carles Martínez Gasol, Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Juan Carrasco, Dra Pilar Ciria, Dra Ml. Solano, Dr. Miquel Rigola & Dr. Joan Rieradevall.Evaluation of the sustainability of energy crops in Spain. Oral Presentation.15th European Biomass Conference. CD Proceedings ISBN 978-88-89407-59-X.Berlin (Germany), May 2007

- Carles Martínez Gasol, Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Juan Carrasco, Dra Pilar Ciria, Dra Ml. Solano, Dr. Miquel Rigola & Dr. Joan Rieradevall. Biomasa Forestal y Cultivos Energético: Aplicación, Oportunidades y Riesgos. (Oral Presentation). Bioenergia 200. Madrid (Spain), March 2007
- Carles Martínez Gasol, Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Juan Carrasco, Dra Pilar Ciria, Dra. Ml. Solano & Dr. Joan Rieradevall. LCA of the logistics of Brassica carinata and Populus sp. in Spain. (Poster). II International Life Cycle Assessment Conference (LCM2005). Barcelona (Spain), September 2005
- Carles Martínez Gasol, Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Juan Carrasco, Dra. Pilar Ciria & Dr. Joan Rieradevall. Life Cycle Assessment of Poplar Energetic Crop System. (Poster). Controversies and Solutions in Environmental Science. SETAC Europe 16th Annual Meeting. The Hague (Holland), May 2006.
- Carles Martínez Gasol, Neus Puy, Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Jordi Bartroli, Dr. Juan Carrasco, Dra. Pilar Ciria, Dr. Francesc Castells, Dr. Miquel Rigola & Dr. Joan Rieradevall. Life Cycle Assessment of two bioenergy systems in Mediterranean regions.(Poster). III International Life Cycle Assessment Conference (LCM2007). Zurich (Switzerland). August 2007.
- Neus Puy, Carles Martínez Gasol, , Dr. Xavier Gabarrell, Dra Assumpció Antón, Dr. Jordi Bartroli, Dr. Miquel Rigola & Dr. Joan Rieradevall. Aplicació, Oportunitats i inconvenients de la biomassa forestall i els cultius energètics destinats a la producció d'energia. (Poster). 2º Congres Forestal Català. Tarragona (Spain), February 2007

## I.5 Justification for this dissertation

The implementation of biomass as a renewable energy source should be accompanied by different studies of its environmental performance on a global and local level and energy balance in order to verify the benefits and barriers of the application of biomass, and specifically energy crops, as a renewable energy source.

The main reasons for analysing the environmental and economic performance of energy crops in southern Europe in this dissertation are:

- Energy crops and biomass generated by the agricultural sector have been claimed by several European and Spanish Renewable Energy Plans to be the main contributors in terms of biomass to energy purposes.

- The importance of using the available biomass as effectively as possible in terms of climate change and the energy supply perspective.

- The energy crop expectancy generated and the fact that most EU governments recognized that an increase in the use of energetic crops should be accompanied by a detailed analysis.

- North-western and central European countries have put the most effort into the use of energy crops for power and heat generation in recent decades, while in southern Europe the introduction of energy crops to agriculture has been slower. In this sense, environmental research applying LCA to energy crops is incipient.

- The need for a reliable quantitative assessment of the environmental, energetic and economic performance of biomass energetic crop production under the existing conditions in southern Europe.

- The need for territorial planning of the implementation of energy crops considering the pre-existent use of soils in order to optimize the production of limited renewable energy sources such as biomass energy crops.

## I.6 Objectives

The overall objective is to determine the environmental and economic viability of implementing *Brassica carinata, Brassica napus* and *Populus spp.* energy crops in a local scenario context to be applied as a renewable energy source (biomass and biofuels) in southern European environmental conditions.

In particular the following specific objectives are formulated:

- To acquire and compile local data for *Brassica carinata*, *Populus spp.* and *Brassica napus* agricultural production destined to generate electricity, heat or biodiesel.

- To quantify the environmental and energy balance in 10 global environmental categories, including Global Warming Potential of bioenergy systems studied applying Life Cycle Assessment.

- To compare the environmental performance of *Brassica carinata, Populus spp. and Brassica napus* bioenergy systems with conventional systems based on non-renewable energy such as: natural gas or diesel.

- To integrate environmental tools such as Life Cycle Assessment (LCA) and Geographic Information Systems (GIS) in order to complete the feasibility assessment of biomass projects.

- To determine the costs and benefits of biomass energy production in a local energy crop production scenario considering the current Spanish biomass subsidy framework.

- To plan and propose a local strategy implementation of the bioenergy systems capable of contributing to the global environmental targets determined by REPs.

### I.6.1 Structure of the present dissertation

The present thesis is divided into 9 chapters, which are distributed into 5 sections, see table I.7.

Table I.7 Structure of this dissertation.

| Topics | Main contents of the chapter |
|---|---|
| Topic 1 General aspects. Introduction and Objectives | Chapter I. Introduction and Objectives<br>Subchapter I.6 Objectives of the dissertation<br>Chapter II. Methodologies |
| Topic 2. Environmental assessment | Chapter III. LCA of *Brassica carinata* in a local scenario.<br>Chapter IV. LCA of *Populus spp.* in a local scenario.<br>Chapter V. LCA of *Brassica napus* in a local scenario |
| Topic 3. Economical assessment | Chapter VI. Feasibility assessment of *Brassica carinata* as renewable energy source.<br>Chapter VII. Feasibility assessment of *Populus spp.* as renewable energy source. |
| Topic 4. Integrated assessment. Territorial planning and LCA focused on $CO_2$ eq. category. | Chapter VIII. Territorial planning of *Brassica spp*. and *Populus spp*. implemention and $CO_2$ eq. balance |
| Topic 5. Conclusions summarize and future research | Chapter IX. General conclusions of this dissertation and future research. |

- Section 1: General Aspects. Introduction and Objectives. As has been seen, the first chapter has included a definition of such main concepts as bioenergy, biomass and energy, and their contextualization in the energy policies of Europe and Spain; in addition to that, the justification of the study carried out in this dissertation and the main objectives and structure of this thesis are presented. Furthermore a brief description of the methodologies applied and their integration are showm in chapter II.
- Section 2. Environmental assessment. This part includes a detailed Life Cycle Assessment of three case studies: case study 1: *Brassica carinata* biomass cultivation applied to generate electricity or heat (chapter III); case study 2: *Populus spp.* cultivation also to generate electricity or heat (chapter IV) and case study 3: *Brassica napus* to generate biodiesel (chapter V). In addition, local inventories have been made in this section. The local data compiled has provided enough information to carry out environmental and economic assessments. Furthermore environmental results in the category of global warming ($CO_2$ eq.) have been applied in order to carry out an agroclimatic analysis of the local implementation of energy crops, see chapter VIII.
- Section 3. Economic assessment. This part includes an economic assessment of the power (electricity and heat) generation of case studies 1 and 2 (chapters VI and VII) from the point of view of the generation of profits by energy plants. Sensitivity assessment is carried out using such variables as biomass cost production, investment related to generation of power plants and the price of $CO_2$ eq. emission in order to take into account the maximum aspects that can modify the feasibility of energy power plants.

- Section 4. Integrated Assessment. Geographic assessment and $CO_2$ eq. balance. This part includes a geographic assessment that considers the agroclimatic conditions of the case study area of Catalonia. Potential biomass production from cultivating *Brassica spp (B.carinata and B.napus).* and *Populus spp.* is calculated along with $CO_2$ eq. balance combining LCA and GIS (Chapter VIII).
- Section 5. In this last section, the general conclusions are summarized and the future outlook is presented in order to generate new interest and research.

## I.7 References to Chapter I

[1] European Environment Agency. Maximising the environmental benefits of Europe's bioenergy potential. Luxembourg: Office for Official Publications of the European Communities, 2008. ISBN 978-92-9167-375-9

[2] CIEMAT. La biomasa: fuente de energía y productos para la agricultura y la industria. Madrid: Editorial CIEMAT, 1996. ISBN 84-7834-067-X

[3] Venendaal R., Jorgensen U. & Fosters C.A.European Energy Crops: A synthesis. Biomass & Bioenergy. 13 (3) (1997) 147-185.

[4] European Comission. Biomass, Green Energy for Europe. Luxembourg D: Office for official publications of the European Communities, 2005a. ISBN 92-894-8466-7

[5] Faaij A. Modern biomass conversion technologies. Mitigation and Adaptation Strategies for Global Change. 11 (2006) 343-375.

[6] European Comission. Council Decision 2002/358/EC: Council Decision of 25 April 2002 concerning the approval on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments there under, 2002. Available from: http://unfccc.int/resource/docs/convkp/kpeng.pdf .Accessed in: April 2007

[7] European Comission. Green Paper: Towards a European Strategy for Energy Supply Security. Luxembourg: Office for Official Publications of the European Communities, 2001.

[8] European Comission. Report on the Green Paper on Energy – Four years of European initiatives, European Commission 2005. Luxembourg: Office for Official Publications of the European Communities, 2005b.

[9] European Comission. White Paper: Energy for the future – renewables sources of energy –. Luxembourg: Office for Official Publications of the European Communities, 1997.

[10] European Comission. Proposal for a Directive 2008/0016 (COD) of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, 2008.

[11] European Commission. Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, 2001.

[12] European Comission. Communication from the European Commission on the Biomass Action Plan, Luxembourg: Office for Official Publications of the European Communities, 2005c.

[13] European Comission. Communication from the European Commission on An EU strategy for Biofuels. Luxembourg: Office for Official Publications of the European Communities, 2006.

[14] European Parliament 2003. Industry Commitment of European Parliament. European Directive 2003/30/CE.

[15] Eurostat. Energy, transport and environment indicators. Luxembourg: Office for Official Publications of the European Communities, 2007. ISBN 978-92-79-07044-0

[16] European Environmental Agency. How much bioenergy can Europe produce without harming the environment? EEA Report 7/2006. Luxembourg: Office for Official Publications of the European Communities, 2006.

[17] European Comission. Communication of the European Commission of 26/05/2004 on the share of renewable energy in the EU, COM (2004) 366 final. 2004.

[18] European Environmenal Agency. Estimating the environmentally compatible bioenergy potential from agriculture. Luxembourg: Office for Official Publications of the European Communities, 2007.

[19] Vannini L., Arangrande M, Gentile E., Guarnieri A. & Molari G. . Study On Implementing The Energy Crops CAP Measures And Bio-Energy Market. Funded by European Commision, 2006 .Available on: http://ec.europa.eu/agriculture/eval/reports/bio_energy/full_text_en.pdf

[20] REAL DECRETO 2818/1998, de 23 de diciembre, sobre producción de energía eléctrica por instalaciones abastecidas por recursos o fuentes de energía renovables, residuosy cogeneración.Jefatura de Estado. Boletin Oficial del Estado. Available from: http://www.boe.es/boe/dias/1998/12/30/pdfs/A44077-44089.pdf

[21] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversificación y Ahorro de la Energía (IDAE). Resumen Plan de Energías Renovables en España, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspx

[22] Ministerio de Industria, Turismo y Comercio e Instituto para la diversificación y ahorro de la energía (IDAE). Estrategia de Ahorro y Eficiencia Energética en España 2004-2012. Plan de Acción 2008-2012. Resumen Ejecutivo, 2007.

[23] Ministerio de Industria, Turismo y Comercio. Real Decreto 661/2007. BOE número 126 de 26/5/2007, España 2007.

[24] Juan Carrasco. La Investigación: base para el avance hacia un desarrollo sostenible. CONAMA 2008 Congreso Nacional del Medio Ambiente, 2008. Available from: http://www.conama8.org/datoscd/view_persona.php?id=2306&idnavegacion=http://www.conama8.org/datoscd/view_persona.php?id=2306&idnavegacion=

[25] Personal Communication with Jordi Salvia. Agronomic Engineering of Institut de Recerca i Tecnologia Agroalimentaria (IRTA), 2009.

# Topic 1. General Aspects
# Chapter II. Methodologies

*Contents of the chapter.*

This methodological chapter aims to provide the reader with a description of the main methodologies applied to the analysis of the environmental, economic and territorial planning of energy crops in local and regional scenarios. Life Cycle Assessment, applied economic indicators and the Geographical Information System are briefly described in the following chapter.

## II.1 Summary of the methodologies applied in this dissertation

In order to analyse the environmental and economic performance of energy crops for energy purposes in southern Europe; several methodologies have been applied to energy crops systems with major potential for adaptation and production in southern Europe [1,2]:

- *Brassica carinata* or Ethiopian mustard for producing solid biomass.
- *Brassica napus* or rapeseed for producing biodiesel.
- *Populus spp.* or poplar for producing solid biomass.

Table II.1 shows the methodologies applied and their level of integration with other methodologies (*unilaterally or combined*).

Table II.1 Methodologies and level of integration applied to this dissertation.

| Main methodology applied: | Sustainability aspect analysed | | | Integration level |
|---|---|---|---|---|
| Topic 2:<br>Environmental assessment | Global Impacts | | | Unilaterrally |
| Topic 3:<br>Economic Assessment | | Feasibility | | Combining inventory carried out in topic 2. |
| Topic 4:<br>Integrated Assessment | | | Impact associated to territorial planning | Combining<br>GIS and LCA results |

## II.2 Environmental tool: Life Cycle Assessment

The following lines introduce and explain Life Cycle Assessment in order to define the environmental tool applied in this thesis.

Life Cycle Assessment in relation to other environmental tools

To fulfil the goals of sustainability in environmental aspects, several tools to support decision-making have been developed. Tools such as: Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA), Input-Output Analysis (IOA), Life Cycle Assessment (LCA), Material Flow Accounting/ Substance Flow Analysis or Material Intensity Analysis (MIA) [3].

Some of these tools include the concept of life-cycle in their definition. The simplistic perspective that emission source control (end-of-pipe technologies) was a way to improve the environmental behaviour of industrial or human activities has been replaced by the idea that we are only protecting the environment as a whole if we adopt a systematic approach that considers the whole life cycle of an activity, product or service. This is known as the life cycle approach, also called the cradle-to-grave approach, because it follows an activity from the extraction of the raw materials –cradle- to the return of the waste to the ground – grave -.

Impacts of all life cycle stages need to be considered in order to make informed decisions regarding production and consumption patterns, policies and management strategies [4]. In order to systematically consider the environmental impacts of a product or service's life cycle, the LCA methodology is the most widely accepted tool, being the only tool which is in the process of harmonisation [5].

As LCA is the instrument used in this thesis to perform different case studies, a description of the methodology is presented in chapter II.2.

### *II.2.1 Definition*

Life Cycle Assessment (hereinafter LCA) is a management tool that enables assessment of the impacts inflicted on the environment throughout a product's life cycle, from extraction of the resource to waste management, including all the production, transport and usage stages. The assessment is made in such a way that environmental burden transfers between environmental media or life cycle stages are avoided. Fundamentally, LCA is a material and energy balance applied to the product's system, combined with an assessment of the environmental impacts related to the inputs and outputs to and from the product system. From this assessment, LCA provides criteria for decision-making on issues such as product development, policy making, strategic planning, etc. The first official definition of the LCA methodology was provided by the Society for Environmental Toxicology and Chemistry (SETAC) after seven international workshops and conferences between 1990 and 1993. This document represents one of the most cited references in this field [6]:

"Life-Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance; recycling and final disposal."

The ISO has also provided highly relevant input to the process of defining LCA. According to the ISO 14040 standard, LCA is [7]:

A technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system.
- Evaluating the potential environmental impacts associated with those inputs and outputs.
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA studies environmental aspects and potential impacts throughout the product's life cycle (from cradle to grave), from the acquisition of raw materials to production, use, and final disposal. As can be seen, both definitions are fairly similar, highlighting the need for the analysis to take into account the entire product chain and the potential consequences on the environment, based on the compilation of a mass and energy balance of the product and/or system process [8].

## II.2.2 LCA history and current developments

One may consider that the origin of LCA lies in the energy crisis of the late sixties and early seventies, which forced industries to look for energy efficient solutions for their products. Hence the concept of product life cycle was born, as it was necessary to reduce energy consumption in all stages implied in the product's cycle: from extraction of raw materials to waste management. The first study considered to be an LCA was a project commissioned by the Coca-Cola Company to the Midwest Research Institute in 1969 that aimed to compare different possibilities for packaging from the point of view of emissions and material and energy consumption. This study was called REPA: Resource and Environmental Profile Analysis [9]. More studies such as the one described were performed during the seventies, but in the late seventies and until the mid eighties the interest in such analyses decreased, probably due to the improvement in the economy [9].

From the mid eighties, however, the interest in minimising resource consumption and emissions increased again as institutions such as EMPA and BUWAL in Switzerland and CML in the Netherlands developed methods for the aggregation of substances into "impact categories".

In the nineties the generalised use of LCA as a support tool for decision making began, both in industries and in the public sector. In this sense, the publication of several LCA methodology guides by different institutions (U.S. Environmental Protection Agency; BUWAL; CML; the Nordic Council of Ministers; SETAC, etc.) was crucial. These institutions also provide basic databases [10].

In 1992 the Society for the Promotion of LCA Development (SPOLD) was founded by 20 European companies, with the goal of fostering and standardizing the use of LCA. In 1993 the ISO Technical committee 207 started work on the development of international LCA standards, leading to the 14.04X series, see figure II.1.

Figure II.1 The ISO 14.04X series on LCA.

- ISO 14040:1997 Environmental Management – LCA – Principles and Framework
- ISO 14041:1998 Environmental Management – LCA – Goal and Scope Definition and Inventory Analysis
- ISO 14042:1999 Environmental Management – LCA – Life Cycle Assessment
- ISO 14043.2000 Environmental Management – LCA – Life Cycle Interpretation
- ISO/TR 14047:2003 Environmental Management – LCA – Examples of application ISO 14042
- ISO/TR 14049:2000 Environmental Management – LCA – Examples of Application of ISO 14041 to goal and scope definition and inventory analysis

Source: [4]

More recently, in 2006, the 14.04 X series was updated to improve its readability, while the requirements and technical content were left unaffected, except for errors and inconsistencies.

Figure II.2 The ISO 14,04X updated series on LCA.

- ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework provides a clear overview of the practice, application and limitations of LCA to a broad range of potential uses and stakeholders, including those with a limited knowledge of Life Cycle Assessment.

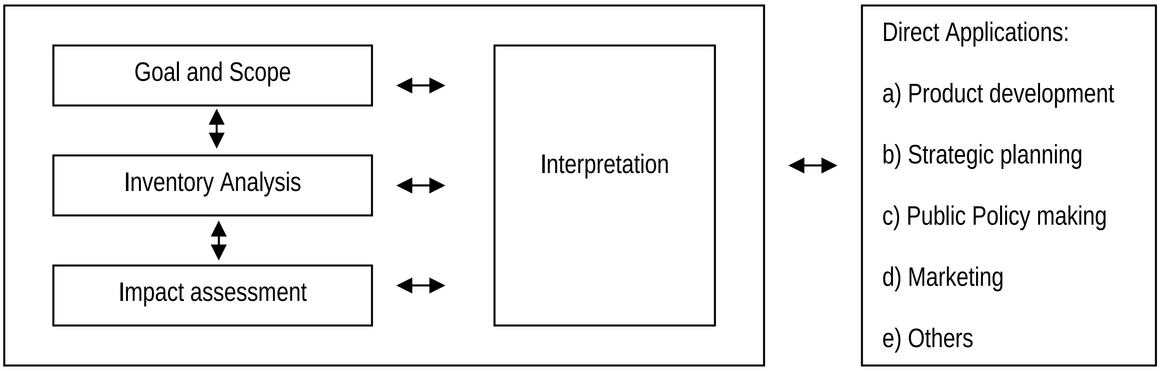
- ISO 14044:2006 Environmental Management – Life Cycle Assessment – Requirements and guidelines, is designed for the preparation of, conduct of, and critical review of, life cycle inventory analysis. It also provides guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected.

Source: [11]

ISO 14040: 2006 and ISO 14044:2006 replace the previous standards (ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000).The new standards are the work of ISO technical committee ISO/TC 207, Environmental management, subcommittee SC 5, Life Cycle Assessment [11].

## *II.2.3 Methodology*

The ISO 14040 standard determines four basic stages for LCA studies, schematically represented in Figure II.3, and briefly described in this section.



Source: [12]

### II.2.3.1 Definition of goal and scope

This is the first stage of the study and probably the most important, since the elements defined here, such as the purpose, scope, and main hypothesis considered are the keys to the study.

The goal of the study is the first item to be defined, as well as the reasons leading to it, the kind of decisions that will be made from the results obtained, and whether these will be of internal use (for company, for instance) or external use (to inform the general public or an institution)[8].

Secondly, the scope of the study is defined. This implies, among other elements, defining the system, its boundaries (conceptual, geographical and temporal), quality of data used, the main hypothesis, as well as the limitations of the study. A key issue in the scope is the definition of the functional unit [12]. This is the unit of the product or service whose environmental impacts will be assessed or compared. It is often expressed in terms of amount of product, but should really be related to the amount of product needed to perform a given function [8].

### II.2.3.2 Inventory analysis

Inventory analysis is a technical process of collecting data, in order to quantify the inputs and outputs of the system, as defined in the scope [12, 14]. Energy and raw materials consumed, emissions to air, water, soil and solid waste produced by the system under study are split up into several subsystems and unit processes, and the data obtained is grouped in different categories in a Life Cycle Inventory (LCI) table [8].

### II.2.3.3 Impact assessment

Life Cycle Impact Assessment (LCIA) is a process to identify and characterise the potential effects produced in the environment by the system under study [12,15]. The starting point for LCIA is the information obtained in the inventory stage. As a consequence, the quality of the data obtained in the latter is a key issue for this assessment. LCIA is considered to consist of four steps that are briefly described below [8].

- The first step is **Classification**, in which environmental interventions (resources consumed, emissions to the environment) identified in the inventory analysis are grouped in different impact categories or indicators, according to the environmental effects they are expected to produce. For example, $CO_2$ and $CH_4$ emissions are classified in the Global Warming Potential category.
- The second step, called **Characterisation**, consists of weighting the different substances contributing to the same environment impact. For each impact category included in LCIA, an aggregated result is produced, in a given unit of measure. For example, Global Warming Potential is calculated in kg eq. $CO_2$, from the contribution of $CO_2$ and $CH_4$ emissions, among others. At this point, the so-called environmental profile of the system is obtained, consisting of a set of indicator scores.
- The third step is **Normalisation**, which involves relating the environmental profile of the system to a broader data set situation, for example, relating the system's Global Warming Potential to a country's yearly Global Warming Potential.
- The last step is **Weighting**, where the environmental profile is reduced from a set of indicators to a single impact score, by using weighting factors based on subjective value judgements. For instance, a panel of experts or members of the general public could be formed to weight the impact categories. The advantage of this stage is that different criteria (impact categories) are converted to a numerical score of environmental impact, thus making it easier to make decisions. However, a lot of information is lost, and very much simplified [8].

### II.2.3.4 Interpretation

This is the last stage of an LCA study, where the results obtained are presented in a synthetic way, presenting the critical sources of impacts and the options to reduce them.

Interpretation involves a review of all stages of the LCA process, in order to check the consistency of the assumptions and the data quality, in relation to the goal and scope of the study [8,16].

### *II.2.4 Benefits and limitations of the LCA*

LCA involves a holistic approach. All necessary inputs and emissions in many stages and operations of the life cycle are considered to be within the system boundaries. This not only includes inputs and emissions for production, distribution, use and disposal, but also indirect inputs and emissions – such as from the initial production of the energy used – regardless of when or where they occur. If real environmental improvements are to be made by changes to the product or service, it is important not to cause greater environmental deteriorations at another time or place in the life cycle. The power of LCA is that it expands upon the debate on environmental concerns beyond a single issue, and attempts to address a broad range of environmental issues, by using a quantitative methodology, providing an objective basis for decision making.

According to Guinée et al [17], the core characteristic of LCA, its holistic nature, in addition to being its main strength is also its main limitation, since the broad scope of analysing the entire life cycle of products and processes can only be achieved at the expense of simplifying other aspects. Particular limitations of LCA can be summarized as follows [8]:

- LCA addresses potential rather than actual impacts. This is due to the fact that in LCA, global impacts are not specified in space and time. The ISO 14.042 standard, dealing with Life Cycle Impact Assessment, specially cautions that LCA does not predict actual impacts or assess safety, risks, or whether thresholds are exceeded. The actual environmental effects of emissions will depend on when, where and how they are released into the environment. Concerning spatial differentiation, it is possible to identify regions where certain emissions take place, and take into account the different environmental sensitivities of these regions. However, LCA does not provide the framework for a complete Risk Assessment, in which the actual impacts associated to the operation of a facility in a specific place can be predicted. The same can be applied for the impact aspect, since LCA is typically a steady-state, rather than a dynamic approach.
- The LCA model focuses on the physical characteristics of industrial activities and other economic process. Market mechanisms or other secondary effects on technological development are not included.
- LCA generally regards all processes as linear, both in the economy and the environment. Doubling the production of a material is assumed to have double impact, and the same applies for doubling the release of a pollutant to the environment. Although some progress is being made in reducing this limitation, LCA at its core is based on linear modelling [8].

- LCA focuses on environmental issues associated to products and processes, excluding economic and social consequences. Where economic aspects are concerned, Life Cycle Cost (LCC) can be expected to become a standard addition to LCA applications. However, the inclusion of social issues in LCA or the integration of LCA with tools for social assessment is still in its infancy.
- Finally, availability of data is another limitation. Databases are being developed in various countries, but in practice, data is frequently obsolete, incomparable, or of unknown quality.

## II.3 Economical tool: economic indicators

Clearly no single tool can provide answers to all the questions posed by sustainable issues. The limitations of LCA highlight the fact that in order to fill these gaps, other assessment and analytical tools must be added to given decision situations. Taking this in mind, an economic assessment has been carried out in order to provide economic results for the bioenergy systems under study.

The criteria for choosing the methodology to assess the economic performance of the bioenergy systems under study were the results that we expect to obtain. Knowing that there are several incipient economic methodologies that include environmental and social costs in the whole analysis, we preferred to demonstrate the classic economic feasibility of biomass projects. The private sector can observe in the results of this thesis that Spanish Royal Decree 661/2007 can help to develop biomass energy projects under sustainability criteria.

However, a prospective assessment has been carried out including in one of the analyses the avoided cost of $CO_2$ emissions when biomass substitutes a renewable energy source like carbon (see chapter VI).

The economic assessment carried out in this thesis is focused on the calculation of three indicators: Net Present Value (NPV), Simple Payback Period (SPP) and Internal Rate of Return (IRR). See chapters VI and VIII.

There are several reasons for valuing one monetary unit differently at different points of time, when knowing the Simple Payback Period or Internal Rate of Return, such as [18-20]:

- Productivity capital: cash amounts received earlier can be reinvested earlier thereby earning additional returns.
- Uncertainty and risk: project cost or revenues taking place in the future are assumed to do so with a certain degree of uncertainty, especially risky projects.
- Time preference: in other words, impatience of the person, company or society.

### II.3.1 Net Present Value (NPV)

The discount rate is the interest rate used in economic science to find the present value of future costs and benefits. By means of a properly chosen discount rate, the investor becomes indifferent regarding cash amounts received at different points of time [20,21]. In economics, the Net Present Value (NPV) of an investment is calculated as a function of benefits, costs and the discount rate (equation I.1):

$$NPV = \sum_{t=1}^{T}\left[\frac{(Bt - Ct)\cdot 1}{(1-r)^{t}}\right] - k \qquad \text{(eq. I.1)}$$

Where:
*B* represents the benefits,
*C* represents the costs,
K represents the initial investment
*r* is the discount rate, expressed in real terms, net of any changes in the price level (inflation),
*t* is the time horizon of the project.

NPV results will determine the projects feasibility, as it is showed in table II.1.

Table II.2 Interpretation of NPV results.

| NPV Value | Meaning | Project adaptation |
|---|---|---|
| NPV > 0 | Investment will be profitable | Project can be accepted |
| NPV = 0 | Investment will not be profitable neither making losing money | Project can be rejected |
| NPV < 0 | Investment will make losing money | Project has to be rejected |

Source: [20,21]

### II.3.2 Simple Payback Period (SPP)

An energy investment's simple payback period is the time that will take to recover the initial investment in energy savings, dividing initial investment cost by the annual energy cost savings [21].

$$SPP = \frac{Investment}{Annual\ benefits} \qquad \text{(eq. I.2)}$$

### II.3.3 Internal Rate of Return (IRR)

Another efficient economic indicator of the feasibility of projects is the Internal Rate of Return. This indicator can be defined as the annualised effective return can we earn on the invested capital, in other words the yield on the investment. Put another way, the internal rate of return is the discount rate at which NPV is equal to 0 [20]. See equation (I.3)

$$IRR = 0 = \sum_{t=1}^{T} \left[ \frac{(Bt - Ct) \cdot 1}{(1-r)^t} \right] - k \qquad \text{(eq.I.3)}$$

Where:
*B* represents the benefits,
*C* represents the costs,
K represents the initial investment
*r* is the discount rate, expressed in real terms, net of any changes in the price level (inflation),
*t* is the time horizon of the project.

A project is a good investment proposition if its IRR is greater than the rate of return that could be earned by alternate investments of equal risk (investing in other projects, buying bonds, even putting the money in a bank account).

## II.4 Territorial Planning Tool: Geographic Information Systems (GIS)

To complete the sustainability analysis of the bioenergy systems under study, we passed from a functional unit perspective (used in LCA study) to a territorial perspective. This change of scale was made possible by applying a Geographical Information System (GIS).

### II.4.1 Definition

The use of the term Geographic (Geographical) Information System (hereinafter GIS) dates back to the mid-1960s, where it seems to have originated in two quite different contexts. In Canada, it was devised to refer to the use of mainframe computer associated peripherals (notably a scanner) to manage the mapped information being collected by the Canada Land Inventory, and to process it to compute estimates of the area of land available for certain types of uses.

Almost at the same time, researchers in the U.S. were struggling with the problems of accessing the many different types of data required by the large-scale transportation model then in vogue, and conceived GIS as a system capable of extracting appropriate data from large stores, making it available for analysis, and presenting the results in map form [22]. Such models combined information on population distribution with other spatially distributed information on places of employment and transportation routes, and required access to data in a variety of formats.

Almost 50 years later, these same arguments are still among the most frequently heard justifications for the use of GIS, particularly in environmental modelling and policy development. GIS is seen as a general-purpose technology for handling geographic data in digital form, and satisfying the following specific needs, among others [23]:

- The ability to pre-process data from large stores into a form suitable for analysis, including such operations as reformatting, change of projection, resampling, and generalization.
- Direct support for analysis, calibration of models, forecasting, and production are all handled through instruction to the GIS.
- Post processing of results, including such operations as reformatting, tabulation, report generation, and mapping.

### II.4.1.1 Geographic data

GIS works with geographic data which has three components: spatial, thematic and temporal [24].

The spatial component refers to the localization of the objects and elements expressed by a geographic coordinates system.

The thematic component is also called an attribute. It refers to the description of the object or element represented in the map. This descriptive data is stored in a database linked to the map.

The temporal component refers to the time, normally expressed in years of compiled and stored data.

Geographic data can be represented in a map by means of [24]:

- A vectorial model representing elements by means of georeferenced points, lines and polygons.
- A raster model representing elements by means of cells and pixels. Both are georeferenced and their cells are organized by rows and lines.

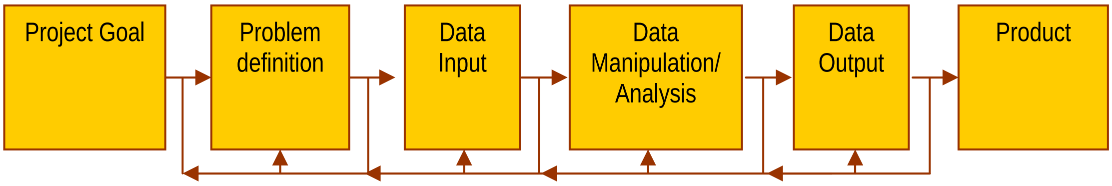
Both models are related to several databases which contain the attribute information on each point, line or polygon in the case of the vectorial model or each cell or pixel in the case of the raster model [24].

## *II.4.2 Procedural perspective – the nature of GIS work flow*

A GIS workflow process primarily consists of four steps (1) definition of the problem (and system setup if needed); (2) data input/capture (with subsequent data storage/management); (3) data manipulation/analysis; and (4) data output/display (see figure II.4). Data storage/management functions support all the others [23].

As in any problem-solving environment, the definition of a problem follows from some goal, no matter how well or ill defined the goal may be. Each of the steps is taken in turn. Some overlap might exist in terms of what is done, when some amount of iteration among steps occurs depending on the results of each step.

Figure II.4 GIS as work-flow process from a procedural perspective.



Source: [23]

In the definition of the problem step in GIS, just as in any scientific study, one examines what must be done with regard to an understanding of the problem and the needs for information processing. The nature of the problem is described by doing the best that can be done with the information at hand.. The information that is needed to solve the problem at hand is the basis for the data required for processing.

In the data input step, data is either converted to digital form from hardcopy sources or is acquired from digital sources and reformatted to make it appropriate for use. The digitalizing process involves the use of an instrument to capture spatial coordinates in computer-compatible form for a sample or phenomenon of interest on the map. Both vector digitizing and raster scanning are used for data capture. Maps may or may not be of suitable form and resolution to be digitized. Alternatively, the acquisition of digital data is usually a much less expensive undertaking than digitizing data [22].

Data management functions focus on preparing data for the analysis processing phase. Manipulation functions prepare data for further processing. Conversion from one structure to another (vector to raster or raster to vector formats) is often necessary to support spatial data analysis.

Functions to support GIS data analysis focus on developing and synthesizing spatial relationships in geographic data to provide answers. These functions produce answers that take the form of single numbers or several thousand numbers or words as the basis of a map display [22].

## II.5 Integration tools: Geographic Information Systems (GIS) and Life Cycle Assessment (LCA)

In most GIS applications, the decision making situation must also take into account the global environmental impact carried out for the territorial planning proposal. Taking into account the fact that in the previous chapter II.2, LCA was suggested as being the right tool for addressing global environmental aspects, the complementariness between tools will be presented.

Table II.3 shows the contributions that LCA can make to territorial planning proposals and GIS applications and vice versa.

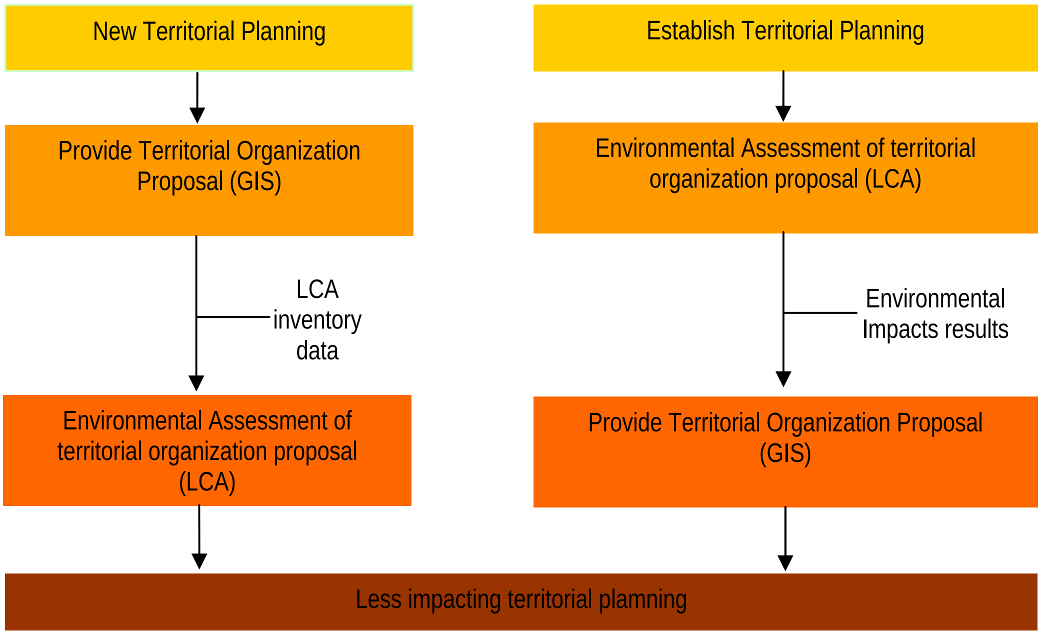
Table II.3 Contributions of LCA with GIS integration and vice versa.

| LCA contribution to GIS | GIS contribution to LCA |
|---|---|
| To check the global environmental impacts related to territorial proposal | To provide quality inventory data for LCA application, such as: transport distance, infrastructure manufactured, surface of soil changed… |
| To check the energy balance determination related to territorial proposal | Effect of the territorial proposal on the total energy balance behaviour of the product or service |
| | To analyse the effect of territorial proposal on the total environmental life cycle behaviour of the product or service |
| | Effect of the territorial proposal on environmental impact and energy balance of determining stages of life cycle's products or services. For example: transport stage, occupation area, number of production centers or parcels… |
| | To locate environmental impact sources |
| To improve the representation of results locating in a determined area | |

GIS and LCA can be applied to retrospective assessment, i.e. results coming from either of the tools can be used as the starting point for the assessment of the other, or vice versa. See figure II.5

In other words, GIS provides reliable territorial scenarios based on the scientific assessment of geographical, climate or other environmental variables. These scenarios can supply huge quantities of data that is usable to make LCA inventories. At the same time, the application of LCA provides environmental impact results on the performance of the proposal for territorial organization and new environmental data to be taken into account in territorial planning. The final planning obtained should be that of less impact and will be the result of different interactions between both tools, LCA and GIS. See figure II.5

Figure II.5 Schematic representation of retrospective assessment applying GIS and LCA.



As shown in figure II.5, LCA is applied first when the project is already established in the territory in order to obtain environmental data that can help to redesign the territorial organization. However, if it is a new project, GIS will be the first tool applied and will provide LCA inventory data that will be applied to obtain the environmental performance of the territorial proposal. In both cases, the result will be the same - a less impacting territorial plan. Projects where territorial organization discipline is needed for them to be developed should be analysed by combining GIS with the application of LCA in order to improve and reduce the global impacts in such aspects as:

- Need for user mobility
- Transport distance inputs and/or outputs
- Soil and use occupation
- Infrastructures applied
- Material flow and energy demand between production and consumption areas

The bioenergy implementation case studies in this thesis are clear examples of projects that can be improved if GIS and LCA analysis are done together. This kind of project has a demand for soil occupation, transport logistics and a clear relation between the demand for energy consumption and the need for a soil surface. Taking these reasons in mind, chapter VIII develops an analysis that combines both tools in a case study area.

## II.6 References to Chapter II

[1] Venendaal R., Jorgensen U. & Fosters C.A.European Energy Crops: A synthesis. Biomass & Bioenergy. 13 (3) (1997) 147-185.

[2] Cardone M, Mazzoncini M, Menini S, Rocco V, Senatore A, Seggiani M and Vitolo S. Brassica carinata as an alternative oil crop for the production of biodiesel in Italy. Agronomic evaluation, fuel production by transesterification and characterization. Biomass & Bioenergy 25 (2003) 623-636.

[3] Leiden University. Availabre from: http://cml.leiden.edu/research/industrialecology/researchprojects/chainet.jsp. Accessed: April 2009.

[4] Hospido A. Life Cycle Assessment as a tool for analysing the environmental performance of key food sectors in Galicia (Spain): Milk and Canned Tuna. (Doctoral thesis). Santiago de Compostela: Universidade de Santiago de Compostela, 2005. 286 p.

[5] Sonnemann G. The Life Cycle Initiative: an international partnership to improve the applicability of Life Cycle Assessment and enhance the use of Life Cycle Thinking worldwide. In Castells F. and Antón A. (Eds). Integració de les eines d'Anàlisi de Cicle de Vida i Anàlisi de Risc; Tarragona. Artyplan S.A.

[6] Consoli F., Allen D., Boustead I., de Oude N., Fava J., Franklin W., Quay B., Parrish R., Perriman R., Postlethwaite D., Seguin J. and Vigon B. Guidelines for Life-Cycle Assessment: A 'Code of Practice' SETAC. Pensacola (USA), 1993.

[7] ISO. ISO 14040:1997. Environmental management. Life Cycle Assessment. Principles and Framework. International Organisation for Standarisation (ISO) (Switzerland.), 1997.

[8] Muñoz I. Life Cycle Assessment as a tool for green chemistry: application of different advanced oxidation process for wastewater treatment. (Doctoral Thesis). Barcelona: Universitat Autònoma de Barcelona (UAB), 2006. 258 p.

[9] Fullana & Puig R. El Análisis de Ciclo de Vida. Ed. Rubes: Barcelona (Spain), 1997. (In Spanish).

[10] Milà i Canals Ll. Contribution to LCA methodology for agricultural systems. Site-dependency and soil degradation impact assessment (Doctoral thesis). Barcelona: Universitat Autònoma de Barcelona, 2003. 250 p.

[11] Data available on: www.iso.org. Accessed: March 2009.

[12] ISO. ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standarisation (ISO) (Switzerland.), 2006.

[13] Muñoz I, Rieradevall J, Domènech X. Definición de la unidad funcional e implicaciones en el ACV. In: Clemente G, Sanjuán N, Vivancos J L. (Eds.). Análisis de Ciclo de Vida: aspectos metodológicos y casos prácticos. Ed. Universidad Politécnica de Valencia, 2005.

[14] ISO. ISO 14041:1998 Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis. International Organisation for Standarisation (ISO) (Switzerland.), 1998.

[15] ISO. ISO 14042:1999 Environmental Management – Life Cycle Assessment – Life Cycle Assessment. International Organisation for Standarisation (ISO) (Switzerland.), 1999.

[16] ISO. ISO 14043:2000. Environmental Management –Life Cycle Assessment – Life Cycle Interpretation. International Organisation for Standarisation (ISO) (Switzerland), 2000.

[17] Guinée J B, Gorree M, Heijungs R, Huppes G, Kleijn R, Udo de Haes H A, Van der Voet E, Wrisberg M N. Life Cycle Assessment. An operational guide to ISO standards.Volume 1, 2, 3. Centre of Environmental Science, Leiden University (CML), The Netherlands, 2002.

[18] Schmidt W P. Life Cycle Costing as part of Design for Environment. Environmental business cases. International Journal of Life Cycle Assessment, 8 (3) (2003), 167-174.

[19] Hellweg S, Hofstetter T B, Hungerbühler K. 2003. Discounting and the environment. Should current impacts be weighted differently than impacts harming future generations?. International Journal of Life Cycle Assessment, 8 (1), (2003) 8-18.

[20] Fuller S K, Petersen S R. Life-Cycle Costing Manual for the Federal Energy Management Program. National Institute of Standards and Technology, Handbook 135. Prepared for U.S. Department of Energy. Washington DC, 1996 Available at: http://aesl.hanyang.ac.kr/resource/blcc/blcc-handbk1.pdf

[21] Ceña F. & Romero C. Evaluación Económica y Financiera de Inversiones Agrarias. Madrid: Banco de Crédiot Agrícola. 1982. 15-64.

[22] Coppock J.T. and Rhind D.W. The history of GIS. In Maguire D.J., Goodchild M.F. and Rhind D.W. (Eds.) Geographical Information Systems: Principles and Applications (2 volumes), London: Longman and New York: Wiley, 1991. 21-43.

[23] Goodchild M.F. The state of GIS for Environmental Problem Solving. In Goodchild M.F., Parks B.O., Steyaert L.T. (Eds.) Environmental Modelling with GIS, New York: Oxford University Press,1993, 9-15

[24] Marble D.F.. Geographic Information Systems: an overview. In Peuquet D.J. and Marble D.F. (Eds.). Introductory Readings in Geographic Information Systems, London: Taylor and Francis, 1990 pp. 8-17.

# Chapter III. Life Cycle Assessment of a *Brassica carinata* cropping system in southern Europe.

*Published as: Gasol C.M., Gabarrell X. Anton A., Rigola M., Carrasco J., Ciria P., Solano ML. & Rieradevall J. Life Cycle assessment of a Brassica carinata bioenergy cropping system in southern Europe. Biomass & Bioenergy 31 (2007) 543-555.*

*Photografy by Carles Martinez Gasol. Soria (Castilla León), 2004*

# Abstract

The energetic and environmental performance of production and distribution of the *Brassica carinata* or *B.carinata* biomass crop in Soria (Spain) is analysed using Life Cycle Assessment (LCA) methodology in order to demonstrate the major potential that the crop has in southern Europe as a lignocellulosic fuel for use as a renewable energy source.

The Life Cycle Impact Assessment (LCIA) including midpoint impact analysis that was performed shows that the use of fertilizers is the action with the highest impact in 6 of the 10 environmental categories considered, representing between 51% and 68% of the impact in these categories.

The second most important impact is produced when the diesel is used in tractors and transport vehicles which represents between 48% and 77%. The contribution of the *B. carinata* cropping system to the global warming category is 12.7 g $CO_2$ eq·$MJ^{-1}$ biomass produced. Assuming a preliminary estimation of the *B. carinata* capacity of translocated CO2 (631 kg $CO_2 \cdot ha^{-1}$) from below-ground biomass into the soil, the emissions are reduced by up to 5.2 g $CO_2$ eq·$MJ^{-1}$.

The production and transport are as far as a thermoelectric plant of the *B. carinata* biomass used as a solid fuel consumes 0.12 MJ of primary energy per 1 MJ of biomass energy stored. In comparison with other fossil fuels such as natural gas, it reduces primary energy consumption by 33.2% and greenhouse gas emission from 33.1% to 71.2% depending on whether the capacity of translocated $CO_2$ is considered or not.

The results of the analysis support the assertion that *B.carinata* crops are viable from an energy balance and environmental perspective for producing lignocellulosic solid fuel destined for the production of energy in southern Europe. Furthermore, the performance of the crop could be improved, thus increasing the energy and environmental benefits.

*Keywords: Energetic crops; Life cycle assessment; Energy crops; Environmental analysis; Energetic analysis*

## III.1 Introduction

During the nineties, biomass for energy conversion came to be seen as one of the sources of renewable energy with the largest potential for market growth in Europe [1,2].

Biomass, and in particular energy crops (crop plants used to obtain energy) received attention as a promising, sustainable energy source [1,3,4]. Due to the expectancy, this aroused and the fact that most of the EU governments recognized that an increase in the use of energetic crops should be accompanied by a detailed analysis [5,6], several studies were made that focused on the energy and environmental performance of biomass and energy crops [4,7–9]. North-western and central European countries put the biggest effort into the research and use of energy crops for power and heat generation over recent decades, while in southern Europe the introduction of energy crops to agriculture is slower [4,8,10–14]. For example, only in Spain, it is foreseen that by 2010 one million hectares will be destined for the production of 1.09 Mtep by energetic crops, but the fact is that the energy produced by energy crops is inexistent [15].

Nowadays there is a need for a reliable quantitative assessment of the environmental, energetic and economic performance of biomass energetic crop production under the existing conditions in southern Europe.

The Spanish Centre of Energy, Environment and Technology Research (CIEMAT) has compiled agricultural production data for *Brassica carinata* (from now *B.carinata*) from 160 ha. The agricultural fields where *B. carinata* has been cultivated have been monitored using current agricultural production procedures. As a consequence, the final results of the environmental and energetic performance can be extrapolated to other southern European regions with similar soil and climate conditions.

*B. carinata* is an annual allotetraploid herbaceous species derived by crossing *B. oleracea* and *B. nigra*, which is considered to have major potential as an energetic crop in southern Europe due to its adaptation and productivity in such Mediterranean areas as Spain, Italy and France [16].

There are studies that demonstrate the high possibilities of *B. carinata* for producing biodiesel by transesterification of the oil extracted from the *B. carinata* seed but not as a lignocellulosic biomass crop used to generate heat and power [16–18].

This paper demonstrates the environmental and energy viability of this crop for producing lignocellulosic biomass destined for the generation of heat and power under the current agricultural production conditions in southern Europe. In the *B. carinata* cropping system analysed, the biomass and the seeds are collected together, so the agricultural harvesting work includes the collection of the plant in its entirety.

Furthermore, it presents the stages of the system with higher energy consumption and environmental impact, and suggests improvements of the system that could increase the potential for this crop as a source of renewable energy in southern Europe. Finally, the study compares the environmental and energetic performance of *B. carinata* biomass and an equivalent quantity of natural gas, in order to demonstrate the advantages of this renewable energy source in comparison with this fossil fuel. Natural gas extraction and distribution stages were the reference system used in the study as biomass is expected to substitute such fossil fuels as natural gas in Spanish thermoelectric generator plants [19].

## III.2 Methodology

To evaluate the environmental and energetic performance of the production and distribution of *B. carinata* as an energy crop, a standard hectare plot was selected from all the 160 ha cultivated in Soria (42.02 N, 2.5 W). This assumption was made through the application of the average value of the following parameters:

- Production of biomass in Mg (d.b.) · $ha^{-1} \cdot yr^{-1}$
- Application dose of fertilizers within the rank of doses applied in the 160 ha
- Application dose of herbicides within the rank of doses applied in the 160 ha

The selected plot presented the values shown in Table III.1.

Table III.1 Values of the selection parameter of the selected experimental plot.

| Production Mg (d.b)·$ha^{-1} \cdot yr^{-1}$ | Extension (ha) | Doses of fertilizer | | Doses of Herbicide |
|---|---|---|---|---|
| 4.71 | 9.51 | Ammonium Nitrate 27%:<br>250 kg.$ha^{-1} \cdot yr^{-1}$ | NPK fertilize 8/24/8:<br>350 kg.$ha^{-1} \cdot yr^{-1}$ | Glyphosate:<br>2 l .$ha^{-1} \cdot yr^{-1}$ |

The climate conditions in the region analysed are continental-Mediterranean. The mean annual temperature is 10.5 1C and annual rainfall is about 500 mm. The texture of the soil was sandy loam: sand 5–9%, organic matter 22–23% and clay 68–73%. Oxidable organic matter was about 1% and pH about 6. This soil is light, with good drainage.

Furthermore, the biomass nutrient composition of *B. carinata* was used in order to obtain data that could enable us to evaluate the nutrients removed by cropping and to estimate the emissions of the fertilizers. Table III.2 shows the experimental results obtained for the nutrient composition of *B.carinata* biomass which are confirmed for another study [20].

The methodology used to determinate the environmental impacts and energetic balance of the *B. carinata* cropping system and natural gas system consists of energy assessment of the energy inputs and outputs of the system and environmental assessment using Life Cycle Assessment (LCA) methodology.

Table III.2 Nutrient composition of *B.carinata* biomass.

| C | H | N | S |
|---|---|---|---|
| (% d.b) | (% d.b) | (% d.b) | (% d.b) |
| 47.36 | 6.44 | 1.48 | 0.48 |

### *III.2.1 Energy assessment*

For the energy assessment, the energy inputs of both systems, natural gas and biomass, were calculated by ‘‘Cumulative Energy Requirements Analysis (CERA)’’ [21,22] using SimaPro 7.0 while the energy outputs were taken from experimental data. CERA has been used to investigate the energy used throughout the life cycle of an asset or a service used in the system including direct as well as indirect uses.

The energy output of the *B. carinata* cropping system depends on the total yield production per hectare. It can be calculated as the direct energy stored in biomass understood as the lower heating value (LHV); the calorific energy production or the electric energy production. The LHV of *B. carinata* biomass was 17.73 $MJ \cdot kg^{-1}$ dry matter. The LHV was obtained by combusting a 1 g sample in a LECO AC-300 calorimeter to determine the gross calorific value (norm ASTM E 711-87 ‘‘Gross calorific value of refuse derived fuel by bomb calorimeter’’) and was calculated from HHV and hydrogen. Other studies confirm the LHW value we obtained [20]. The natural gas’ LHV assumed in this study in order to compare the environmental impacts and energetic balance is 45.4 $MJ \cdot kg^{-1}$ [23].

The energy conversion factor considered in the case of the calorific energy production of the *B. carinata* cropping system is 85% of the LHV and in the case of electricity production is 27% of the LHV.

### *III.2.2 Environmental assessment*

The methodology selected to perform the environmental analysis was LCA in both analysed systems: natural gas and *B. carinata* biomass. LCA is a methodology used to assess all environmental impacts associated with a product, process or activity by accounting for and evaluating the resource’s consumption and emissions [24].

This environmental tool follows the ISO14040 guidelines [24], according to which, LCA is divided into four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. The environmental analysis was developed using the software program SimaPro 7.0 by Pre´ Consultants.

## III.3 LCA of *B. carinata*

In the following lines LCA applied to *B.carinata* bioenergy system is presented.

### *III.3.1 Goal and scope definition*

The main aim of the study was to evaluate the environmental impacts and energy balance of the *B. carinata* cropping system in a continental-Mediterranean area (Spain) destined for the production and distribution of solid biomass fuel as far as a thermoelectric plant is considered. The study has two significant additional specific goals; the hot spots of the agricultural and transport phases of the system were identified and measures were suggested for environmental improvement. The second specific goal was to demonstrate the better environmental and energy performance of the biomass as a renewable energy source in comparison with conventional non-renewable fuels such as natural gas.

## *III.3.2 Functional unit*

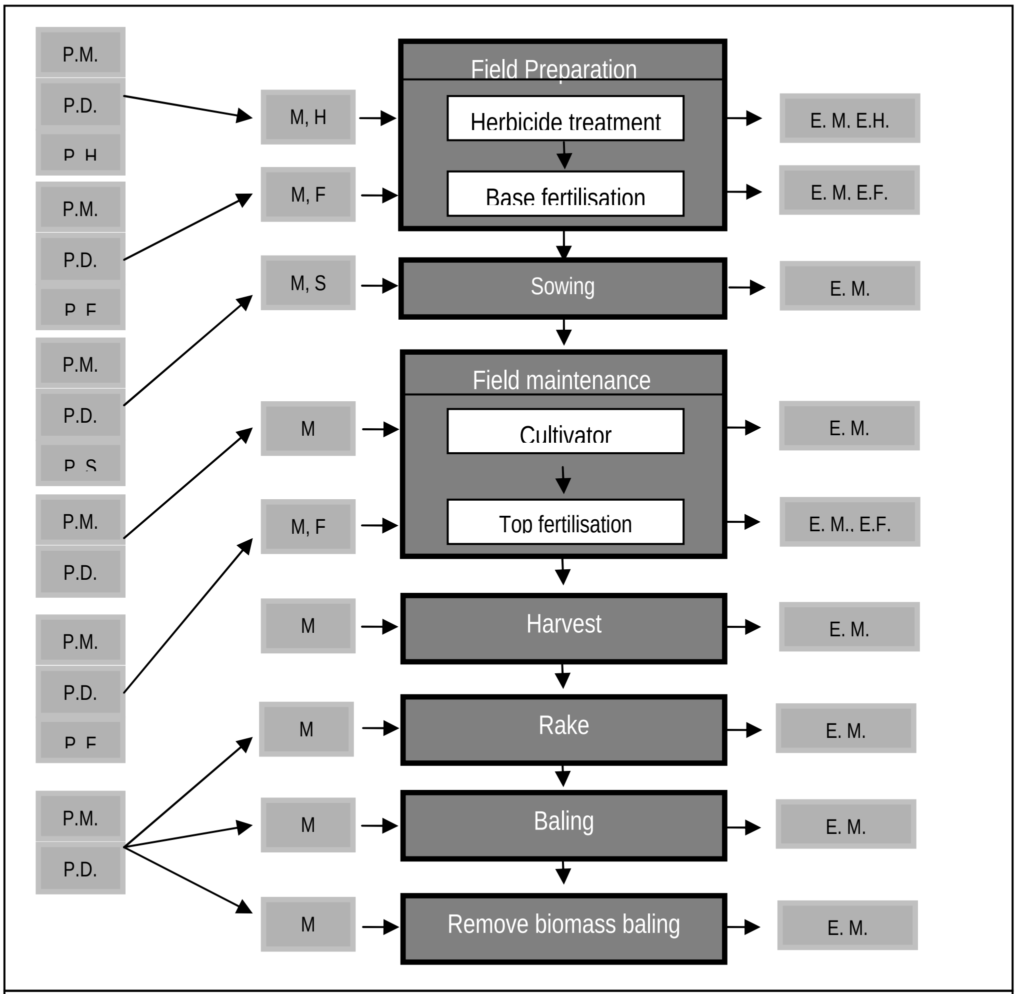
In this study, the function of the agricultural system is to cultivate 1 ha of *B. carinata* for 1 year. Moreover, the energy stored in the crop from 1 ha, 83.69 GJ was used as an energy reference value in order to compare the natural gas and biomass systems.

## *III.3.3 Systems description*

The analysed energy crop system includes the agricultural production subsystem and transport subsystem as far as the thermoelectric plant is considered.

In Figure III.1, a representation of the agricultural activities included in an agricultural subsystem is shown.

Figure III.1 Schematic of the B.carinata cropping system boundary.



Legend

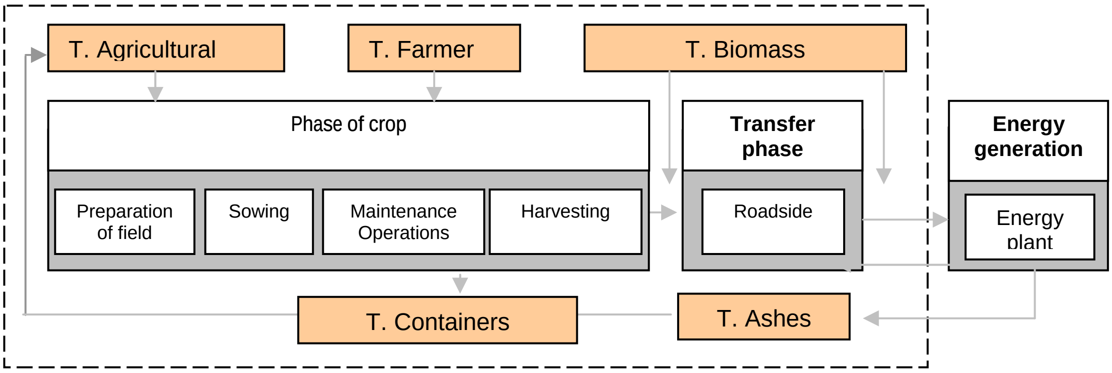
M: Use of the tractor and implement; F: Application of the fertilizers; H: Application of the herbicides; S: Application of the seeds; M.P: Farm Machinery (tractor and implement) production; D.P: Diesel fuel production and distribution; F.P: Fertilizer production; H.P: Herbicide production; S.P: Seed production; E.H: Emissions from the application of herbicide; E.M: Emissions from the combustion of the diesel fuel; E.F: Emissions from the application of fertilizers.

Apart from all the farm work in the field, the production processes of the different agricultural inputs are also presented, such as: fuel, herbicides, fertilizers, seed, tractor and agricultural utensils and transport stages.

The *B. carinata* biomass cropping system is similar to the cropping system currently being used by farmers in southern Europe. The system also includes the transport of both inputs and outputs. As inputs: farmer, fertilizers with their corresponding containers, herbicides and seeds are considered; while outputs are: residues (containers), ashes and biomass as bales, see figure III.2.

The farmer transport phase includes all the journeys needed to accomplish the required work as well as to supervise the crop. A total number of 8 journeys have been considered.

Figure III.2 Transport stages implied in the studied crop.



## III.3.3.1 Transport scenario in the agricultural system

The suggested transport scenario is based on a regional/local national scale (25 km), but a distance of 500km for the transport of agrochemicals is included when taking into account the capacity for distribution of the main agrochemical-producing enterprises in Spain [25]. With respect to the transport distances, from the centre point of the hectare to the roadside, 0.5 km has been considered.

Table III.3 summarizes the distance and characteristics of the vehicles used in the transport of inputs and outputs in the transport scenario defined.

Table III.3 Characteristic of transport scenario.

| Vehicle | Input / Output | Maximum load (Mg) | Total weight of the vehicle (Mg) | Fuel consumption without load (L.100 Km$^{-1}$) | Fuel consumption with maximum load (L.100 Km$^{-1}$) | Distance (km) |
|---|---|---|---|---|---|---|
| Local distribution lorry [26] | Seeds | 8.50 | 14.00 | 20.00-25.00 | 25.00-30.00 | 25 km from plant to roadside |
| Regional distribution lorry [26] | Fertilizers and herbicides | 14.00 | 24.00 | 25.00-30.00 | 30.00-40.00 | 500 km from plant to roadside |
| Tractor with trailer [27] | Biomass | 12.50 | 17.50 | 56.00-70.00 | 70.00-84.00 | 0.50 km from field to roadside |
| Regional distribution lorry [26] | Biomass | 12.50 | 17.50 | 56.00-70.00 | 70.00-84.00 | 25 km from roadside to plant |
| Passenger vehicle[28] | Worker | 5 passengers | 1.90 | 5.40-6.70 | 6.70-8.00 | 25 km from town to roadside |
| Van [29] | Containers residues | 3.50 | 5.00 | 9.50-12.00 | 12.00-14.50 | 0.50 km from field to roadside |
| Regional distribution lorry [26] | Containers residues | 14.00 | 24.00 | 25.00-30.00 | 30.00-40.00 | 25 km from transfer point to plant |
| Regional distribution lorry [26] | Ashes | 14.00 | 24.00 | 25.00-30.00 | 30.00-40.00 | 25 km |

The stages included within the boundary transport subsystem are: fuel extraction, processing fuel, fuel transport to commercial point and vehicle engine combustion.

The transport subsystem does not include the manufacture of the vehicles, and the impact of this is considered negligible, adding up to 5% [30] to the total impact generated during their life cycle. The impacts related to the roads are also excluded as these are not explicitly built for the transport of inputs and outputs of the analysed system.

### III.3.3.2 Gas natural system

The inventory system for natural gas includes gas field exploration, natural gas production, gas purification, long distance transportation and regional distribution. For all these steps air- and waterborne pollutants as well as energy and working material requirements, production waste and the production of the equipment are considered. Transport services needed to supply the process with energy and materials and waste treatment processes are included as well. The energy conversion stage was excluded due to its similarity to the *B. carinata* cropping system.

The distribution of high-pressure gas to industrial Spanish users (industry, power plants, etc.) is based on the main composition of countries supplying to Spain. The origins of imported natural gas in Spain considered in this study are: Algeria 78% of the imported natural gas, Norway 13.8% and the natural gas imported from the Union for the Co-ordination of Production and Transmission of Electricity is 8.2% [31].

## *III.3.4 Quality of the data*

The *B. carinata* agricultural production system uses field data collected during the establishment of 160 ha in Northern Spain in 2003 such as: agrochemical application dose (kg ha$^{-1}$·yr$^{-1}$), seed application dose (kg ha$^{-1}$·yr$^{-1}$), type of machinery used, diesel fuel consumption (l·ha$^{-1}$·yr$^{-1}$) and operating rate (h·ha$^{-1}$·yr$^{-1}$). The data for generalized and standard production processes for inputs such as fertilizers, herbicides, tractors, utensils as well as data related to the life cycle of the fuel (production, distribution and consumption), were taken from the Ecoinvent Database [32].

The characterization of *B. carinata* biomass (nutrients and heating value) was obtained directly from analysis carried out at the CIEMAT Centre (see Section 2).

The latest updated information available and used for the accomplishment of the inventory is summarized in Table III.4.

Table III.4 Field operations experimental data for base case.

| Operation | Tractor | Implement | | | | Inputs rates |
|---|---|---|---|---|---|---|
| | Weight and power | | Weight (kg.) | Operating rate (h.ha$^{-1}$.yr$^{-1}$) | Fuel diesel consumption (l.ha$^{-1}$.yr$^{-1}$) | |
| Herbicide Treatment | 8000 kg.<br>130 kW | Boom sprayer | 1,020.00 | 0.22 | 6.00 | Glyphosate:<br>2 l.ha$^{-1}$.yr$^{-1}$ |
| Base fertilization | 8000 kg.<br>130 kW | Spreade | 410.00 | 0.20 | 6.00 | Ammonium Nitrate 27%:<br>250 kg.ha$^{-1}$yr$^{-1}$ |
| Sowing | 8000 kg.<br>130 kW | Broadcaster | 1,735.00 | 0.50 | 10.00 | *Brassica spp.* seeds:<br>7,50 kg.ha$^{-1}$.yr$^{-1}$ |
| Cultivator | 8000 kg.<br>130 kW | Rototille | 300.00 | 0.20 | 4.00 | NPK fertilize 8/24/8:<br>350 kg.ha.yr$^{-1}$ |
| Top fertilization | 8000 kg.<br>130 kW | Spreade | 410.00 | 0.22 | 6.00 | |
| Harvest | 6300 kg.<br>104 kW | Harvest | 700.00 | 0.84 | 8.40 | |
| Rake | 5800 kg.<br>70 kW | Rake | 1,000.00 | 0.21 | 2.52 | |
| Baling | 8000 kg.<br>130 kW | Baling packer | 8,400.00 | 0.29 | 7.54 | |
| Remove Bales | 6800 kg.<br>70 kW | | | 0.13 | 1.30 | |
| Supervision of the crop | | | | 77.00 | | |

In reference to the natural gas system, the data used were obtained directly from the ETH-ESU 96 database, the inventory considered was specifically Natural Gas HP user in E (Spain) which considers all the life cycle stages until the delivery of this fuel to a regional Spanish power plant [31].

## *III.3.5 Life cycle inventory methodology*

The methods used in the life cycle inventory phase were mainly based on the Life Cycle Inventories of Agricultural Production Systems methodology [33] and on the EU Concerted Action AIR-CT94-2028 ''Harmonization of Environmental Life Cycle Assessment for Agriculture'' [34].

### III.3.5.1 Tractor and agricultural utensils manufacture

An estimation of the energy and the material required to manufacture the proportional fraction of tractors and agricultural utensils used in the agricultural phase was included in the life cycle inventory.

The proportional fraction of machinery or utensils was estimated using the following [33]:

$$AMF = \frac{W \cdot OT}{LT} \qquad \text{(eq. II.1)}$$

Where ''AMF'' is the fraction for the amount of machinery (kg.FU$^{-1}$) used in the field work; ''FU'' is the functional unit selected in this study, ''W'' is the weight of tractors or agricultural utensils (kg); ''OT'' is the operation time for each field operation (h.FU$^{-1}$) and ''LT'' is the life time of the tractors or agricultural utensils (12,000 h for tractors and 800–3000 h for implements) [35,36].

Data on materials, energy use and emissions of the tractors and agricultural implement production process were obtained from the Ecoinvent database [37–39].

The material used in the maintenance and repair of the tractor during its lifetime should also be scored as part of the total value of the fraction of the amount of machinery required [38].

In reference to the maintenance of the tractors and agricultural utensils, specific parameters from the specialized bibliography were used [37–39]. Considering the repair factor, this is defined as the repair cost during life divided by the price of new machinery. In this study, it has been assumed to be 20% for tractors and 54% for agricultural utensils [37].

### III.3.5.2 Fuel Consumption and emissions associated to the use of agricultural machinery and transportation of the biomass

Fuel consumption of each field operation was well documented in the field records of the experimental 160 ha. On the other hand, fuel consumption associated with transport stages has been obtained by quantifying the transport needs in terms of MJ .t$^{-1}$. Km$^{-1}$ by means of the Volvo Truck Model [26] and the density of the different materials transported. See table 5.

Table III.5 Density or weight of the inputs and outputs transported.

| Input or Output transported | Density of the material (kg.m$^{-3}$) |
|---|---|
| Seeds | 278.00 |
| Herbicide | 1.24 |
| Fertilizer | 310.00 |
| Biomass | 100.00-150.00 |
| Containers | 30.00-35.00 |
| Ashes | 80.00 |
| Farmer | 80.00 Kg. |

The equations (2) and (3) [26] were used to calculate the fuel consumption of the different vehicles implied in the transport of the inputs and outputs of the system.

$$Cxt = Co + \frac{[(Cf - Co)]}{Qt} \cdot Qx \qquad \text{(eq. II.2)}$$

Where “Cxt” is the fuel consumption of the vehicle with “Qx” load (L .100 Km$^{-1}$).

“Co” is the fuel consumption of the empty vehicle (L.100 Km$^{-1}$), “Cf” is the fuel consumption of the fully loaded vehicle (L.100 Km$^{-1}$) (see table III.3). “Qt” is the maximum transportable load (kg) and “Qx” is the actual transportable load (kg).

Equation (3) was used to calculate the fuel consumption when the vehicle departs from the facility carrying “Qx” load and returns empty to the same place.

$$Cxta = Co + Cxt \qquad \text{(eq. II.3)}$$

Where “CXTA” is the total fuel consumption. (L.100 Km$^{-1}$).

Emissions from fuel combustion were estimated according to equation (4) and the emission factors proposed by the Swiss Agency for the Environment, Forests and Landscapes and other authors of the Ecoinvent database [40, 41]

$$WG = FC + EF \qquad \text{(eq. II.4)}$$

Where “WG” is the waste gases emitted (g. F.U$^{-1}$), “FC” is fuel consumption of the different vehicles (kg fuel·FU$^{-1}$) and “EF” is the emission factor of each gas (g waste gas. Kg·fuel$^{-1}$).

### III.3.5.3 Production of fertilizers

The fertilizer inventory used takes into account the use of resources for all production stages ranging from extraction of the raw materials to the production of the intermediates and the final product. The ammonium nitrate manufacturing process (the base-case fertilizer) considered is the neutralization of ammonia using nitric acid. The resulting solution is evaporated and then granulated [42]. Data related to the energy use and emissions involved in the production process was obtained from the Ecoinvent database [42].

### III.3.5.4 Production of herbicides

Data related to energy emissions used in the production of pesticides has been obtained from the Ecoinvent Data base [43]. The emissions of herbicide active ingredients into the environment during manufacture were not included in the inventories.

### III.3.5.5 Production of the seed

Production of sowing seed is considered in entirely the same way as in the production of the crop. In order to take into account the burdens produced in the production of these seeds, the field surface required to produce these seeds is added to the surface area used for the crop (0.005 ha). We also added the electrical energy consumption in the processing of the seed.  In this study the electricity consumed was assumed to be 58 kWh · $Mg^{-1}$ seed [44].

### III.3.5.6 Diffuse emissions in the application of fertilizers

Earlier LCA studies have shown the importance of calculating the air emissions, such as ammonia ($NH_3$) and enhanced $NO_x$ and $N_2O$ formation, produced by the addition of nitrogen to agricultural systems in the form of synthetic fertilizer [45, 46, 47].In this study, we decided to calculate diffuse emissions using emission factors proposed by several authors [48, 34].

#### Ammonium volatilization

In this study, an ammonia volatilization factor of 2% for simple nutrient fertilizer (ammonium nitrate) and 4% for multinutrient fertilizer (NPK 8/24/8) were assumed. [34].

#### Nitrous oxide ($N_2O$)

The $N_2O$ emission factor assumed for both fertilizers is 1.25 % of N addition [48]. Note that estimated N loss due to ammonium volatilization is subtracted from the N addition before estimating $N_2O$ emissions with this relation.

#### Oxides of nitrogen (NOx)

The $NO_x$ emissions were calculated as 10% of the $N_2O$ emissions [34].

#### Nutrient leaching

In this study it was assumed that nutrient leaching does not occur because the nitrogen air emissions (see table 10) and the plant's capacity for nitrogen extraction (0.0148 kg.kg-1 o.d.b) [20] exhaust the dose of fertilizer applied per hectare.

### III.3.5.7 Diffuse emissions of herbicides

The diffuse emissions from the application of herbicides to the crop were estimated according to the method proposed by Hauschild [49].

### III.3.5.8 $CO_2$ fixation by Rhizodeposits

Some of the C fixed by growing biomass through the photosynthesis process is translocated to the soil in the form of roots, organic acids and some immobilised forms of C known as rhizodeposits. Rhizodeposits are the part of the underground biomass that does not evolve into $CO_2$ by root respiration and microbial utilization of a rootborne organic substance [50]. In order to quantify this amount of C certain experimental results in cereals were used. These results conclude that, on average, cereals transfer 20-30% of total assimilated C into the soil [50]. Half of this amount is subsequently found in the roots and eventually evolves into $CO_2$. One third is emitted from the soil through root respiration and microbial utilisation of rootborne organic substances. The remaining part of underground translocated C is incorporated into the soil microorganisms and soil organic matter as a net fixation of atmospheric $CO_2$ [50].

This estimate must be considered preliminary. It is only intended to demonstrate the order of magnitude of potential carbon storage by translocation of C from underground biomass to soil.

## *III.3.6 Life cycle impact assessment methodology*

Of all the steps included in the life cycle impact assessment methodology [51], only the classification and characterization stages were carried out (excluding normalization and valorisation in order to avoid subjectivity in the analysis).

In the classification stage, each burden is linked to one or more impact categories, while in the characterization stage the contribution of each burden to each impact category is calculated by multiplying the burdens by a characterisation factor [52]. The classification and characterization method used was CML 2000 [52].

The impact categories analyzed are: Abiotic depletion potential (ADP); Global warming potential (GWP) Ozone layer depletion potential (ODP); Human toxicity potential (HTP); Fresh water aquatic ecotoxicity potential (FWAEP); Marine aquatic ecotoxicity potential (MAEP); Terrestrial ecotoxicity potential (TEP); Photochemical oxidation potential (POP); Acidification potential (AP) and Eutrophication potential (EP).

# III.4 Results and discussion

In the following lines energy and environmental results obtained about *B.carinata* cropping system are presented.

## *III.4.1 Energy analysis of the B. carinata cropping system*

The total energy primary consumption of the *B. carinata* cropping system (agricultural production subsystem and transport subsystem) has been estimated at 10.26 GJ. ha$^{-1}$. Published studies of this same crop carried out in Italy had obtained results that oscillated between 19.27 GJ.ha$^{-1}$ and 23.53 GJ.ha$^{-1}$ depending on the intensity of the cultivation [16]. The energy consumption calculated, despite including all the transportation stages, is lower overall than the cited reference. The main difference between our study and the state of the art literature is the 32% lower fertilizer dose applied to the soil, since it is fitted as the minimum crop requirement.

The primary energy consumed by the agricultural production subsystem was estimated at 76% of the total energy consumption of the complete system (7.79 GJ.ha$^{-1}$) and the energy consumption of the transport subsystem at 24% (2.47 GJ.ha$^{-1}$).

According to the energy conversion factors taken into account in this study, the three energy outputs of the system and the net energy ratios between energy inputs (energy outputs divided by the primary energy consumed in production and transport phases of *B. carinata* biomass within the period of 1 year) are shown in table III.6.

Table III.6Total energy production and net energy ratios.

| Type of energy production | Total Energy Production | Net energy ratios |
|---|---:|---:|
| Direct energy stored in biomass | 83.69 GJ.ha$^{-1}$ | 88 |
| Calorific energy production | 71.11 GJ.ha$^{-1}$ | 86 |
| Electric energy production | 22.60 GJ.ha$^{-1}$ | 55 |

### III.4.1.1 Contribution of life cycle stages of the *B. carinata* cropping system to total energy consumption

The actions with the greatest energy consumption in the system (agricultural subsystem and transport subsystem) are the use of diesel fuel and fertilizer production. The energy consumption of the production, distribution and use of diesel fuel represents 47.2 % (4.84 GJ.ha$^{-1}$) of the total energy used in the *B. carinata* cropping system over one year.

Table III.7 Contribution of life cycle to total energy consumption.

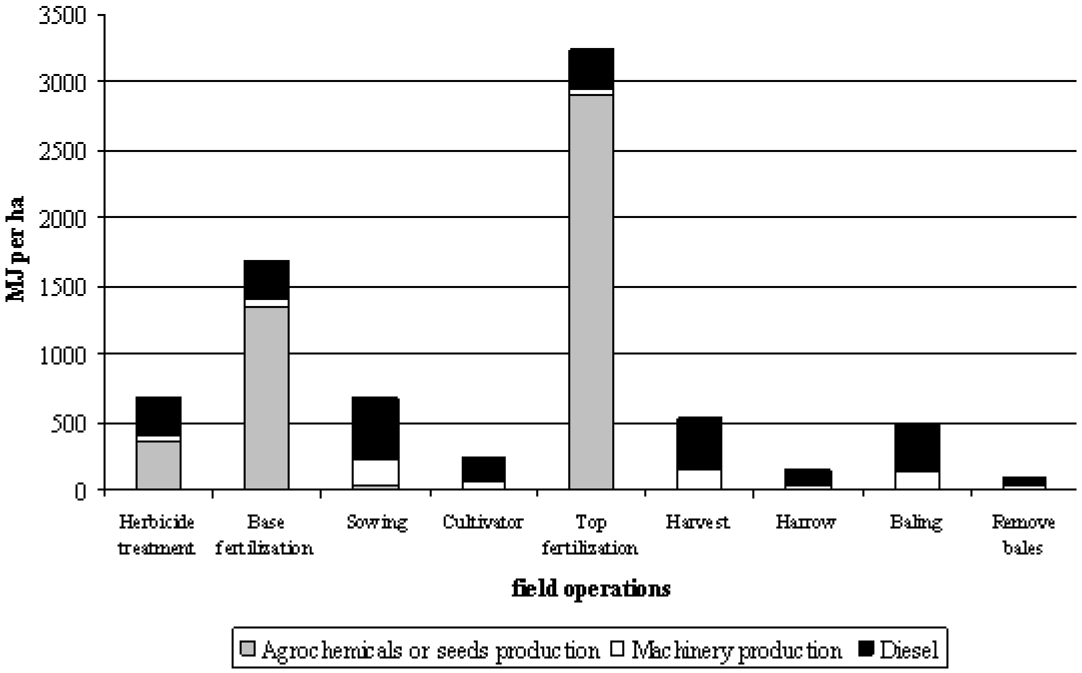
| Analyzed system stages | Primary energy consumption (GJ.ha$^{-1}$) | | | |
|---|---|---|---|---|
| Diesel fuel used in agricultural and transport phases. (Manufacture, distribution and use). | Transport phase: | 47.20% | 24.00% | 2.47 |
| | Agricultural phase | | 76.00% | 2.37 |
| Fertilizer manufacture | Agricultural phase | 41.50% | | 4.25 |
| Herbicide manufacture | | 11.30% | | 0.04 |
| Seed manufacture | | | | 0.35 |
| Tractor manufacture | | | | 0.52 |
| Utensil manufacture | | | | 0.25 |
| TOTAL | | | | 10.25 |

Energy consumption in the fertilizer production supposes 41.5 % (4.25 GJ.ha$^{-1}$) of the energy consumption in the *B. carinata* cropping system and is the production process with the highest energy consumption analyzed in this system. The remaining 11.3 % of the energy consumption is attributed to other production processes such as: seed, herbicide, tractor and agricultural utensils (see table III.7).

### III.4.1.2 Agricultural production subsystem

The most critical energy field operations are both fertilization stages. The realization of these field operations signify a primary energy consumption of 4.92 GJ.ha$^{-1}$ corresponding to 50.4% of the total energy consumption of the subsystem. See figure III.3

Figure III.3 Energy consumption of the each field operation in the agricultural subsystem.



The two field operations with the next highest primary energy consumption are the application of herbicide (0.65 GJ.ha$^{-1}$) and (0.65 GJ.ha$^{-1}$) sowing. These are both field operations that required agricultural inputs such as herbicides or seeds, representing 13.2% of the total primary energy consumption of the agricultural phase. The remaining field operations contribute 15.5% (1.51 GJ.ha$^{-1}$) to total energy consumption

Fertilizer manufacturing itself makes up to 80% (1.35 GJ.ha$^{-1}$) in base fertilization and 89% (2.90 GJ.ha$^{-1}$) in top fertilization operations, while herbicide production constitutes 51% (0.35 GJ.ha$^{-1}$) of the application; herbicide labour and seed manufacture represent only 6% of the sowing labour.

In agricultural field operations in which no agrochemical inputs are required (fertilizers, herbicides), fuel use is the action with the biggest influence on the energy consumption, constituting a range of between 46-58%.

### III.4.1.3 Transport subsystem

The primary energy consumed by the transport of agricultural inputs is 2.47 GJ.ha$^{-1}$. The farmer's transport represents 57% (1.40 GJ.ha$^{-1}$) of the total energy consumption of the transport subsystem and 13.6% of the total primary energy consumption of the system. Biomass transport on a local level supposes 28% (0.69 GJ.ha$^{-1}$) of the energy used in the transport subsystem and 6.7% of the total primary energy consumption of the system. The third largest energy consumption stage occurs during the transport of fertilizers where 0.31 GJ.ha$^{-1}$ is consumed. This consumption represents 12.5% of the non renewable energy used in the transport subsystem and 3% of the total primary energy consumption of the system.

### III.4.1.4 Energy comparison between *B.carinata* cropping and natural gas production and distribution systems

In reference to a natural gas system the total primary energy consumed in the stages of production and distribution as far as a regional Spanish power plant is 15.37 GJ per functional unit of energy. Table III.8 shows the total energy balance of the two fuel production and distribution systems.

Table III.8 Energy balance of two analysed systems.

| | *B.carinata* biomass cropping system | Gas natural Production and distribution system |
|---|---|---|
| Energy inputs (GJ per U.F.) | 10.26 | 15.37 |
| Energy output (GJ per U.F.) | 83.69 | 83.69 |
| Balance (GJ per U.F.) | 73.43 | 68.32 |

The results obtained show that the lower energy input in order to obtain biomass in comparison with natural gas has a positive effect on the energy balance.

In comparison with natural gas, the production and distribution of *B.carinata* biomass consumes 33.2% less per MJ of the energy stored in fuel.

## *III.4.2 Environmental analysis of the B.carinata cropping system*

In this paper we demonstrate the relative magnitudes of various contributors to all impact categories analyzed in an attempt to highlight their respective importance.

The environmental impact of the *B. carinata* biomass production system is shown in table III.9.

Table III.9 Environmental impact of *B.carinata* whole system (agricultural and transport phases).

| Impact Category & Unit | Field Works | Production of agricultural inputs | | | | Diffuse emissions | | Transport | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | Simple fert. | NPK fert. | Seed | Herbicide | From Herbicide | From Fertilizers | | |
| ADP (kg Sb eq.) | 1.31 | 0.61 | 1.24 | 0.06 | 0.13 | | | 1.08 | 4.43 |
| GWP (kg $CO_2$ eq.) | 195.00 | 198.00 | 301.00 | 3.88 | 11.80 | | 186.00 | 172.00 | 1068.00 |
| ODP (mg CFC 11 eq) | 23.80 | 9.27 | 17.80 | 1.03 | 1.79 | | | 21.00 | 73.90 |
| HTP (kg 1,4-DB eq.) | 177.00 | 49.30 | 99.60 | 6.75 | 5.61 | 21.90 | 0.57 | 205.00 | 566.00 |
| FWAE (kg 1,4-DB eq) | 16.20 | 6.98 | 23.20 | 0.82 | 0.81 | 9.52 | | 16.10 | 58.50 |
| MAEP (T 1,4-DB eq) | 3.48 | 25.80 | 99.00 | 4.54 | 6.25 | | | 14.30 | 184.00 |
| TEP (kg 1,4-DB eq) | 0.59 | 0.68 | 1.42 | 0.08 | 0.22 | 0.05 | | 0.09 | 3.13 |
| POP (g $C_2H_4$ eq) | 48.60 | 10.40 | 23.50 | 1.81 | 3.12 | | | 178.00 | 262.00 |
| AP (kg $SO_2$ eq ) | 1.46 | 0.55 | 0.88 | 0.07 | 0.07 | | 2.57 | 0.78 | 6.38 |
| EP (kg $PO_4^{---}$ eq) | 0.39 | 0.11 | 0.24 | 0.04 | 0.003 | | 0.48 | 0.15 | 1.38 |

The results presented in table III.9 reveal that the magnitude of the environmental impacts associated with the biomass agricultural subsystem is bigger than that of those linked to the transport stage, as they represent 72%-97% of the total impact generated in all categories.

### III.4.2.1 Contribution of life cycle stages to total environmental impacts

Manufacturing agricultural inputs (fertilizers, herbicide and seed) are the production processes with highest impact in 4 of the 10 categories analyzed (Global warming potential (GWP), Fresh Water Aquatic

Ecotoxicity Potential (FWAEP), Marine Aquatic Ecotoxicity Potential (MAEP) and Terrestrial Ecotoxicity Potential (TEP)).

In the other impact categories (Human Toxicity Potential (HTP), Abiotic Depletion Potential (ADP), Ozone Layer Depletion Potential (ODP), Photochemical Oxidation Potential (POP), Acidification Potential (AP) and Eutrophication Potential (EP)) the diesel fuel used by tractor and transport vehicles is the main action of impact. In the case of diffuse emissions of fertilizers being added to the impact of fertilizer manufacturing, the use of mineral fertilizer is also the action with the greatest impact in the Acidification Potenital and Eutrophication Potential categories augmenting the impact of diesel fuel's life cycle.

The estimated emissions from the soil after the application of fertilizers and the relative contribution to the total impact of the system are shown in table III.10.

Table III.10 Diffuse emissions, impact and contribution to the total impact of the system.

| Emissions | Emission Estimated | Characterisation Factor | Impact generated | Contribution to total impact of the system |
|---|---|---|---|---|
| Dinitrogen oxides ($N_2O$) | 0.63 $kg.ha^{-1}$ | 296.00 | 186.48 kg $CO_2$ eq .$ha^{-1}$ | 17.30% |
| Ammonium ($NH_3$) | 1.59 $kg.ha^{-1}$ | 0.10 | 0.16 kg 1,4DB eq.$ha^{-1}$ | 0.03% |
|  |  | 1.60 | 2.54 kg $SO_2$eq.$ha^{-1}$ | 39.81% |
|  |  | 0.35 | 0.56 kg $PO_4^{2}$-eq.$ha^{-1}$ | 40.58% |
| Nitrogen oxides $NO_x$ | 0.06 $kg.ha^{-1}$ | 1.20 | 0.07 kg 1,4DB eq.$ha^{-1}$ | 0.01% |
|  |  | 0.50 | 0.03 kg $SO_2$eq.$ha^{-1}$ | 0.47% |
|  |  | 0.13 | 0.01 kg $PO_4^{2}$eq.$ha^{-1}$ | 0.72% |

The results presented in tableIII.9 show that the main potential impacts of the diffuse emissions from application of fertilizers on agricultural soils are in the categories of global warming, acidification and eutrophication.

In reference to the global warming category and $CO_2$ eq. emissions, these resulted in 1,068 kg per cultivated hectare. Taking into account the C fixed in the soil, results decrease to 437 kg per hectare.

### III.4.2.2 Contribution of field operations to the total environmental impact of the *B. carinata* cropping system.

Fertilizations, considering all the inputs and emissions, are the most critical field operations, as they represent a range between 34% and 75% of the all impact categories.

The contribution to the environmental impact of field operations such as: sowing, cultivating, harvesting, raking, baling and removing bales have been estimated at 0.5-8% in the all impact categories.

### III.4.2.3 Comparison of the total environmental impacts between *B. carinata* cropping system and gas natural

The natural gas system has more impact in 6 of the 10 environmental categories analysed.

Specifically in the potential for global warming the *B.carinata* cropping system presents a reduction of 442 kg $CO_2$ eq per functional unit (33.2%) or 1073 kg $CO_2$ eq per functional unit (71.2%) when the crop's capacity for translocating $CO_2$ from underground biomass into the soil is considered. See table III.11

Table III.11Environmental impacts of the production and distribution of biomass and natural gas fuels.

| Impact Category & Unit | *B. carinata* cropping system | Gas natural |
|---|---:|---:|
| A.D.P. (kg Sb eq.) | 4.43 | 52.90 |
| G.W.P. (kg $CO_2$ eq.) | 1068.00 | 1510.00 |
| O.D.P. (mg CFC 11 eq.) | 73.90 | 108.00 |
| H.T.P. (kg 1,4-DB eq.) | 566.00 | 517.00 |
| F.W.A.E.P. (kg 1,4-DB eq.) | 58.50 | 164.00 |
| M.A.E.P. (T 1,4-DB eq.) | 184.00 | 607.00 |
| T.E.P. (kg 1,4-DB eq.) | 3.13 | 1.58 |
| P.O.P. (g $C_2H_4$ eq.) | 262.00 | 555.00 |
| A.P. (kg $SO_2$ eq.) | 6.38 | 2.20 |
| E.P. (kg $PO_4^{---}$ eq.) | 1.38 | 0.29 |

However, the environmental categories of Human Toxicity Potential, Terrestrial Ecotoxicity Potential, Acidification Potential and Eutrophication Potential present greater impact in the *B.carinata* cropping system.

In the case of the Human Toxicity Potential category, the impact is higher due to the combustion diesel used in agricultural tractors and transport vehicles. Terrestrial Ecotoxicity Potential has more impact due to the fertilizer production process. Finally, in the Acidification Potential and Eutrophication Potential categories, the *B.carinata* cropping system has poorer environmental performance mainly due to the diffuse emissions from the application of fertilizers to the agricultural field.

## III.5 Conclusions

The main conclusion of this study is that the implementation of *B. carinata* crop systems is viable in order to produce lignocellulosic biomass destined for the production of power and heat in the southern European region. Furthermore the performance of the crop could be improved by increasing the energy and environmental benefits.

According to our calculations, the *B. carinata* system cultivated in southern Europe is energetically efficient. In order to store 1 MJ of renewable energy in biomass, in the form of solid fuel, a total of 0.12 MJ of primary energy are required. Furthermore it has a better energy balance than the natural gas system which consumes 0.18 MJ per 1 MJ stored in the natural gas fuel.

Nevertheless, the energetic efficiency of the *B.carinata* cropping system is altered, including energy conversion factors, depending on the final type of energy obtained. In other words, heat generation from *B.carinata* biomass appears to be more efficient in terms of primary energy consumption (0.14 MJ per MJ of heat generated) than electricity generation (requiring 0.45 MJ per MJ of electricity generated).

In reference to the environmental performance of the *B. carinata* cropping system, the greatest environmental impacts are associated with the use of fertilizers, considering their manufacturing stage and diffuse emissions, representing 51-68% in the following categories: Global Warming Potential, Fresh Water Aquatic Ecotoxicity Potential, Marine Aquatic Ecotoxicity Potential, Terrestrial Ecotoxicity Potential, Acidification Potential and Eutrophication Potential.

The use of diesel fuel by tractors and transport vehicles also significantly affects the system's environmental behaviour, as it represents between 48-77% of the impact in the categories of Human Toxicity Potential, Abiotic Depletion Potential, Ozone Layer Depletion Potenital and Photochemical Oxidation Potential.

In comparison with the natural gas system, the *B.carinata* cropping system has a better environmental performance in six of the ten categories and presents more environmental impact in Human Toxicity Potential, Terrestrial Ecotoxicity Potential, Acidification Potential and Eutrophication Potential.

The results obtained from the comparison indicate that the *B.carinata* biomass system has a high potential for becoming more environment friendly than non-renewable fuels in all analysed categories after some improvements have been carried out.

With that in mind, one of the main objectives in the establishment of energetic crops in the EU is the fulfilment of commitments to the reduction of greenhouse gases [1,5], the stages included inside the system's boundaries and the capacity for $CO_2$ fixation in agricultural soil are the key points that should be analysed in more depth. According to the B.carinata cropping system, the net greenhouse gas emissions are 12.7 g $CO_2$ eq. $MJ^{-1}$ biomass produced, considering that the $CO_2$ emitted during biomass combustion is balanced by the amount adsorbed in the growing of biomass. If the preliminary estimation of $CO_2$ fixation in the soil (631 kg CO2.$ha^{-1}$) is considered, the net greenhouse gas emission decreases to 5.2 g $CO_2$ eq. $MJ^{-1}$. The net greenhouse gas emissions avoided in comparison with the natural gas system are 5.34 g CO2 eq $MJ^{-1}$ fuel produced or 13.20 g $CO_2$ eq $MJ^{-1}$ fuel produced in the case that is considered the preliminary estimation of $CO_2$ fixation in the soil. These results confirm the suitable use of the biomass as a substitute for the non-renewable fuels in terms of commitments to greenhouse gas reduction.

Based on the results obtained, the environmental and energy performance of the system could be improved by changing the mineral fertilisers used to alternative ones from agriculture, agribusiness, livestock wastes, etc [45].

Unlike other biomass production systems, such as, for example, forestry biomass production [52], the transport stage in a biomass energetic crop system carries a major energetic burden (2.47 GJ.$ha^{-1}$). The system’s high input requirements lead to the implication of various actors (agrochemical manufacturers, farmers, power generation plants and residue treatment plants), therefore having an elevated need for transport. So, strategic planning, as a key factor in the environmental and energetic performance of the system, is required, taking into account the location of the crop and the distances between the different actors, in order to guarantee low levels of environmental impact and energetic consumption during the transport stage.

Due to the simplifications made during the study, a more detailed and accurate analysis of the capacity of $CO_2$ fixation in agricultural soil is suggested as a priority for future studies.

## III.6 References to chapter III

[1] European Commission. Energy for the future-renewable sources of energy. White paper for a Community Strategy and Action Plan. COM (97)599, Brussels, 1997.

[2] European Commission. Towards a European strategy for the security of energy supply. Green Paper. : Office for Official Publications of the European Communities, 2000.

[3] Sebastián F, Cebollada M. P, Izquierdo I. Atlas de Biomasa para Usos Energéticos de Aragón". Diputación General de Aragón and CIRCE. Aragon. Spain, 1997. 66-73. (In Spanish).

[4] Venendaal R, Jorgensen U, Fosters C.A. European energy crops: a synthesis. Biomass & Bioenergy 13 (3) (1997) 147-185.

[5] Instituto para la Diversificación y Ahorro de la Energía (IDAE). Plan de Fomento de las energías renovables en España. Ministerio de Industria, Turismo y Comercio. Madrid, Spain 1999.

[6] European Comisión. Biomasa action plan. COM (2005)628.2005, Brussels, 2005.

[7] Hall D.O and Scrase J.I. Will Biomass be the environmentally friendly fuel of the future? Biomass & Bioenergy 15 (4/5) (1998) 357-367.

[8] Hanegraaf M. C, Biewinga Edo E and Van der Bijl G. Assessing the ecological and economic sustainability of energy crops. Biomass & Bioenergy 15 (4/5) (1998) 345-355.

[9] Gagnon L, Bélanger C, Uchiyama Y. Life-cycle assessment of electricity generation options: The status of research in year 2001. Energy policy 30 (2002) 1267-1278.

[10] Börjesson P and Gustavsson L. Regional production and utilization of biomass in Sweden. Energy 21(9) (1996) 747-764.

[11] Börjesson P. Energy Analysis of biomass production and transportation. Biomass & Bioenergy 11(4) (1996) 305-318.

[12] Börjesson P, Gustavsson L, Christersson L. and Linder S. Future Production and utilisation of Biomass in Sweden: Potentials and CO2 mitigation. Biomass & Bioenergy 13(6) (1997) 399-412.

[13] Hall DO. Biomass energy in industrialised countries- a view of the future. Forest Ecology and Management 91 (1997)17-45.

[14] Van den Broek R, Van Wijk Ad and Turkenburg W. Electricity from energy crops in different settings – a country comparison between Nicaragua, Ireland and the Netherlands. Biomass & Bioenergy 22 (2002) 79-98.

[15] Instituto para la Diversificación y Ahorro de la Energía. (IDEA). Plan de Energías Renovables en España, 2005-2010; Ministerio de Industria, Turismo y Comercio. Madrid , Spain 2005.

[16] Cardone M, Mazzoncini M, Menini S, Rocco V, Senatore A, Seggiani M and Vitolo S. Brassica carinata as an alternative oil crop for the production of biodiesel in Italy. Agronomic evaluation, fuel production by transesterification and characterization. Biomass & Bioenergy 25 (2003) 623-636.

[17] Bouaid A, Diaz Y, Martinez M, Aracil J. Pilot plant studies of biodiesel production using Brassica carinata as raw material. Catalysis Today 106 (2005) 193-196.

[18] *Brassica carinata* the outset of a new crop for biomass and industrial non-food oil, FAIR CT96 1946 European Project Final Report.

[19] Instituto parala Diversificación y Ahorro de la Energía (IDAE).Eficiencia Energética y Energías Renovables. Boletín IDAE: Eficiencia Energética y Energías Renovables (Nº 7).Madrid, Spain 2005. Available from: http://www.idae.es/index.asp?i=es

[20] Ciria P, Fernández M, González E, Solano M.L and Carrasco J.E. "Study of the effect of the viability in energy and chemical characteristics of *Brassica carinata* biomass on the behaviour of this biomass as a solid fuel. In: Van Swaaij W.P.M, Fjällström T, Helm P and Grassi A, (Eds). Proceedings of the conference BIOMASS FOR ENERGY, INDUSTRY AND CLIMATE PROTECTION. Florence, Italy 2004.

[21] Boustead I, Hancock G.F. Handbook of Industrial Energy Analysis. In: Frischknecht R, Jungbluth N (Eds). Implementation of life cycle assessment methods, Ecoinvent report No. 3 p. 22-28. Swiss Centre for Life Cycle Inventories. Dübendorf: Switzerland 2003.

[22] Pimentel D. Food Production and the Energy Crisis. In: Frischknecht R, Jungbluth N (Eds). Implementation of life cycle assessment methods, Ecoinvent report No. 3. p. 22-28 Swiss Centre for Life Cycle Inventories Dübendorf: Switzerland 2003.

[23] Frischknecht R, Jungbluth N, Althaus H.-J., Doka G, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G and Spielmann M. Overview and Methodology. Ecoinvent report No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf: Switzerland 2004.

[24] Asociación Española de Normalización y Certificación (AENOR). Environmental management. Life cycle assessment. Principles and framework (ISO 14040:1997). Spain 1998.

[25] FERTIBERIA. Enterprise leader of the sector of agrichemicals in Spain, 2005. Available from: http://www.fertiberia.com

[26] Volvo Truck Corporation. Emission from Volvo's Truck Emissions, standard diesel fuel, 2003.
Available from: www.volvo.com.pe/NR/rdonlyres/EF65E6D8-BF98-4BBF-B539-18C925B53844/0/Emis_eng_20640_03017.pdf

[27] Arnó and Masip. Cost horari de la maquinaria forestal. 1er Quaderns d'informació tècnica. Volume 7. Àrea d'Infraestructures, Urbanismo i Habitatge. Oficina Técnica de Prevenció Municipal d'Incendis Forestals. Diputació de Barcelona, Xarxa de Municipis; Barcelona, Spain 2003.

[28] Schweimer G W, Bambl T, Wolfram H. Inventario del ciclo de vida del SEAT ibiza.
Publicaciones de Investigación, Medio Ambiente y Tráfico (Z00.519.504.60). Volkswagen. Madrid, Spain 2003.

[29] Ministerio de Fomento. Observatorio del transporte de mercancías del transporte por carreteras.nº4, Ministerio de Fomento. Madrid, Spain 2003. Available from: http://www.fomento.es/MFOM/LANG_CASTELLANO/DIRECCIONES_GENERALES/TRANSPORTE_POR_CARRETERA/SERVICIOS_TRANSPORTISTA/OBSERVATORIO_COSTES/OBSERVATORIO_MERCADO/omercado4-pdf.htm.

[30] Castro M.B.G, Remmerswaal J.A.M. , Reuter M.A. Life Cycle Impact Assessment of the average passenger vehicle in the Netherlands. The International Journal of Life Cycle Assessment 5 (2003) 294-303.

[31] Faist E. M., Heck T. and Jungbluth N. Erdgas. In: Dones, R. (Ed.). Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die, Schweiz. Final report ecoinvent 2000 No. 6-V, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland 2000. Available from: www.ecoinvent.ch.

[32] Frischknecht R, Jungbluth (Eds). Ecoinvent project. . Swiss Centre for Life Cycle Inentories. Dübendorf , Switzerland 2004. Available from http://www.ecoinvent.ch/

[33] Nemecek T, Heil A, Huguenin O, Meier S, Erzinger S, Blaser S, Dux. D and Zimmermann A. Life Cycle Inventories of Agricultural Production Systems. Final re-port ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories. Dübendorf, Switzerland 2004. Retrieved from: www.ecoinvent.ch.

[34] Audsley E. Harmonisation of environmental life cycle assessment. Final Report Concerted action AIR3-CT94-2028, European Commission DG VI Agriculture, 1997.

[35] Márquez L. Maquinaria para la preparación del suelo, la implantación de los cultivos y la fertilización VIII. Blake & Helsey. Madrid, Spain 2001.

[36] Márquez -Delgado L. Maquinaria agrícola: preparación primaria, trabajo del suelo, siembra, plantación y trasplante. Blake and Helsey. Madrid, Spain 2004.

[37] Amman H. “Maschinenkosten 2000 – Kostenansatze Gebaudeteile und mechantsche Einrichtungen. In: Nemecek T, coord. Life cycle inventories of agricultural production system, p. 45-51. Dübendorf, Switzerland 2003.

[38] Frischknecht R, Bollens U, Bosshart S, Ciot M, Ciseri L, Doka G., Dones, R. Gantner U, Hirschier R. and Martin A. Ökoinventare von Energiesystemen. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. In: Nemecek T, coord. Life cycle inventories of agricultural production system, p. 45-51. Dübendorf, Switzerland 2003.

[39] Maibach M, Peter D and Seiler B. Ökoinventar Transporte. Grundlagen für den ökologischen Vergleich von Transportsystemen und für den Einbezug von Transportsystemen in Ökobilanzen. In:

Nemecek T, coord. Life cycle inventories of agricultural production system, p. 45-51. Dübendorf, Switzerland 2003.

[40] SAEFL. Handbuch Offroad-Datenbank. In: Nemecek T, coord. Life cycle inventories of agricultural production system, p. 56-59. Dübendorf; Switzerland 2003.

[41] Rinaldi M. and Stalder E. "Trends im Abgasverhalten landwirtschaftlicher Traktoren - Neue Modelle deutlich sauberer." In: Nemecek T, coord. Life cycle inventories of agricultural production system, p. 56-59. Dübendorf, Switzerland 2003.

[42] Davis J and Haglund, C. Life cycle inventori (LCI) of Fertilizer Production-fertilizer products used in Sweden and Western Europe. In: Nemecek T, coord. Life cycle inventories of agricultural production system, p. 64-86. Dübendorf, Switzerland 2003.

[43] Green MB. Energy in pesticide manufacture, distribution and use. In Nemecek T, coord. Life cycle inventories of agricultural production system, p. 93-99. Dübendorf, Switzerland 2003.

[44] Narain M. & Singh B.P.N. Energy profile of a seed-processing plant. Applied Energy; 30 (1998) 227-234.

[45] Brentrup F, Küsters J, Kuhlmann, H and Lammel J. Environmental impact assessment of agricultural production systems using life cycle assessment (LCA) methodology. II. The application to N fertilizer use in winter wheat production systems. European Journal of Agronomy 20 (2004) 265-279.

[46] Heller MC, Keloeian GA, Volk T.A. Life cycle assessment of a willow bioenergy cropping system. Biomass & Bioenergy 25 (2003) 147-165.

[47] Brentrup F, Küsters J, Kuhlmann, H and Lammel J. Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilizers. European Journal of Agronomy 14 (2001) 221-233.

[48] Bentrup F, Küsters, J. Methods to estimate to potential N emissions related to crop production. In: Weidema B. and Meeusen M. (Eds). Agricultural data for life cycle assessments 1:133-151, Agricultural Economics Research Institute. The Hague, The Netherlands 2000.

[49] Hauschild M. Estimating pesticide emissions for LCA of agricultural products. In Weidema B. and Meeusen M. (Eds.): Agricultural data for life cycle assessments pp. 64-79. Chapter 22, Volume 2. LCANet Food. The Hague, The Netherlands 2000.

[50] Kuzyakov Y. and Domanski G. Carbon input by plants into the soil. Review; 2000.Institute of Soil Science and Land Evaluation, University of Hohenheim Germany and Institute of Agrophysics, Lublin. Poland 2000.

[51] Asociación Española de Normalización y Certificación (AENOR). Environmental management. Life cycle assessment. Life cycle impact assessment.(ISO 14042:2000). Madrid, Spain 2001.

[52] Guinèe J.B. (Final Ed). Life cycle assessment; An operational guide to the ISO standars; Part 1 and 2. Ministry of Housing. Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML). Den Haag and Leiden, The Netherlands; 2001.

[53] Forsberg G. Biomass energy transport. Analysis of bioenergy chains using life cycle inventory method. Biomass & Bioenergy 19 (2000) 17-30.

# Chapter IV. Life Cycle Assessment of *Populus spp.* bioenergy system compared with *Brassica carinata* energy crop and natural gas in local scenario.

*Published as: Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P. & Rieradevall J. LCA of poplar bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario. Biomass & Bioenergy 33 (2009) 119-129.*

*Photografy by Carles Martinez Gasol. Soria (Castilla León), 2005.*

# Abstract

The *Populus spp.* bioenergy system has been analysed applying Life Cycle Assessment (LCA) to compare its environmental performance to: *B. carinata* bioenergy system and natural gas. The life cycle impact assessment (LCIA) shows that the use of fertilizers is the highest impact in 4 of the 10 environmental categories analysed, representing between 39 and 67% of the impact in them. The diesel used in transport vehicles and agricultural tractors also has a significant impact in another 5 of the 10 analysed categories 40-85%. The *Populus spp.* bioenergy system contributes to Global Warming category with 1.90-1.98 g. $CO_2$ eq. $MJ^{-1}$ biomass produced.

The production and transport as far as the thermoelectric plant of the *Populus spp.* biomass consumes 0.02 MJ of primary energy per 1 MJ of stored energy in biomass. In comparison with *B. carinata* and natural gas, it reduces primary energy consumption by 83 % and 89% and the greenhouse gas emission by 84% and 89%, respectively. The results of the analysis support that the *Populus spp.* bioenergy system is viable from an energy balance and environmental perspective for producing energy in southern Europe, as long as it is cultivated in areas where water is available. This latter point and the better environmental performance of both crops in comparison to natural gas allows us to affirm that the combination of several crops adapted to the different local agro-climatic conditions of the territory will be the most suitable strategy in Mediterranean areas that wish to reach the global energy production targets in terms of biomass established by the European Union (EU).

*Keywords: life cycle assessment; Populus spp.; Brassica carinata; Natural Gas; Energy Analysis; Environmental Analysis.*

## IV.1 Introduction

The replacement of fossil fuels with biomass in the generation of energy is an important strategy promoted by the European Union (UE) to mitigate the effects of climatic change and enhance the security of the supply and diversification of energy sources [1]. For this purpose bioenergy is being promoted through several EU Directives, as well as national policies [2, 3]. Biomass-based electricity is being promoted by the Renewable Electricity Directive, which aims to increase the use of renewable energy sources (RES) to 20% by 2010 [2, 3] Biomass, and in particular energy crops, have attracted attention as a promising, renewable and local energy source [4-6] which could help the European Union reduce its dependency on external energy sources, i.e., the main oil-exporting and gas-exporting countries. Spain is a significant example of energy-dependent European country as around 75% of its total energy demand is imported [7]. Due to the expectancy that this aroused and the fact that most 55 st EU governments recognized that an increase in the use of energy crops should be accompanied by detailed analysis [4, 5, 8], several studies were made that focused on the energy and environmental performance of biomass energy crops [9-13]. North-western and central European countries put the most effort into the research and use of several biomass sources, mainly forest residue biomass, energy crops and biomass wastes destined for electricity and heat generation in recent decades, while in southern Europe the introduction of biomass, and specifically energy crops, is proving slower and more difficult [5, 8, 9, 14]. For example, only in Spain, it is foreseen that by 2010 one million hectares will destined for the production of 3.35 Mtep by energy crops, but the fact is that the current energy produced by energy crops is inexistent [5]. The state of the art of energy production by biomass from energy crops in southern European countries justifies the study of energy crops destined for producing biomass as a local RES in order to reduce the dependency on external sources and the environmental impacts produced by the current mix of forms of energy production in the several southern European countries.

The study has selected *Populus spp.* as a realistic case study of the implementation of energy crops in southern European countries. *Populus spp.* commonly known as poplar is one of the most widely considered forest species of energy crop in North-western and central Europe [15,16]. In different areas all over southern Europe the *Populus spp.* is important in traditional wood use; in 2002 in Spain alone, 2,482 hectares were cultivated for this purpose [17]. The fact that *Populus spp.* is not an unknown crop could facilitate its growth for energy application in high density and short rotation conditions [16]. The advantages of the agricultural production of *Populus spp.* as a short rotation energy crop include the fact that it is a crop with a known tradition in the area analysed [17], high yields, high ecological interest in terms of biodiversity and low fertilizer doses required and comparatively low biomass production costs[11, 16, 18-20]. On the other hand, the disadvantages of the *Populus spp.* crop include the high requirement for water, which restricts the natural distribution of the *Populus spp.* [21]. The amount of water applied during irrigation of these crops in southern Europe should be low or eliminated, especially in an area where water is a limited resource. However, the *Populus spp.* could be an alternative energy crop worthy of consideration by the agricultural sector from an economic point of view and in terms of its compatibility with other crops [16].

In this chapter, we study the environmental and energy behaviour of cultivation *Populus spp*. for producing lignocelluloses biomass destined for the generation of heat and electricity in southern Europe using current agricultural techniques. Furthermore, this bioenergy system is compared with other renewable energy sources such as the *B. carinata* energy crop commonly known as Ethiopian mustard that could be a realistic option for implementation in Spain [6] and also with an equivalent quantity of a non-renewable fuel such as natural gas in order to present the advantages and barriers of the production of biomass by means of the cultivation of *Populus spp.*.

## IV.2 Methodology

To evaluate the environmental and energetic performance of the production and distribution of *Populus spp.* as far as a plant, a hectare of experimental plot cultivated in Soria (northern Spain) is analysed using life cycle assessment methodology. This environmental tool follows ISO14040 guidelines [22, 23], according to which, LCA is divided into four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, (4) interpretation. The environmental analyses were developed using SimaPro 7.1 software by PréConsultants.

### *IV.2.1 Experimental parcel location*

The plot is situated at 41º36’ N and 2º30’W (Greenwich meridian) at an altitude of 1,000 m above sea level. The mean annual temperature is 10.50ºC and the mean annual rainfall is about 500 mm (250 mm April-September). The texture of the soil is sandy loam: sand 70-85%, slime less than 10% and clay less than 15%. Oxidable organic matter was about 1% and pH about 6. This soil is light, with good drainage [16].

The experimental *Populus spp*. plantation was established at a density of 10,000 plants.ha$^{-1}$ during three consecutive cycles (three cuts) of 5 years each, the plants were severed at the ground line [24].

### *IV.2.2 Biomass productivity, composition and low heating values*

Regarding to the use of the produced biomass as a solid fuel, table IV.1 shows the most outstanding average analytical results of *Populus spp.* biomass on short rotation coppices, and the energy characterisation of the two fuels (*B. carinata* biomass and natural gas) is also compared.

The weight of the aerial biomass, the height and diameter of the dominant stem, and the number of branches and shoots per plant were determined. According to these parameters and the fact that biomass production is irregular for the 16 years of the crop, the average biomass production assumed for this study is 13.50 Mg d.b. · ha$^{-1}$ · year$^{-1}$ and a total biomass production of 216 Mg d.b. · ha$^{-1}$ [24]. The chemical composition is used to obtain data that could enable to us evaluate the nutrients removed by cropping and to estimate fertilizer emissions produced for this application on the field [24].

Table IV.1 Chemical and energy characterisation of *Populus spp.* biomass and energy characterisation of two reference systems. *B. carinata* and Natural gas.

| Chemical composition of *Populus spp.* biomass | | | | |
|---|---|---|---|---|
| C | H | N | S | O |
| (% d.b.) | (% d.b.) | (% d.b.) | (% d.b.) | (% d.b.) |
| 50.29 | 6.12 | 0.42 | 0.03 | 41.52 |
| LHV (MJ.kg$^{-1}$) | | | | |
| *Populus spp.* | *Brassica carinata* | Natural gas | | |
| 18.20 | 17.73 | 45.40 | | |

Soruce: [22]

The low heating value (LHV) of the three fuels has been used to obtain the different energy outputs of the production of the three energy systems. In addition to that, power plants energy conversion factors have been taken into account in this study (0.85 for calorific energy production, 0.27 for electric energy production) to calculate all energy outputs for the *Populus spp.* bioenergy sytem.

## IV.2.3 Life cycle inventory and Life Cycle Assessment methodology

The life cycle inventory stage has been carried out following the same methodology as in this research group's previously published [6] studies in the area of the environmental assessment of the production of energy crops, see chapter III, adding one specific aspect of the *Populus spp.* energy crop.

Of the all steps included in the impact assessment phase [22, 23, 25], only classification and characterisation stages were performed (excluding normalisation and valorisation) to avoid subjectivity and obtain the same mid-point categories as in previous studies.

### IV.2.3.1 Specific aspect considered in Life Cycle Inventory of the *Populus spp*. bioenergy system

The specific aspect considered is the water consumption in the irrigation of the *Populus spp.* crop.

#### IV.2.3.1.1 Water consumption by irrigation

The last aspect added to the *Populus spp.* inventory data is the water consumed during the entire life cycle of *Populus spp.* biomass production over sixteen years. The *Populus spp.* cultivation is irrigated with water in order to obtain the aforementioned level of biomass production (216 Mg d.b. · ha$^{-1}$). The water flow applied to the crop was estimated using a water metre [24].

# IV.3 LCA of *Populus spp.* bioenergy system

In the following lines LCA applied to *Populus spp.* bioenergy system is presented.

## *IV.3.1 Goal and Scope definition*

The main aim of the study is to determine the benefits and barriers of *Populus spp.* cultivation in a Continental-Mediterranean area (Spain) destined for the production and distribution of solid biomass fuel as far as the thermoelectric plant. Additionally, the study had two significant and specific goals; the hotspots of the agricultural and transport phases of the system were identified and measures were suggested for environmental improvement. The second specific goal was to compare the *Populus spp.* bioenergy system with other energy crop systems, *B. carinata* and non-renewable fuels such as natural gas.

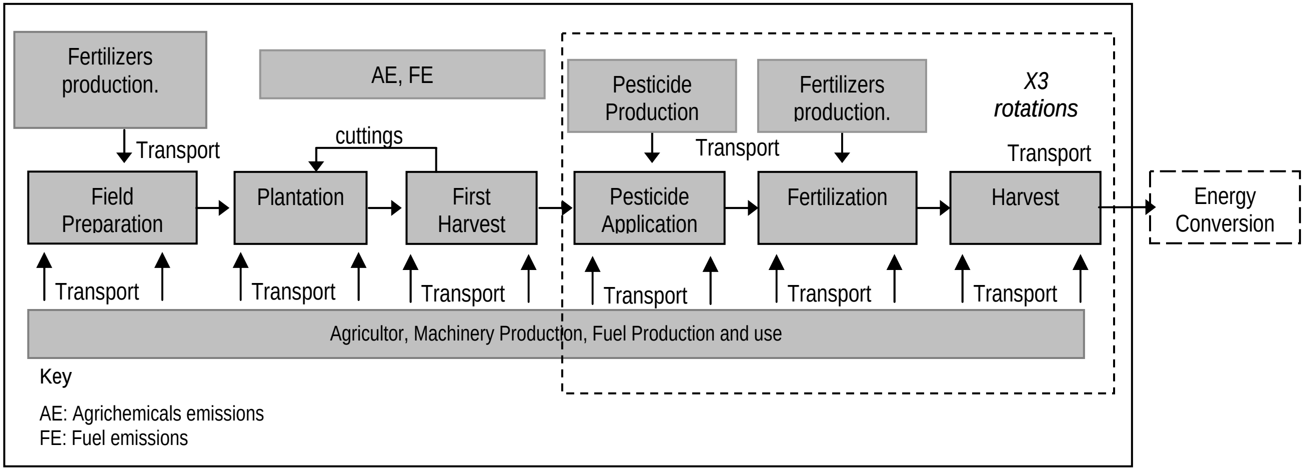
## *IV.3.2 Functional unit*

In this study, the function of the agricultural system is to cultivate 1 hectare of *Populus spp*. destined to produce biomass throughout the entire production cycle. Moreover, 3.93 TJ was used as an energy reference value for purposes of comparison with *B. carinata* bioenergy and the natural system. The total primary energy stored in the *Populus spp.* bioenergy system produced in 16 years is 3.93 TJ.ha$^{-1}$. Considering the average energy production of *B. carinata* per hectare to be 83.69 GJ.ha$^{-1}$.year$^{-1}$)[6], the *Populus spp.* bioenergy system produces 2.94 times more per hectare per year and 46.97 *B. carinata* hectares cultivated over an undefined period would be required to produce the same total quantity of energy. In order to compare the energy balance and environmental impacts of the two bioenergy systems, *B. carinata* inputs and outputs were multiplied by 46.97.

## *IV.3.3 System description*

The analysed energy crop system includes the agricultural production subsystem and transport subsystem as far as the thermoelectric plant. In figure IV.1, a representation of the agricultural activities included in the agricultural subsystem is shown.

Figure IV.1 Scheme of the *Populus spp.* cropping system boundary.



The crop base-cases scenario assumes three 5-year rotations and includes 1 year of site preparation, coppicing after the first year of growth, and the removal of *Populus spp* stools at the end of the rotation avoiding rhizodeposits formation. The LCA model allocates resource demands and associated emissions for all operations shown in Table IV.2 evenly across the total biomass harvested over a 16-year timeline.

Table IV.2 Field operations data for *Populus spp.* base cases scenarios.

| Operation | | | Tractor (A) | Implement (B) | | | A+B | Inputs rates |
|---|---|---|---|---|---|---|---|---|
| | | Time (Year) | Weight & Power | | Weight (kg.) | Operating rate (h.ha$^{-1}$.yr$^{-1}$) | Fuel diesel consumption (l.ha$^{-1}$.yr$^{-1}$) | |
| Field Preparation (*first year*) | Mow existing vegetation | 1 | 7,650 kg. 110 kW | 1.2 brushhog | 1,590 | 0.58 | 20.00 | - |
| | | 1 | 5,800 kg. 66 kW | | 980 | 2.33 | 27.00 | - |
| | Base Fertilization | 1 | 5,800 kg. 130 kW | Spreader | 300 | 0.50 | 5.00 | 600 kg.ha$^{-1}$ (9N/18P/27K) |
| | Cultivator | 1 | 5,800 kg. 130 kW | Rototille | 300 | 0.20 | 10.00 | - |
| | Herbicide treatment | 1 | 8000 kg. 130 kW | Boom sprayer | 410 | 0.22 | 6.00 | 4 l .ha$^{-1}$ Giphosate |
| | Plantation | 1 | 6,300 kg. 104 kW | Planter | 700 | 0.84 | 18.00 | 10.000 Stools . ha$^{-1}$ |
| | Harvest (nails) | 1 | 5,800 kg. 70 kW | Rake | 1,000 | 0.21 | 30.00 | - |
| *First Cycle ( 2-6 years )* | Top Fertilization | 3 | 5,800 kg. 66 kw | Spreader | 1,000 | 0.22 | 3.00 | 250 kg.ha$^{-1}$ (33.50% N) |
| | Insecticide Treatment | 4 | 5,800 kg. 66 kw | Boom sprayer | 720 | 0.17 | 6.00 | 0,5 l .ha$^{-1}$ metil pirimidos |
| | Harvest (scenario 1) | 6 | 9,800 kg 126 kw | - | - | 2.00 | 30.00 | - |
| | Collection (scenario 1) | 6 | 5,800 kg 66 kw | Trailer | 3,200 | 0.50 | 5.00 | - |
| | Harvest (scenario 2) | 6 | 9,400 kg 230 kw | - | - | - | 40.00 | - |
| *Second Cycle ( 7-11 years )*<br>*Third Cycle (12-16 years)* | Base Fertilization | 7 and 12 | 5,800 kg. 130 kW | Spreader | 300 | 0.40 | 5.00 | 600 kg.ha$^{-1}$ (9N/18P/27K) |
| | Fungi[1] or insecticide[2] Treatment | 8 and 13 | 5,800 kg. 66 kw | Boom sprayer | 720 | 0.40 | 6.00 | 0,5 l .ha$^{-1}$ 70% propineb[1]<br>0,5 l .ha$^{-1}$ metil [2]pirimidos |
| | Top Fertilization | 9 and 14 | 5,800 kg. 66 kw | Spreader | 1,000 | 0.22 | 3.00 | 250 kg.ha$^{-1}$ (33.50% N) |
| | Harvest (scenario 1) | 11and 16 | 9,800 kg 126 kw | - | - | 2.00 | 30.00 | - |
| | Collection (scenario 1) | 11and 16 | 5,800 kg 66 kw | Trailer | 3,200 | 0.50 | 5.00 | - |
| | Harvest (scenario 2) | 11and 16 | 9,400 kg 230 kw | - | - | - | 40.00 | - |
| *Field recovery* | Stool killdown | 17 | 7,650 kg 110 kw | - | - | 6.30 | 49.20 | - |
| | Stool Collection | 17 | 5,800 kg 66 kw | - | - | 2.2 | 8.20 | - |

Source: [22]

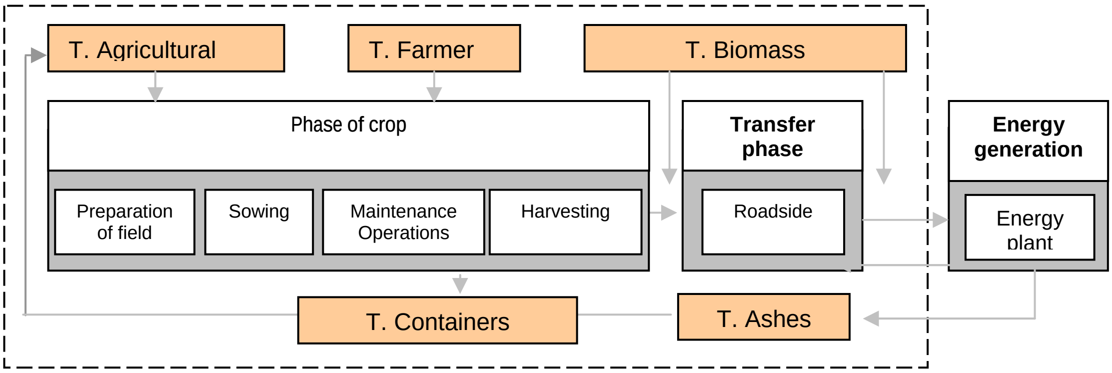
In others words, even though there is more field activity during the first rotation due to site preparation and planting, these burdens are shared equally by biomass being harvested in all three rotations. Apart from all the farm work in the field, the production processes of the different agricultural inputs and outputs are also presented, such as: Fuel, Pesticides, NPK fertilizer (9/18/27), Simple fertilizer (ammonium nitrate 33%), Tractor, Agricultural utensils, likewise the Emissions from the application of agrichemicals.

The system also includes the transport of both inputs and outputs. As inputs: farmer, fertilizers with their corresponding containers and herbicides are considered; while outputs are: residues (containers), ashes and biomass such as packet of stems (cuttings) and chips (figure IV.2).

Farmer transport includes all the journeys needed to accomplish the required work as well as to supervise the crop. An average of eight journeys per year has been considered. The stages included within the boundary transport subsystem are: fuel extraction, processing fuel, fuel transport to commercial point and vehicle engine combustion.

The transport subsystem does not include the manufacture of vehicles, and the impacts of this are considered despicable, adding up to 5% [26] to the total impact generated during their life cycle. The impacts related to roads are also excluded as these are not explicitly built for the transport of inputs and outputs of the analysed system.

Figure IV.2 Transport stages implied in the studied crop.



### IV.3.3.1 Scenarios

For the *Populus spp.* bioenergy system, two determinate scenarios were assumed for the use of the two harvests in the biomass collection field work. In the first scenario the biomass is collected and transported as a packet of stems and in the second in chips.

The suggested transport scenarios are based on a regional/local national scale (25km) and consider the same specific vehicle characteristics, distances and several transport stages as in the published LCA study of a *B. carinata* bioenergy cropping system in southern Europe [6], see chapter III. This assumption allows us to compare both energy crops perfectly.

### IV.3.4 Reference Systems: Brassica carinata bioenergy system and Natural Gas

The results of the environmental and energy performance of one cultivated hectare with *B. carinata* crop and its consequent transport stages and the natural gas system (extraction and distribution) were extracted from the previous published study [6]. In both systems, the energy conversion stage was excluded due to its similitude to bioenergy systems.

The distribution of high-pressure gas to Spanish industrial users (industry, power plants...) is based on the main composition of countries supplying to Spain. The origins of imported natural gas in Spain considered in this study are: Algeria 78.00% of the imported natural gas, Norway 13.80% and the natural gas imported from the UCPTE is 8.20% [27].

### IV.3.5 Quality of data

A reliable quantity of data was necessary in order to carry out this study. As a consequence, the energy sources are numerous and the quality is variable. Table IV.3 shows the sources of the data used in producing the life cycle inventory.

Table IV.3 Summary of the data sources used for the Life Cycle Assessment of the *Populus spp.* bioenergy system and both reference systems.

| Data | Quality |
|---|---|
| Field works: machinery type and operating rate, fuel consumption, agrochemicals used and application rate and waste generated. | Previous studies of our research group: [22] and literatura: [26]. |
| Biomass production per hectare | Previous studies of our research group: [22] |
| Machinery production and agricultural utensil production and the emissions from combustion in the agricultural tractors. | Ecoinvent 1.3. [27-32] and Ecoinvent 1.3 [32-34]. |
| Agrichemicals production and emissions from the application of the fertilizers and pesticides on the field. | Ecoinvent 1.3. [35, 36] and literature:[37-40]. |
| Consumption and emissions from the fuel used by trucks. | Literature: [33, 34, 41] |
| Soil Composition and Structure. | Previous studies of our research group: [22] |
| Energy and Environmental performance *Brassica carinata* reference bioenergy system | Previous studies of our research group: [6] |
| Energy and Environmental performance of natural gas reference non-renewable system | Previous studies of the research group: [6] |

# IV.4 Results and discussion

## *IV.4.1 Energy analysis of the Populus spp. cropping bioenergy system*

The total primary energy consumption of the *Populus spp.* cropping system (agricultural subsystem and transport subsystem) was estimated at 85.17 GJ · ha$^{-1}$ in scenario 1 and 87.56 GJ · ha$^{-1}$ in scenario 2. Resuts are similar to other short rotation energy crops studies (98.30 GJ · ha $^{-1}$) [28]. The main reason for the primary energy input increase of 2.39 GJ · ha$^{-1}$, in scenario 2, is the lower chip density in comparison with stem packet, for which there is an increase of 2.18 GJ · ha$^{-1}$ in the transport of the biomass. The second reason is the added primary energy consumed (0.21 GJ · ha$^{-1}$) during harvesting, in which the harvest has to collect and chip the biomass. Although scenario 2 has more energy inputs than scenario 1, it is the most reliable scenario because combustion plant might not be prepared to carry out directly the combustion of the stem packets, and furthermore the energy increase is negligible considering the total consumption of the system.

Nevertheless, the energy efficiency of the Populus spp. bioenergy system is altered by energy conversion factors, depending on the final type of energy obtained. In other words, heat generation from *Populus spp.* biomass appears to be more efficient in terms of the primary energy consumption (25-26 kJ per MJ of heat generated) than electricity generation (81-83 kJ per MJ of electricity generated).

### IV.4.1.1 Contribution of life cycle stages of *Populus spp.* bioenergy system to total energy consumption

The actions with the greatest energy consumption in the bioenergy system (agricultural subsystem and transport subsystem) are the use of diesel fuel and fertilizer production. The remaining of energy inputs is attributed to other production processes such as: herbicides, pesticides, tractor and agricultural utensils (see table IV.4).

Table IV.4 Contribution of life cycle *Populus spp*. bioenergy stages to total energy consumption.

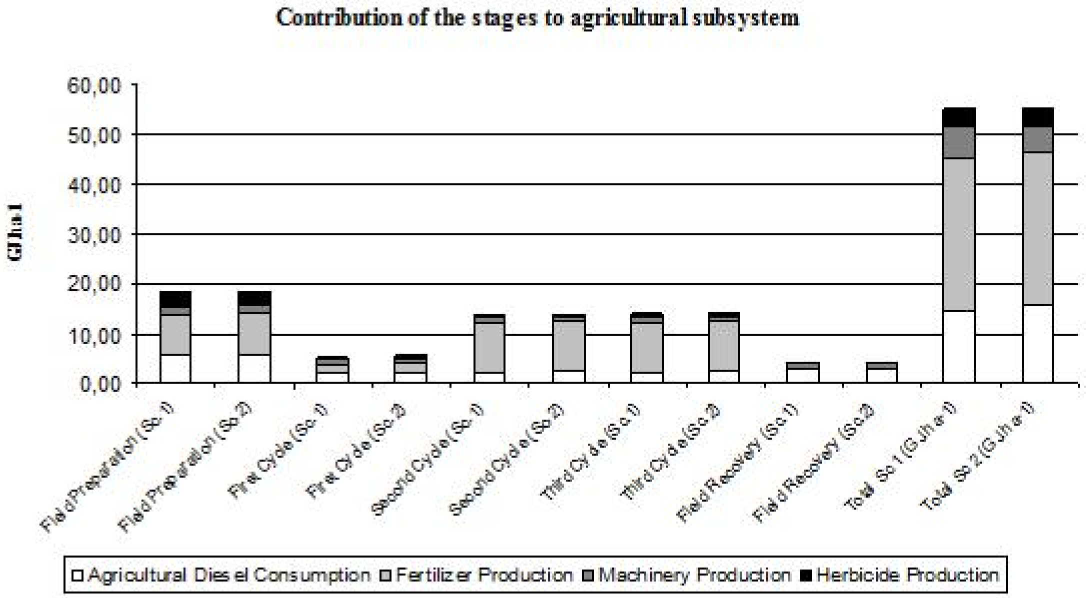
| Analyzed system stages | Primary energy consumption ( GJ · ha$^{-1}$ ) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Scenarios | 1 | | | 2 | | |
| Diesel fuel used in agricultural and transport phases. | Transport phase: | 52.60% | 35.35% | 30.11 | 54.69% | 36.88% | 32.29 |
| | Agricultural phase | | 19.40% | 16.52 | | 17.82% | 15.60 |
| Fertilizer manufacture | Agricultural phase | 47.40% | 35.72% | 30.42 | 45.31% | 34.74% | 30.42 |
| Herbicide manufacture | | | 9.53% | 3.77 | | 12.66% | 3.77 |
| Tractor manufacture | | | | 4.35 | | | 5.48 |
| Utensil manufacture | | | | | | | |
| TOTAL | Bioenergy system | 100% | 100% | 85.17 | 100% | 100% | 87.56 |

### IV.4.1.2 Agricultural production subsystem

The most critical energy field operations groups are those related to the first year of the crop and its establishment in the field (see figure IV.3).

The energy critical labour in the aforementioned field operations groups, with the exception of recovery field work and the first cycle of the crop, is fertilization and more specifically its production stage. Fertilizer manufacture itself amounts to 46% in the establishment of the crop, 32% in the first cycle, 74% in the second cycle, 72% in the third cycle and 0% in the recovery of the field where there is no fertilization work. In the agricultural field operations group in which agrichemical production inputs are required (fertilizers or phytosanitary), fuel use is the action with the greatest influence on energy consumption (see figure IV.3).

Figure IV.3 Energy consumption of life cycle stages to each field group of operations in the agricultural subsystem



### IV.4.1.3 Transport subsystem

The primary energy consumed by the transport agricultural inputs and outputs is 30.11 GJ · ha$^{-1}$ in scenario 1 and 32.29 GJ.ha$^{-1}$ in scenario 2. The farmer's transport consumes 17.89 GJ · ha$^{-1}$ and represents 59.42% in scenario 1 of transport subsystem and 55.40% in scenario 2 of the total primary energy consumption of this subsystem. The transport stage with the second highest consumption is biomass transport on a local level which supposes a total consumption of 8.72 GJ · ha$^{-1}$ (28.97%) in scenario 1 and 10.91 GJ · ha$^{-1}$ (33.77%) in scenario 2. The third largest energy consumption stage occurs during ash transport on a local level from plant to field. This stage consumes 2.55 GJ · ha$^{-1}$ which represents 8.47% in scenario 1 and 7.89% in scenario 2.

### IV.4.1.4 Energy comparison between *Populus spp.* and *B.carinata* bioenergy systems and natural gas production and distribution

The results of the comparison of the energy inputs of the *B. carinata* bioenergy system, natural gas and the *Populus spp.* bioenergy system are shown in table IV.5.

Table IV.5 Energy balance of the *Populus spp.* bioenergy system and the two analysed reference systems.

| Units: GJ per poplar hectare o equivalent | *Populus spp.* bioenergy system | *Brassica carinata* bioenergy system | Natural Gas Production and distribution system |
|---|---|---|---|
| Energy inputs | 85.20 | 481.94 | 721.93 |
| Energy output stored in biomass | 3931.20 | 3931.20 | 3931.20 |
| Balance | 3846.00 | 3449.06 | 3209.27 |

Both bioenergy systems show a better energy balance than Natural Gas production and distribution.

## *IV.4.2 Environmental analysis of Populus spp. bioenergy cropping system*

In this chapter, we demonstrate the relative magnitudes of various contributors to all of the impact categories analysed in an attempt to highlight their respective importance. The environmental impact of the *Populus spp.* bioenergy system is shown in table IV.6.

Table IV.6 Environmental impacts of the *Populus spp.* bioenergy system (agricultural and transport subsystems).

| Impact Category & Unit | Agricultural subsystem | | | | | | Transp. | Total |
|---|---|---|---|---|---|---|---|---|
| | Field Works | | Agrichemicals production | | | Diffuse emissions | | |
| | | | Simple fertilizer | NPK fertilizer | Phytosanitaris | From Fertilizers | Stages | |
| A.D.P. (kg Sb eq.) | Esc 1. | 8.42 | 2.29 | 10.83 | 1.13 | - | 15.34 | 38 |
| | Esc 2. | 8.53 | | | | | 16.45 | 39 |
| G.W.P. (kg CO2 eq.) | Esc 1. | 1,166 | 735 | 2,232 | 106 | 883 | 2,488 | 7,610 |
| | Esc 2. | 1,318 | | | | | 2,668 | 7,942 |
| O.D.P. (mg CFC 11 eq) | Esc 1. | 152 | 35.10 | 166.20 | 14.20 | - | 2,073 | 2,441 |
| | Esc 2. | 155 | | | | | 2,223 | 2,594 |
| H.T.P. (kg 1,4-DB eq.) | Esc 1. | 1,124 | 184.20 | 801 | 51.22 | 1.35 | 472.95 | 2,635 |
| | Esc 2. | 1,194 | | | | | 506.95 | 2,739 |
| F.W.A.E.P. (kg 1,4-DB eq) | Esc 1. | 100 | 26.55 | 159.90 | 7.79 | - | 36.32 | 331 |
| | Esc 2. | 91.71 | | | | | 39.02 | 325 |
| M.A.E.P. (T 1,4-DB eq) | Esc 1. | 243.39 | 98.10 | 585.00 | 62.88 | - | 103.85 | 1,093 |
| | Esc 2. | 231.38 | | | | | 111.35 | 1,089 |
| T.E.P. (kg 1,4-DB eq) | Esc 1. | 5.75 | 2.53 | 8.55 | 1.89 | - | 0.58 | 19.30 |
| | Esc 2. | 5.75 | | | | | 0.62 | 19.34 |
| P.O.P. (kg $C_2H_4$ eq) | Esc 1. | 0.33 | 0.04 | 0.27 | 0.03 | - | 0.56 | 1.23 |
| | Esc 2. | 0.33 | | | | | 0.60 | 1.27 |
| A.P. (kg $SO_2$ eq ) | Esc 1. | 8.78 | 2.06 | 8.46 | 0.67 | 16.06 | 25.74 | 61.77 |
| | Esc 2. | 10.03 | | | | | 27.61 | 64.89 |
| E.P. (kg PO4--- eq) | Esc 1. | 1.79 | 0.41 | 1.70 | 0.04 | 3.52 | 5.63 | 13.09 |
| | Esc 2. | 2.09 | | | | | 6.04 | 13.81 |
| W.C.I ($m^3$. $ha^{-1}$) | 28,000 | | | | | | | |

The results presented in table IV.6 reveal that the magnitude of the environmental impacts associated with the biomass agricultural subsystem is higher in 6 of the 10 impact categories (see table IV.6 ) than those linked to the transport subsystem, as they represent 53-91% of the total impact generated in the 6 categories analysed.

The result for Irrigated Water Consumption shows the probable case for *Populus spp.* cultivation where profitable biomass production requires a minimum of water irrigation when there is not enough rain.

### IV.4.2.1 Contribution of life cycle stages to total environmental impacts

In reference to the environmental performance of the *Populus spp*. bioenergy system, the greatest environmental impacts are associated with the use of fertilizers, considering their manufacturing stage and diffuse emissions from their application to the field, representing 51- 67% in the following categories: global warming potential (GWP), fresh water aquatic ecotoxicity potential (FWAEP), marine aquatic ecotoxicity potential (MAEP) and terrestrial ecotoxicity potential (TEP).

The diffuse emissions from fertilizers also have great contribution in some global impact categories. The results presented in table IV.7 shows that the main potential impacts of the diffuse emissions from the application of fertilizers to agricultural soil are in the categories of global warming potential (GWP) , acidification potential (AP) and eutrophication potential (EP).

The estimated emissions from the soil after the application of fertilizers and the relative contribution to the total impact of the *Populus spp.* bioenergy system are showed in table IV.7

Table IV.7 Diffuse emissions, impact and contribution to the total impact of the system.

| Emissions | Emission Estimated | Characterisation Factor | Impact generated | Contribution to total impact of the system (%) |
|---|---|---|---|---|
| Dinitrogen oxides ($N_2O$) | 2,98 kg.ha$^{-1}$ | 296.00 | 883 kg $CO_2$ eq .ha$^{-1}$ | 11.60-11.12 |
| Ammonium ($NH_3$) | 9,95 kg.ha$^{-1}$ | 0.10 | 0.99 kg 1,4DB eq.ha$^{-1}$ | 0.04 |
| | | 1.60 | 15.91 kg $SO_2$eq.ha$^{-1}$ | 24.52-25.79 |
| | | 0.35 | 3.48 kg $PO_4^{2-}$eq.ha$^{-1}$ | 26.60-25.20 |
| Nitrogen oxides ($NO_x$) | 0.30 kg.ha$^{-1}$ | 1.20 | 1.20 kg 1,4DB eq.ha$^{-1}$ | 0.01 |
| | | 0.50 | 0.50 kg $SO_2$eq.ha$^{-1}$ | 0.24-0.22 |
| | | 0.13 | 0.13 kg $PO_4^{2}$eq.ha$^{-1}$ | 0.28-0.29 |

The use of transport vehicles and agricultural tractors and their corresponding diesel fuel use also have significant effects on the system's environmental behaviour, as it represents between 56% and 92% of the impact in the categories of abiotic depletion potential (ADP), ozone layer depletion potential (ODP), human toxicity potential (HTP), photochemical oxidation potential (POP), acidification potential (AP) and eutrophication potential (EP).

### IV.4.2.2 Comparison of the total environmental impact by *Populus spp.* bioenergy system, *B. carinata* bioenergy system and natural gas production and distribution

The environmental comparison of the two bioenergy systems analysed shows that *B.carinata* has more impact in all of the analysed categories. The environmental impact in all categories is between 79 and 90% higher (Table IV.8). Specifically, in terms of the potential for global warming potential (GWP), the *B.carinata* bioenergy system presents an increase of 85% per functional unit (energy stored in biomass per *Populus spp*. hectare or equivalent) (Table IV.8). Compared to Natural Gas, the *Populus spp.*

bioenergy system also has better environmental performance; the increase in the impact in all categories is between 48 and 99%. The environmental impact of natural gas is the worst of all three fuel production systems compared here, but in the photochemical oxidation potential, acidification potential and eutrophication potential categories it can be more environment friendly than annual energy crops such as *B. carinata* (Table IV.8).

Table IV.8 Environmental comparison of the *Populus spp.* bioenergy system and both reference systems.

| Impact Category & units | *Populus spp.* Bioenergy system. Total | *B.carinata* Bioenergy system. Total | Natural Gas (production and distribution) |
|---|---|---|---|
| A,D, | 38 | 208 | 4,568 |
| (kg Sb eq,) | 39 | | |
| GWP | 7,610 | 50,163 | 130,418 |
| (kg CO2 eq,) | 7,942 | | |
| ODP | 2,441 | 3,471 | 9,328 |
| (mg CFC 11 eq) | 2,594 | | |
| HT | 2,635 | 26,585 | 44,653 |
| (kg 14-DB eq,) | 2,739 | | |
| FWAE | 331 | 2,748 | 14,164 |
| (kg 14-DB eq) | 325 | | |
| MAE | 1,093 | 8,642 | 52,426 |
| (T 14-DB eq) | 1,089 | | |
| TE | 19.30 | 147 | 136 |
| (kg 14-DB eq) | 19.34 | | |
| PO | 1.23 | 12 | 47,935 |
| (kg $C_2H_4$ eq) | 1.27 | | |
| A | 61.70 | 300 | 190 |
| (kg SO2 eq ) | 64.88 | | |
| E | 13.09 | 65 | 25 |
| (kg PO4--- eq) | 13.81 | | |

## IV. 5 Conclusions

According to our calculations, the *Populus spp*. bioenergy system cultivated in souther Europe is energetically efficient. In order to achieve 1 MJ of renewable energy in biomas only 21.67 kJ of primary energy is required. The *Populus spp.* bioenergy system is particulary energy efficient when compared with other systems such as *B.carinata* energy crop and non-renewable fuels such as natural gas, in which cases the primary energy invested to produce 1 MJ up to 120 and 180 kJ respectively [6]. Furthermore, the energy balace of *Populus spp.* bioenergy is always positive regardless of the final type of energy generated (25-26 kJ) per MJ of heat generated or 81-83 kJ per MJ of electricity generated.

According to our energy and environmental results, the choice of solid fuel-type biomass (stems or chips) makes no difference to the environmental performance of the system and the true reason for the decision may be the end consumer of the biomass. In comparison with other systems, such as the *B.carinata* bioenergy system, *Populus spp*. has better environmental performance in all categories analysed.

The biomass production per hectare is greater than B. carinata bioenergy system and the inpust required by the system are the lowest. In the same way Populus spp. bioenergy system also presents better environmental and energy performance than natural gas.

On the other hand, the *Populus spp.* bioenergy system could be improved by changing the mineral fertilisers used to alternatives from agriculture, agribusiness, livestock wastes, etc. Furthermore, strategic planning also is key factor in the environmental and energetic performance of the system, taking into account the location of the crop and the distances between the different actors, in order to guareantee low levels of environmental impact and energy consumption during the transport stage. With that in mind one of the objectives in the establishment of energy crops in the EU is the fulfilment of commitments to the reduction of greenhouses gases, the stage included inside the system's boundaries and the capacity of $CO_2$ fixation in agricultural soil are the key points that should be analysed in more depth. According to the Populus spp. bioenergy system, the net greenhouse emissions are 1.90 – 1.98 g. $CO_2$ eq. · $MJ^{-1}$ biomass produced, considering that the $CO_2$ emitted during biomass combustion is balanced by the amount adsorbed in the growing of biomass. The net greenhouse gas emissions avoided in comparison with the *B.carinata* biomass energy system is 10.72 g $CO_2$ eq · $MJ^{-1}$ abd with natural gas is 16.06 g $CO_2$ eq · $MJ^{-1}$.

As a final conclusion we can affirm that *Populus spp*. (SRF) is more environmentally sustainable than *B.carinata* and natural gas in strict consideration of the global environmental categories analysed, but not for this reason should it necessarily be the only crop implemented in souther Europe.

Comparing other environmental impacts not included in the LCA methodology, such as water consumed in irrigation, the performance of *Populus spp*. is not as good as *B.carinata*. This aspect is especially restrictive in souther Europe where water is a limited resource; the total available area for this crop is only the areas with a high availability of water. The sustainable implementation of energy crops in southern European countries will be mean adapting the ecological crop requirement to the local agroclimatic conditions in order to make the local targets compatible in terms of biomass production and the global targets for energy production and the global targets for energy production promoted by EU.

## IV.6 References to chapter IV

[1] International, Energy, Agency. IEA statistics - renewable information. IEA/OECD, Paris, 2003.

[2] European Commission. Energy for the future-renewable sources of energy.

White paper for a Community Strategy and Action Plan. COM (97)599. . Brussels, 1997.

[3] European Parliament and Council. Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market. Brussels, 2001.

[4] European Commission. Biomass action plan. Brussels, 2005.

[5] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversificación y Ahorro de la Energía (IDAE). Resumen Plan de Energías Renovables en España 2005-2010, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspxInstituto

[6] Gasol C, M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria M, Solano Ml., Rieradevall J. Life Cycle Assessment of a *Brassica carinata* bioenergy system in southern Europe. Biomass & Bioenergy 31 (2007) 543-555.

[7] Perez S., Renedo C.J., Ortiz A., Manana M., Silio D. Energy evaluation of the Eucalyptus globulus and the Eucalyptus nitens in the north of Spain (Cantabria). Thermochimica Acta 451 (1-2) (2006) 2006 57-64.

[8] Instituto para la Diversificación y Ahorro de la Energía (IDEA). Plan de Fomento de las Energías Renovables en España. Madrid, 1999.

[9] Venendaal R., Jorgensen U., Foster C.A. European energy crops: A synthesis. Biomass & Bioenergy 13 (3) 1997 147-185.

[10] Hall D.O., Scrase J.I. Will biomass be the environmentally friendly fuel of the future? Biomass & Bioenergy 15 (4-5) (1998) 357-367.

[11] Hanegraaf M.C., Biewinga E.E., Van der Bijl G. Assessing the ecological and economic sustainability of energy crops. Biomass & Bioenergy 15 (4-5) 1998 345-355.

[12] Borjesson P., Gustavsson L. Regional production and utilization of biomass in Sweden. Energy 21 (9) (1996) 747-764.

[13] Gagnon L., Belanger C., Uchiyama Y. Life-cycle assessment of electricity generation options: the status of research in year 2001. Energy Policy 30 (2002) 1267-1278.

[14] Wright L. Worldwide commercial development of bioenergy with a focus on energy crop-based projects. Biomass & Bioenergy 30 (8-9) (2006) 706-714.

[15] Ciria P., González E., Carrasco J.E. The effect of fertilization and planting density on biomass productivity of Populus spp harvested after three-years rotation. In: 12 th European Conference on Biomass for Energy, Industry and Climate Protection, 17-21 June 2002, Amsterdam, The Netherlands 2002.

[16] Ciria P., Mazón M.P., Carrasco J.E. Poplar productivity evolution on short rotation during three consecutive cycles in extreme continental climate. In: Second World Conference on Biomass for Energy, industry and Climate Protection, 10-14 May 2004, Rome; Italy.

[17] Comisión Nacional del Chopo. Plantaciones Total Nacional de Chopo. http://wwwmapaes/es/agricultura/pags/chopo/cortashtm#art5. Accessed: January 2007.

[18] Labrecque M., Teodorescu T.I.. Field performance and biomass production of 12 willow and Populus spp clones in short-rotation coppice in southern Quebec (Canada). Biomass & Bioenergy 29 (1) 2005 1-9.

[19] Paine L.K., Peterson T.L., Undersander D.J., Rineer K.C., Bartelt G.A., Temple S.A.. Some ecological and socio-economic considerations for biomass energy crop production. Biomass & Bioenergy 10 (4) 1996 231-242.

[20] Gasol C.M. Martínez S., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P., Gabarrell X. Feasibility assessment of poplar bioenergy systems in the southern Europe. Renewable and Sustainable Energy Reviews (RSER). 13 (4) 2009 801-812.

[21] Imbert E., Lefevre F. Dispersal and gene flow of Populus nigra (Salicaceae) along a dynamic river system. Journal of Ecology 91 (3) 2003 447- 456.

[22] AENOR. Gestión Medioambiental. Análisis de Ciclo de Vida. Evaluación de impacto del ciclo de Vida. ISO 14042:2000, Madrid, 2000.

[23] ISO. ISO 14040. Environmental Management – Life Cycle Assessment – principles and Framework. Geneve, Switzerland, 2006.

[24] Ciria P. Efecto del turno de corta y de la densidad de plantación sobre la productividad de diversos clones de chopo en condiciones de corta rotatcion. Tesis doctoral Universidad Politecnica de Madrid, 1998.

[25] Guinee J. Life Cycle Assessment An operational guide to the ISO standards, Volume 1, 2 and 3. Centre of Environmental Science Leiden University, 2001.

[26] Castro M.B.G., Remmerswaal J.A.M., Reuter M.A. Life cycle impact assessment of the average passenger vehicle in the Netherlands. International Journal of Life Cycle Assessment 8 (5) 2003 297-304.

[27] Faist E.M., Heck T., Jungbluth N. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen fur die Schweiz. Final report Ecoinvent 2000 No 6-V, Paul Scherrer Institut Villigen, Swiss 2003.

[28] Heller M.C., Keoleian G.A., Volk TA. Life cycle assessment of a willow bioenergy cropping system. Biomass & Bioenergy 25 (2) 2003 147-165.

[29] Forsberg G. Biomass energy transport. Analysis of bioenergy transport chains using life cycle inventory method. Biomass & Bioenergy 19 (1) (2000) 17-30.

[30] Spinelli P. A review of short-rotation forestry harvesting in Europe. In: First conference of the Short Rotation Woody Crops Operations Working Group.Washington, 1999.

[31] Nemecek T, Heil A, Huguenin O, Meier S, Erzinger S, Blaser S, et al. Life cycle inventories of agricultural production systems. Final report Ecoinvent 2000-19-FAI 491 Reckenholz, Swiss Centre for Life Cycle Inventories, Dundendorf, CH. Retrieved from: www.ecoinvent.ch, 2003.

[32] Márquez L. Máuinaria para la preparación del suelo, la implantación de los cultivos y la fertilización VIII. Blake & Helsey. Madrid (España), 2001.

[33] Márquez L. Maquinaría Agrícola: preparación primaria, trabajo del suelo, siembra, plantación y transplante. Blake & Helsey. Madrid (España), 2004.

[34] Amman HiNT. Maschinenkosten 2000-Kostenansatze Gebau- deteile und mechantsche Einrichtungen [Life Cycle Inventories of agricultural production system], vol. 45, Dübendorf 2003, 2003.

[35] Frischknecht R, Bollens U, Bosshart S, Ciot M, Ciseri L, Doka G, Dones R, Gantner U, Hirschier R, Martin A, in Nemecek, T. Okoinventare von Energiesystemen und den Einbezug von Energiesystemen in Okobilanzenfür die Schweiz. Life Cycle Inventories of agricultural production system, vol. 45, Dübendorf, 2003.

[36] Maibach M, Peter D, Seiler B, Nemececk T. Okoinventar Transporte Grundlagen für den okologischen Vergleich von Transportsystem und fur den Einbezug von Transportsyste- men in Okobilanzen. Life Cycle Inventories of agricultural production systems, vol. 44, Dübendorf 2003, 1999.

[37] SAEFL in Nemecek Tc. Handbuch Offroad-Datebank. Life Cycle Inventories of agricultural production systems, vol. 56, 2003.

[38] Rinaldi MS, E, Nemecek T. Trends im Abgasverhalten land- wirtschaftlicher Traktoren-Neue Modelle deutlich sauberer. Life Cycle Inventories of agricultural production system, vol. 56, Dubendorf 2003, 2002.

[39] Davis JHC. Life Cycle Inventori (LCI) of Fertilize. Production-fertilizer products used in Sweden and Western Europe. Life Cycle Inventories of agricultural production system, vol. 64 Dübendorf , 2003.

[40] Green M. Energy in pesticide manufacture, distribution and use. Life Cycle Inventories of agricultural production system, Dübendorf, 2003.

[41] Brentrup F., Küsters, J. In: Weidema B., Meeusen M.(Eds.), Agricultural data for life cycle assessments, vol.133, Agricultural Economics Research Insitute.TheHague,The Netherlands, 2000.

[42] Audsley E. Harmonisation of environmental life cycle assessment. Final report concerted action AIR-CT94-2028.European Commision DGVI Agriculture, 1997.

[43] Brentrup F., Kusters J., Kuhlmann H.,Lammel J. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology-I.Theoreticalconcept of a LCA method tailored to crop production.European Journal ofAgronomy 20 (3) (2004) 247-264.

[44] VolvoTruck. Emission from Volvo'sTruck emissions, standard diesel fuel.Available from: www.volvotruck.com. Accesed: October 2003.

# Chapter V. Comparative of winter rape (*Brassica napus*) cultivations as energy crop to produce Biodiesel in southern Europe.

*Manuscript draft: Gasol C.M., Salvia J., Serra J., Anton A., Rieradevall J. & Gabarrell X.Comparative of winter rape (Brassica napus) cultivations as energy crop to produce Biodiesel in southern Europe.*
*Journal: Fuel. (Under Revision).*

*Photografy by Carles Martinez Gasol. Caldes de Malavella (Girona), 2007.*

# Abstract

This paper analyses the viability of *Brassica napus* also called *B.napus* as an energy crop cultivated for producing biodiesel in southern Europe. The proposed methodology assessment combines physical variables such as grain production and agroclimate conditions with environmental analysis (LCA) in order to determine the Mediterranean agroclimates areas that could be cultivated for non-food proposes and the transport distance that would be appropriate in order to ensure a suitable environmental performance of the biodiesel system. In addition to that, the most impact actions associated with biodiesel system are determined with the aim of improving the energetic and environmental efficiency of the biodiesel system.

The results obtained in a local production and distribution scenario (25 km) demonstrate that the biodiesel systems analysed have a better energy balance than diesel. Biodiesel obtained a net energy benefit of 16.25 MJ · kg biodiesel$^{-1}$ or 35.10 MJ · kg biodiesel$^{-1}$ when the avoided impacts from coproducts (glycerine and rapemeal) are considered in comparison with conventional diesel which presents a negative energy balance -9.96 MJ.kg$^{-1}$ of diesel equivalent.

In terms of environmental performance, the biodiesel system also has less impact compared with diesel in three categories Abiotic Depletion, Photochemical Oxidation and Global Warming Potential (GWP). The estimated impact reduction in the GWP category when is compared with diesel reached a minimum of 1.76 kg $CO_2$ eq. per kg of biodiesel. Furthermore the study has not considered the emissions produced by vehicle engines when the fuels are used.

Moreover the sensitivity analysis allows us to affirm that any agroclimate (Mediterranean or not) that ensures a grain production over 2000 kg.ha$^{-1}$ would be suitable for growing *B.napus* energy crop to produce grain for biodiesel in a local (25 km) or regional (500 km) grain transport scenario.

The assessment presented in this paper should be taken into account in the design of the government policies as it provides data capable of determining the Mediterranean agroclimates and transport distances are suitable to ensuring that a sustainable biomass to be used as a renewable source of energy in bioenergy projects.

*Key words: Energy crops, Biomass, Environmental Analysis, Energetic Analysis & Life -cycle assessment.*

## V.1 Introduction

In 2003, the European Commission presented the directive 2003/96/EC directive on the promotion of the use of biofuels or other renewable fuels for transport. In this directive, EU member countries set the goal of increasing the production of renewable energy to a minimum of 12% of total domestic energy consumption by the year 2010. In turn, this directive establishes a minimum content of 2 and 5.75% of biofuel for all petrol and diesel used in transport by 31 December 2005 and by 31 December 2010, respectively [1]. Additionally, in certain Latin-American countries the production of biodiesel is promoted and is mixed at 5% with conventional diesel [2, 3] . In this context and as a consequence of the recent petroleum-price increases, there is a growing interest in fatty acid methyl as an alternative diesel fuel in particularly in Spain where Biodiesel production is still low ( 6,000 Mg in 2003 ) in comparison with other countries in the EU [4]. Thus, we expect that Biodiesel production obtained by transesterification (also called Methanolysis) of edible vegetable oils, non-edible oils and recycled or waste oils[5, 6] will increase in the short term in order to comply the European Directive aim[1]. In this context it is necessary to assess the environmental and energetic performance of the different forms of production or collection of raw material (oils) to subsequently obtain Biodiesel.

This study focuses on the assessment of Biodiesel production from edible vegetable oil extracted from Rapeseed Oil crops (*Brassica napus or B.napus*) as a potential local energy resource.

*B.napus* – also known as Canola – belongs to the Brassicacea family and is an ideal raw material (oil) with regard to combustion characteristics, oxidative stability and cold temperature behaviour in producing Biodiesel [5]. Furthermore, it is a crop that well known to farmers and presents a stable range of production.

In this paper an assessment that links agronomic variables such as type of climate and grain production obtained using current agricultural techniques with the environmental and energy performance of the system is carried out as an approach capable of deciding which productions obtained in each Mediterranean agroclimate areas are suitable for non-food use Brassica napus for biodiesel production.

With this purpose the Institute for Food and Agricultural Research and Technology (IRTA) has compiled agricultural production data for several *B.napus* varieties from 265 ha distributed in several areas in northwest Spain (Catalonia) which cover five agro-pedo-climatic areas.

In the *B.napus* cropping systems studied, the seeds are collected separately from the biomass that remains in the field; the agricultural harvesting work therefore does not include the collection of the plant in its entirety. Furthermore, this stage of the system has the highest energy consumption and environmental impact, and points to improvements in the system that could increase the potential for this crop as a resource for renewable energy in southern Europe. Finally, the study compares the environmental and energetic performance of Biodiesel produced from *B.napus* and an equivalent quantity of diesel, in order to demonstrate the advantages of this local renewable energy source in comparison with these fuels.

# V.2 Methodology

In the following lines methodology applied to *B.napus* bioenergy system assessment is presented.

## *V.2.1 Agronomic Aspects*

Twenty-five plots cultivated with *B.napus* are located at a range of points in Catalonia (North Spain), covering a total of 5 agroclimate areas. A detailed description of the climatic conditions in the regions taken into account is shown in the table V.1 where mean annual temperature, annual rainfall and average frozen risk are the main variables considered.

Table V.1 Agroclimatic conditions of the areas under study.

| Agriclimate | Mean annual Temperature (ºC) | Annual rainfall (mm) | Frozen risk (average days · yr-1) |
|---|---|---|---|
| (a) | 17 | 400 | 6 |
| (b) | 14 | 600 | 14 |
| (c) | 10 | 700-1000 | 10 |
| (d) | 16 | 700 | 10 |
| (e) | 13 | 600-700 | 8 |

The most standard agricultural cultivation protocol was then taken into account (see table V. 2).

In addition, a sensitivity analysis was conducted with the purpose of analysing to what extent uncertainty in input data affected the results. Therefore, the influence of the seed production obtained and the variation in grain transport distance (25km and 500 Km) were studied.

The methodology used to determine energy balance and the environmental impacts of the biodiesel production based on *B.napus* cropping systems and diesel production and distribution system is that of life cycle assessment (LCA) methodology [7,8]. The environmental analysis was developed using the software program SimaPro 7.0.2 software program by Pré Consultants.

## *V.2.2 Energy assessment*

For the energy-input assessment was calculated by "Cumulative Energy Requirements Analysis" (CERA) [9, 10] using SimaPro 7.1 while the energy outputs was calculated with the low heating value LHV, 37.20 MJ·kg$^{-1}$, of the Biodiesel taken from bibliographic reference[5]. Seed-energy content was also considered as an input of the biodiesel system considering an energy content of approximately 17.73 MJ·kg$^{-1}$ [11].

The diesel LHV assumed in this study in order to compare the environmental impacts and energetic balance is 42.8 MJ·kg$^{-1}$ [12], energy input consumed in the diesel production system also has been estimated with the CERA indicator.

### *V.2.3 Environmental assessment*

Following other studies published in the ambit of agricultural and energy, production and environmental assessment [11, 13-15], the methodology selected to perform the environmental analysis was LCA in all systems analysed: *B. napus* cropping systems and diesel production and transport to Spanish regional storage. LCA is a methodology used to assess all environmental impacts associated with a product, process or activity by accounting for and evaluating resource consumption and emission [7]. This environmental tool follows the ISO 14040 guidelines [7], according to which, LCA is divided into four steps: (1) definition of goal and scope, (2) inventory analysis, (3) impact assessment and (4) interpretation.

## V.3 LCA of Biodiesel production by means of *B.napus* cropping systems

In the following lines LCA applied to *B.napus* bioenergy system is presented.

### *V.3.1 Goal and Scope definition*

The aim of this study was to evaluate the environmental impacts and energy balance of several *B. napus* cropping systems in different agroclimatic conditions in order to determine those grain productions that allow production of biodiesel with a positive energy and environmental balance. In addition, the study has two significant specific goals; determining the hot-spots of the agricultural, transport and Biodiesel production phases in the system and ascertaining potential measures for environmental improvement. The second specific goal was to demonstrate the higher environmental and energy performance of Biodiesel as renewable biofuel in a national production scenario in comparison with conventional diesel.

### *V.3.2 Functional Unit*

In this study, the functional unit selected is the production of 1 kg of Biodiesel by means of the transesterification of the edible vegetable oil coming from *B.napus* crops produced in southern Europe. Furthermore, for comparison, the equivalent quantity of diesel (0.87 kg) was assumed taking the previously indicated LHV's into consideration.

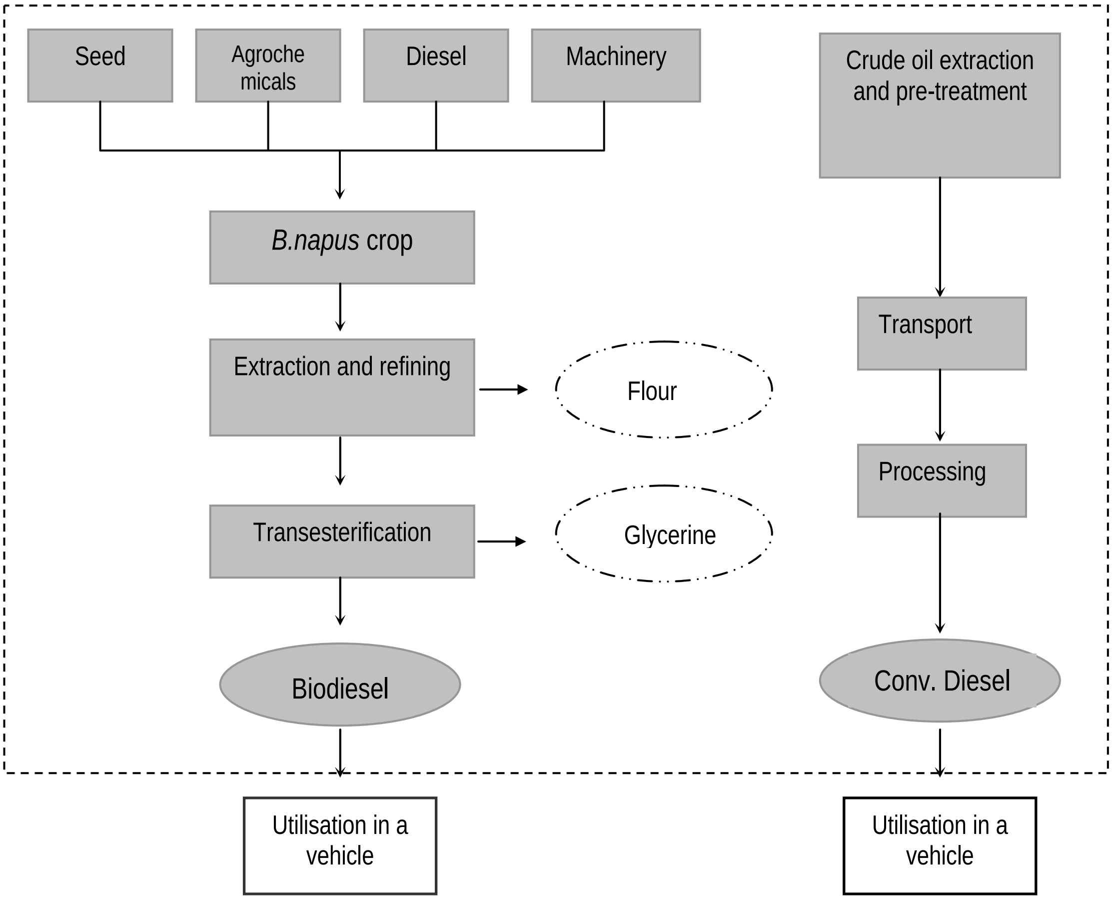
### *V.3.3 Systems description*

In the following lines *B.napus* bioenergy system description is presented.

#### V.3.3.1 Biodiesel system

The energy crop systems analysed include the following stages: agricultural production, transport input and outputs and Biodiesel production. This last stage includes oil extraction from the seed, oil refining and oil transesterification to obtain Biodiesel. In Figure V.1 represents the main stages analysed in the whole life cycle of the Biodiesel production; in addition, the life cycle of conventional diesel production is used as a reference system to compare the energy balance and the environmental impacts produced by both systems.

Figure V.1 Boundaries of the biodiesel production system and conventional diesel.



The system includes all the agricultural input and output produced during the crop stage and their corresponding emissions; it also includes the transport of these input and output. Inputs are farmers, fertilizers with their corresponding containers, herbicides and seeds; outputs are: residues (containers), and seed. Transportation of grain from field to extraction plant and transportation of oil to the Biodiesel refinery have also been considered as output. Farmer-transport phase includes all journeys involved in accomplishing the required work as well as in supervising the crop. A total number of 10 journeys were considered [11]. Finally, the Biodiesel production phase includes the extraction of the oil from the seed, its refinement and the application of transesterification in order to obtain the final product.

The oil extraction efficiency considered is 97% with respect to 41% of seed-oil content [16, 17]. The extraction efficiency chosen corresponds to an oil extraction capacity that is realistic in this type of expeller practice. The extraction took place in two steps, pressing and hexane extraction. The more advanced solvent extraction technique with hexane was used in order to extract more oil from the seeds[16-19]. These processes have oil and meal as products (1.48 kg meal · kg of biodiesel$^{-1}$)[19]; in this study, this is considered a co-product of biodiesel.

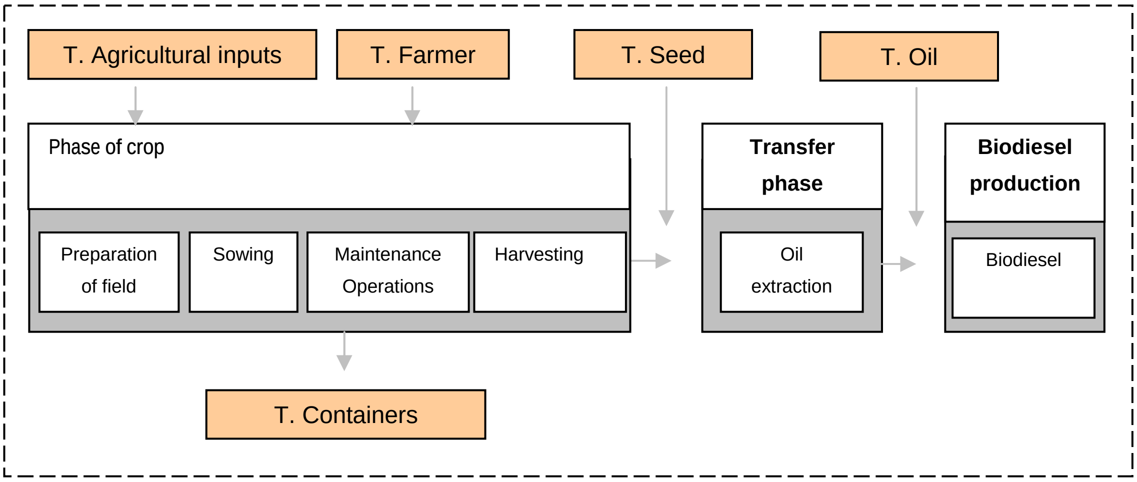
Oil refinement and transesterification also has been considered. Transesterification consists of replacing the glycerine molecule by three methanol molecules in the presence of a catalyst [5, 6].

The final use of Biodiesel, meal and glycerine was not included in the study, as is shown in figure VII.2. However, the avoided impact and energy consumption from glycerine and meal have been taken into account in an expanded system allocation procedure (see chapter V. 3.3.4.).

### V.3.3.2 Transport scenario in the biodiesel system

The suggested transport scenario is based on a regional/local national scale (25 km), but a distance of 500 km for the transport of agrochemicals is included when taking into account the capacity for distribution of the main agrochemical-producing enterprise in Spain [20]. 0.50 km has been established, from the centre point of the hectare to the roadside as regards transport distance. The characterization of the vehicles used in the transport of input and output in the transport scenario defined has been extracted from studies about biomass agricultural production [11]. Transport of biodiesel from the industry to commercial point is excluded from the transport stages considered in this study. Stages relating to the diesel used during the transport stages included within the boundary transport subsystem are: diesel extraction, processing, diesel transport to commercial point and vehicle (i.e., tractors and trucks) engine combustion. The transport subsystem does not include the manufacturing of vehicles, the impact of this being considered negligible, representing up to 10% [21] of the total impact generated during their life cycle. The impact related to the roads is also excluded as these are not explicitly constructed for the transport of the input and output of the system analysed.

Figure V.2 Transport stages implied in the studied crop.



### V.3.3.3 Diesel system

The reference system used as a comparison between the Biodiesel productions by means of *B.napus* crop is the production and subsequent transport of diesel as far as a refinery. The system includes three main stages, namely, crude extraction, transport by pipeline from the petrol field to the initial port and a second transport by ship from the initial port to the final destination. In the refinery the crude undergoes a process that produces the conventional diesel (see figure V.2). The transport of this diesel to a commercial point is also excluded in order to compare both systems.

### V.3.3.4 Allocation procedures

The environmental load and energy consumption of the system under study was shared between biodiesel, meal and glycerine. The allocation method was an expanded system so that the rapemeal produced could avoid soymeal meal production. Glycerine from the transesterification process was assumed to replace that produced from propane gas. The emissions and energy needed for the production of soymeal and fossil glycerine [22] were subtracted from those needed to produce Biodiesel in this allocation procedure.

## *V.3.4 Quality data*

The *B.napus* agricultural production system uses field data collected and obtained from as survey carried out during the 2004 agricultural season, such as, agrochemicals application dose ( kg · $ha^{-1}$ . $yr^{-1}$), seed application dose (kg · $ha^{-1}$ . $yr^{-1}$ ), type of machinery used, diesel fuel consumption ( l · $ha^{-1}$ . $yr^{-1}$) and operating rate ( h · $ha^{-1}$ . $yr^{-1}$ ). The data for generalized and standard production processes for input such as fertilizers, herbicides, tractors and utensils as well as data relating to the life cycle of the fuel (production, distribution and consumption), were taken from the ecoinvent database[23]. The experimental information available used for the compilation of the agricultural inventory is summarized in the table V.2.

Table V.2 Field operations experimental data used in the assessment .

| Operation | Tractor | Implement | | | Inputs rates | |
|---|---|---|---|---|---|---|
| | Weight and Power | | Weight (kg.) | Operating rate ($h.ha^{-1}.yr^{-1}$) | Fuel diesel consumption ($l.ha^{-1}.yr^{-1}$) | |
| Turn over the soil | 6,700 kg.<br>155 CV | Rototiller | 3,200 | 0,63 | 11,90 | |
| Chisel pass | 6,700 kg.<br>155 CV | Chisel | 300 | 0,88 | 16,67 | |
| Base fertilization | 6,700 kg.<br>155 CV | Spreader | 350 | 0,10 | 1,25 | NPK fertilize 8/16/18 (30% $SO_3$): 300 $kg.ha^{-1}.yr^{-1}$ |
| Herbicide application | 6,700 kg.<br>155 CV | Boom Sprayer | 1,020 | 0,08 | 0,75 | Trifluraline 3 $l.ha^{-1}$ |
| Insecticide application | 5,200 kg.<br>92 CV | Boom Sprayer | 1,020 | | | Clorpirifos 48% 1.5 $l.ha^{-1}$ |
| Grinder pass | 6,700 kg.<br>155 CV | Rototiller | 1,050 | 1,00 | 19,05 | |
| Sowing | 5,200 kg.<br>155 CV | Harvest | 1,500 | 0,75 | 9,02 | *Brassica spp.* seeds: 3.5 $kg.ha^{-1}.yr^{-1}$ |
| Top fertilization | 6,700 kg.<br>155 CV | Spreader | 350 | 0,10 | 1,25 | Nitro ammonic sulphate 26% 135 $kg.ha^{-1}.yr^{-1}$ |
| Grain Harvest | 7,600 kg.<br>170 CV | | 8400 | 1,13 | 22,56 | |

The data associated with oil extraction factor (41%) and oil conversion factor to biodiesel (0.97) and biodiesel production processes have been collected from bibliography [19, 22] and from an enterprise in the oil sector [17]. The need for methanol assumed during the transesterification process and the other input is shown in table V.3.

Table V.3 Input considered in the transesterification process.

| Transesterification | | | |
|---|---|---|---|
| Inputs (kg. kg of oil$^{-1}$ refined) | | Outputs (kg . kg of oil$^{-1}$ biodiesel) | |
| Oil refined | 1.02 | Biodiesel | 1 |
| Methanol | 0.06 | Glycerine | 0.096 |
| Phosphoric acid | 0.0000385 | | |
| Water | 0.8775 | | |
| Soda | 0.0011 | | |
| Hydrochloric acid | 0.0052 | | |
| Aluminium sulphate | 0.0000732810 | | |
| Amoniacal nitrate | 0.00077 | | |

## *V.3.5 Life Cycle Inventory Methodology*

The methods used in the life-cycle inventory phase were mainly based on the Life Cycle Inventories of Agricultural Production Systems methodology [23] and on the EU Concerted Action AIR-CT94-2028 “Harmonization of the Environmental Life-cycle assessment for Agriculture[13].

### V.3.5.1 Tractor and agricultural implement manufacture

An estimation of the energy and the material required to manufacture the proportional fraction of tractors and agricultural implements used in the agricultural phase was included in the life cycle inventory.

The proportional fraction of machinery or implements was estimated using the following[23]:

$$AMF = \frac{W \cdot OT}{LT} \cdot BP \qquad \text{(eq. V.1)}$$

Where “AMF” is the fraction for the amount of machinery (kg / FU) used in the field work; “F.U.” is the functional unit selected in this study (1 kg of biodiesel), “W” is the weight of tractors or agricultural implements (kg); “OT” is the operation time for each field operation (h / ha), “B.P.” is biodiesel production (kg/ha) and “LT” is the life time of the tractors or agricultural implements (12,000 h for tractors and 800-3,000 h for implements)[24, 25].

$$BP = SP \cdot OE \cdot OC$$ (eq. V.2)

Where "SP" is seed production (kg / ha), OE is oil extraction factor (41%) and OC is oil conversion factor to biodiesel (97%).

Data on materials, energy use and emissions of the tractors and agricultural implement production process was obtained from the Ecoinvent database[26-28].

The material used in tractor maintenance and repair during its lifetime should also be scored as part of the total value of the fraction of the amount of machinery required[27]. In reference to the maintenance of the tractors and agricultural implements, specific parameters from the specialized bibliography were used [26-28]. The repair factor, is defined as the repair cost during life divided by the price of new machinery. In this study, it has been assumed to be 20% for tractors and 54% for agricultural implements[29].

### V.3.5.2 Fuel Consumption and emissions associated with the use of agricultural machinery and transportation of the biomass

Fuel consumption of each field operation was well documented in the field records of the experimental 264 ha. On the other hand, fuel consumption associated with transport stages has been obtained by quantifying the transport needs in terms of MJ · $Kg^{-1}$ of biodiesel. km by means of the Volvo Truck Model [29], LHV diesel (see chapter 2.2 Energy Assessment) and the density of the different materials transported. See table V.4.

Table V.4 Density or weight of the input and output transported.

| Input or Output transported | Density of the material ($kg.m^{-3}$) |
|---|---:|
| Seeds | 278 |
| Herbicide and insecticides | 1.24 |
| Fertilizer | 310 |
| Biomass | 100-150 |
| Containers | 30-35 |
| Ashes | 80 |
| Farmer | 80 Kg. |
| Oil and Biodiesel | 880 |

Source: [11]

The equations (3) and (4) [29] were used to calculate the fuel consumption of the different vehicles involved in the transport of the input and outputs of the system.

$$Cxt = Co + \frac{[(Cf - Co)]}{Qt} \cdot Qx \qquad \text{(eq. V.3)}$$

Where "CXT" is the fuel consumption of the vehicle with "Qx" load (L .Km$^{-1}$).

"Co" is the fuel consumption of the empty vehicle (L.Km-1), "CF" is the fuel consumption of the fully loaded vehicle (L.Km-1) (see table 3). "QT" is the maximum transportable load (kg) and "Qx" is the actual transportable load (kg).

Equation (3) was used to calculate the fuel consumption when the vehicle departs from the facility carrying "Qx" load and returns empty to the same location.

$$Cxta = Co + Cxt \cdot \left( \frac{SP}{Qx \cdot BP} \right) \qquad \text{(eq. V.4)}$$

Where "CXTA" is the total fuel consumption. (L · Km$^{-1}$ . FU$^{-1}$).

Emissions from fuel combustion were estimated according to equation (5) and the emission factors proposed by the Swiss Agency for the Environment, Forests and Landscapes and other authors of the Ecoinvent database [30].

$$WG = FC \cdot \frac{EF}{BP} \qquad \text{(eq. V.5)}$$

Where "WG" are the waste gases emitted (g / F.U.), "FC" is fuel consumption of the different vehicles (kg fuel. ha-1), "EF" is the emission factor of each gas (g waste gas. kg. fuel) and "BP" is the biodiesel production (kg / ha).

### V.3.5.3 Production of fertilizers

The fertilizer inventory used takes into account the use of resources for all production stages ranging from extraction of the raw materials to the production of the intermediates and the final product. The ammonium nitrate manufacturing process (the fertilizer applied in all plots) considered is the neutralization of ammonia using nitric acid. The resulting solution is evaporated and then granulated [31]. Data relating to the energy use and emissions involved in the production process was obtained from the ecoinvent database [31] .

### V.3.5.4 Production of herbicides

Data relating to energy emissions used in the production of pesticides has been obtained from the Ecoinvent Data base [32]. The emissions of herbicide active ingredients into the environment during manufacture were not included in the inventories.

### V.3.5.5 Seed Production

The production of a dose of sowing hybrid seed (3.5 kg.ha$^{-1}$) is considered in entirely the same way as in the production of the crop. In order to take into account the burdens incurred in the production of these seeds, the field surface required to produce these seeds is added to the surface area used for the crop (0.005 ha). We also added the electrical energy consumed in the processing of the seed. In this study the electricity consumed was assumed to be 58 kWh · Mg seed$^{-1}$ [33].

### V.3.5.6 Emissions produced by the application of fertilizers

Earlier LCA studies have shown the importance of calculating air emissions, such as ammonia ($NH_3$) and enhanced NOx and $N_2O$ formation, produced by the addition of nitrogen to agricultural systems in the form of synthetic fertilizer [14, 34-36]. In this study, we decided to calculate diffuse emissions using emission factors proposed by several authors [13, 37].

#### Ammonium volatilization

In this study, an ammonia volatilization factor of 2% for simple nutrient fertilizer (ammonium sulphate nitrate) and 4% for multinutrient fertilizer (NPK 8/6/18 with a 30% $SO_3$) were assumed [13].

#### Nitrous oxide ($N_2O$)

The N2O emission factor assumed for both fertilizers is 1.25 % of N addition [37].

Note that estimated N loss due to ammonium volatilization is subtracted from the N addition before estimating $N_2O$ emissions with this relationship.

#### Oxides of nitrogen (NOx)

The NOx emissions were calculated as 10% of the $N_2O$ emissions[13].

#### Nutrient leaching

In this study it was assumed that nutrient leaching does not occur since the nitrogen air emissions and the plant's capacity for nitrogen extraction (0.0148 kg.kg$^{-1}$d.b.) [38] exhaust the dose of fertilizer applied per hectare.

### V.3.5.7 Emissions produced by the application herbicides and insecticides

The diffuse emissions from the application of pesticides to the crop were estimated according to the method proposed by Hauschild [39].

### V.3.6 Life cycle impact assessment methodology

Of all the steps included in the life cycle impact assessment methodology [7], only the classification and characterization stages were carried out (excluding normalization and valorisation in order to avoid subjectivity in the analysis). In the classification stage, each burden is linked to one or more impact categories, while in the characterization stage the contribution of each burden to each impact category is calculated by multiplying the burdens by a characterisation factor [40]. The classification and characterization method used was CML 2000 [40]. The impact categories analyzed are Abiotic depletion potential (ADP); Global warming potential (GWP), Ozone layer depletion potential (ODP); Human toxicity potential (HTP); Fresh water aquatic ecotoxicity potential (FWAEP); Marine aquatic ecotoxicity potential (MAEP); Terrestrial ecotoxicity potential (TEP); Photochemical oxidation potential (POP); Acidification potential (AP) and Eutrophication potential (EP).

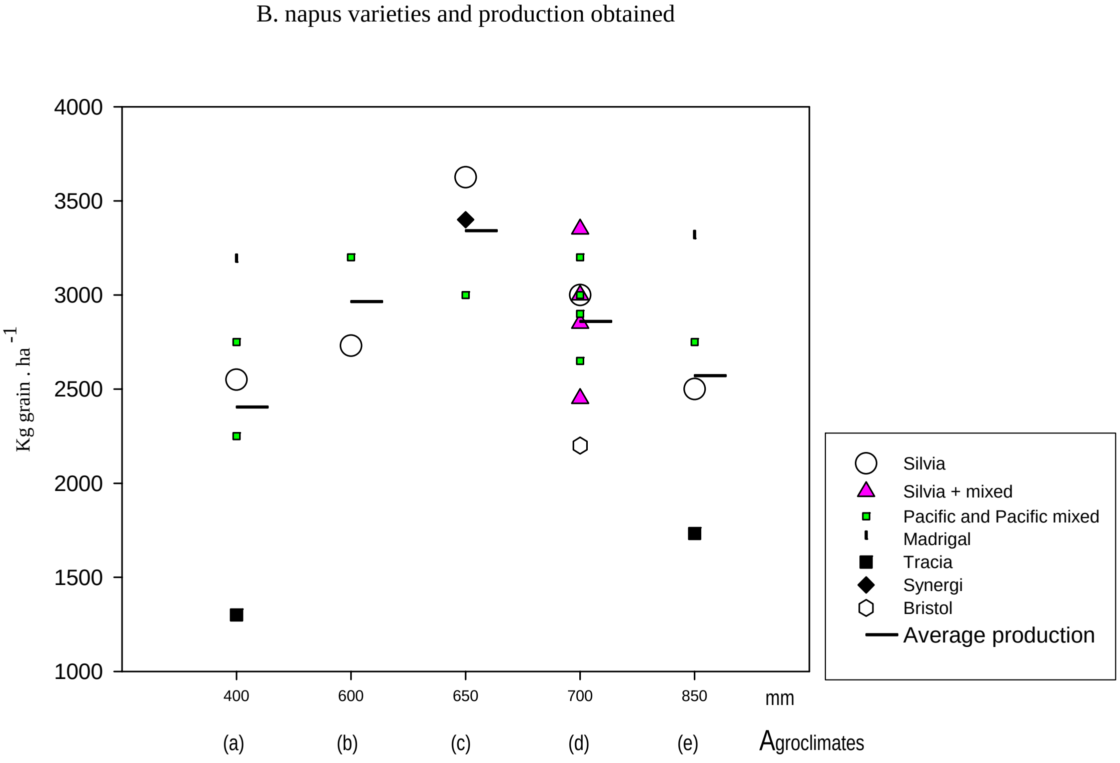
## V.4 Results

In the following lines the results obtained about *B.napus* bioenergy system are presented.

### V.4.1 Varieties cultivated and production obtained

Figure V.3 shows the production and the average production for each agroclimate and the total average production of 5 agroclimate regions (2,786 kg seed · $ha^{-1}$ which implies approximately 1,097 litres of Biodiesel). This result has been used to analyse the environmental performance in base case scenario.

Figure V.3 Varieties cultivated and average production for each Agroclimate area according to rape producers survey.



## *V.4.2 Energy analysis of the Biodiesel production using B.napus oil seed*

Referring to total energy primary consumption of the Biodiesel production case study by means of the oil extracted from *B.napus* has been estimated at 20.95 MJ · kg biodiesel$^{-1}$, which means a positive net energy balance of 16.25 MJ · kg biodiesel$^{-1}$. The crop cultivation stage reaches 45 % (9.43 MJ · kg biodiesel$^{-1}$), transport stages in a local scenario (25 km), 3.4 % (0.72 MJ ·kg biodiesel$^{-1}$) and conversion stages of the grain to biodiesel 51.6 % (10.80 MJ · kg biodiesel$^{-1}$).

Published studies of this crop applied to produce biodiesel had obtained similar results for these three main stages [5], obtaining a Cumulated Energy Demand of 11.35 MJ. Kg ·biodiesel$^{-1}$ in the crop cultivation, 0.41 MJ · kg biodiesel$^{-1}$ during transport stages and 13.01 MJ · kg biodiesel$^{-1}$ in the conversion stages.

### V.4.2.1 Contribution of the life cycle stages to the total energy consumption of the system

The actions with the greatest energy consumption in the system are transesterification and oil extraction. These processes imply 25.22 % (5.28 MJ · kg biodiesel$^{-1}$) of the energy consumption in the system analysed in the case of transesterification and 21.30 % (4.46 MJ · kg biodiesel$^{-1}$) in the case of oil extraction. The production and use of diesel during the biodiesel system life cycle stages is the third action with highest energy demand, represents 19.93 % (4.71 MJ · kg biodiesel$^{-1}$) of the total energy used. This diesel is mainly (72%) used in the agricultural stage as a fossil for the tractors and harvesting when a local transport scenario (25km) is considered.  Fertilizer production appears as the fourth highest energy consumption action of the whole system reaching 18.36 % (3.85 MJ · kg biodiesel$^{-1}$) and shows the highest energy consumption of the agricultural stage (41% of the energy applied in this stage). Table V.5 shows the consumption of the different actions of the system.

Table V.5 Quantification of the energy input and contribution to the total consumption of the system.

| | | MJ per 1 kg biodiesel | Contribution (%) |
|---|---|---|---|
| Agricultural & Transport stage | Agricultural Machinery production | 0.92 | 4.39 |
| | Fertilizers production | 3.85 | 18.36 |
| | Pesticides production | 1.13 | 5.41 |
| | Seed energy content and production | 0.07 | 0.34 |
| | Diesel production and use (agricultural and transport) | 4.71 | 19.93 |
| Conversion stage (biodiesel production) | Oil extraction process (including chemical inputs) | 4.46 | 21.30 |
| | Oil refined process (including chemical inputs) | 1.06 | 5.04 |
| | Transesterification (including chemical inputs) | 5.28 | 25.22 |
| | Total | 21.49 | 100 |

### V.4.2.2 Energy balance of the two analysed systems (Biodiesel and Diesel)

In reference to a diesel system, the total primary energy consumed in the stages of production and distribution to a regional European refinery is 46.16 MJ · functional unit $^{-1}$. Table V.6 shows the total energy balance of the two fuel production and distribution systems.

Table V.6 Energy Balance of three analysed systems (Biodiesel, Biodiesel and avoided impacts from the subproducts and diesel).

| MJ per U.F. | Biodiesel from *B.napus* | Biodiesel less avoided energy consumptions (glycerine and soymeal) | Diesel production and distribution system |
|---|---|---|---|
| Energy inputs | 20.95 | 1.49 | 46.16 |
| Energy output | 37.20 | 37.20 | 37.20 |
| Balance | 16.25 | 35.10 | -9.96 |

The energy balance obtained shows that the higher energy input associated with conventional diesel produce a negative energy balance of this non renewable fossil. On the other hand, biodiesel production consumes 54.6% less for the same quantity of energy stored in diesel fuel when compared with conventional diesel. The energy balance of biodiesel improves if we consider the energy credits obtained from the avoided products (soymeal and glycerine). In this case the energy input obtained is 96.70% lower than conventional diesel.

## V.4.3 Environmental analysis of the Biodiesel production using *B.napus* oil seed.

In this paper, we calculated the relative magnitudes of various contributors to all impact categories analysed in an attempt to highlight their respective importance.

The environmental impact of the biodiesel production system using *B.napus* oil seed and the impact contribution of the different actions is shown in table V 7.

Table V.7 Environmental impact of one kg of Biodiesel transported until regional storehouse.

| Impact Category & Unit | Agricultural stage | | | | Transport stage | Conversion stage | | | Total (impact . kg biodiesel $^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | Field works | Fertilizers production & use | Pesticides production & use | Seed | All Transports | Oil Extraction | Oil Refination | Trans-esterification | |
| | Contribution % | | | | | | | | |
| A.D.P kg Sb eq. | 20,08 | 19,27 | 4,97 | 0,05 | 3,43 | 21,22 | 3,96 | 27,00 | 0,009 |
| G.W.P kg CO2 eq. | 19,98 | 45,07 | 2,76 | 0,08 | 3,30 | 17,17 | 2,21 | 9,42 | 1,35 |
| O.D.P kg CFC 11 eq | 12,94 | 10,50 | 2,51 | 0,03 | 14,58 | 38,48 | 3,98 | 16,99 | 0,0000003 |
| H.T.P. kg 1,4 - DB eq | 23,51 | 10,83 | 53,45 | 0,11 | 0,85 | 6,50 | 1,41 | 3,35 | 1,61 |
| F.W.A.E.P. kg 1,4 - DB eq | 4,20 | 5,33 | 83,22 | 0,11 | 0,25 | 2,43 | 2,04 | 2,41 | 0,42 |
| M.A.E.P. kg 1,4-DB eq | 10,42 | 16,83 | 4,77 | 0,04 | 1,28 | 39,15 | 10,75 | 16,76 | 456,54 |
| T.E.P. kg 1,4 - DB eq | 10,41 | 35,65 | 17,02 | 0,08 | 0,73 | 25,10 | 2,63 | 8,37 | 0,0051 |
| P.O.P. kg C2H4 eq | 9,01 | 18,03 | 1,55 | 0,03 | 1,85 | 54,85 | 2,15 | 12,53 | 0,0007 |
| A.P. kg SO2 eq | 18,35 | 54,02 | 2,21 | 0,09 | 4,19 | 12,21 | 3,61 | 5,31 | 0,011 |
| E.P. kg PO4 eq | 29,10 | 52,01 | 1,04 | 0,10 | 6,29 | 3,39 | 4,94 | 3,12 | 0,0015 |

AD: Abiotic Depletion, GWP: Global Warming Potential, HT: Human Toxicity, FWAE: Fresh Water Aquatic Ecotoxicity, MAE: Marine Aquatic Ecotoxicity, TE. Terrestral Ecotoxicity, PO: Photochemical Oxidation, A: Acidification, E: Eutrophication.

The results shown in table V.7 indicate that the magnitude of the environmental impact associated with the agricultural stage is greater than that of those linked to transport and conversion stage in 6 of the 10 categories analysed (GWP, HTP, FWAEP, TEP, AP and EP) with a contribution between 63-88%. In the other categories (ADP, ODP, MAEP and POP), the transformation from the grain to biodiesel is the action having the greatest impact in the system attaining a contribution of between 52-70%.

### V.4.3.1 Contribution of the life cycle stages to the total environmental impact

Manufacturing and use of agrochemicals such as fertilizers and pesticides is the action having the highest impact in 6 of the 10 categories. Fertilizer production and use have more impact in 4 of the 6 categories

(GWP, TEP, AP and EP) which attains a contribution on impact in these categories of between 36-54%. Pesticide production and use represent 53 and 83% respectively of the impact in the categories HTP and FWAEP.

In the other 4 categories ADP, ODP, MAEP and POP the process associated with the extraction, seed-oil refining and transesterification are actions having the greatest impact. These contribute between 48-67% of the impact in these categories.

### V.4.3.2 Comparison of the total environmental impacts between biodiesel using *B.napus* edible oil and diesel

Table V.8 Environmental impacts of biodiesel and diesel.

| Impact Category & Unit | Biodiesel from *B.napus* | Biodiesel less avoided energy consumptions (glycerine and soymeal) | Diesel production (to refinery) |
|---|---:|---:|---:|
| A.D.P. (kg Sb eq.) | 0,009 | 0,0028 | 0,02 |
| G.W.P. (kg CO2 eq.) | 1,35 | 1,28 | 0,41 |
| O.D.P. (kg CFC 11 eq.) | 0,0000003 | -0,0000005 | 0.0000004 |
| H.T.P. (kg 1,4 -DB eq.) | 1,61 | -0,32 | 0,40 |
| F.W.A.E.P. (kg 1,4 -DB eq.) | 0,42 | 0,35 | 0,03 |
| M.A.E.P. (kg 1,4 -DB eq.) | 456,54 | 143,86 | 270,51 |
| T.E.P. (kg 1,4 -DB eq.) | 0,0051 | -0,019 | 0,0017 |
| P.O.P. (kg $C_2H_4$ eq.) | 0,0007 | 0,0004 | 0,0003 |
| A.P. (kg SO2 eq.) | 0,011 | 0,003 | 0,005 |
| E.P. (kg PO4--- eq.) | 0,0015 | -0,0259 | 0,0005 |

Biodiesel compared with Conventional Diesel has clearly less impact in two categories ADP and ODP. The reduction of the impact in the ADP resources category attains 86% when the avoided impacts associated with biodiesel coproducts are considered and 55% when not. In the GWP category, biodiesel system seems to be worse than Diesel as the emissions of the combustion in engine vehicles are not considered. In order to demonstrate the benefits in this category the quantity of carbon dioxide emitted for the equivalent quantity of diesel (0.87 kg diesel) used in a vehicle engine (car) is subtracted from the biodiesel GWP category (2.7 kg $CO_2 \cdot UF^{-1}$). The contribution of the biodiesel system is – 1.35 kg $CO_2$ eq. in the first case and -1.42 kg $CO_2$ eq. in the second case.

In all categories of toxicity (HTP, FWAEP, MAEP and TEP) and also in POP Biodiesel presents a poorer environmental performance except when biodiesel and the avoided impact of coproducts are subtracted, see table V.8. For acidification and eutrofization biodiesel has more impact than diesel: 52% and 66.7% respectively. The reductions of impact in these last categories when avoided impacts are considered in the biodiesel system are 34% and 50% less, respectively, when compared with conventional diesel.

## *V.4.4 Sensitivity analysis*

Results shown in table V.9 indicate that, in the worst case (minimum production 1,300 kg · $ha^{-1}$) the impact of the biodiesel system can be 52.42% higher than in the base case. On the other hand when the production of grain from *B.napus* reaches 3,635 kg · ha$^{-1}$, the environmental impact of the biodiesel system falls to 32.73%. In this case the biodiesel system only shows better environmental performance in the same categories, ADP, GWP and POP.

Table V.9 Environmental Balance variation according to the seed production obtained.

| Grain Production Variation | | | | |
|---|---|---|---|---|
| Categories analysed: | | AgroClimate | kg.ha$^{-1}$ | Biodiesel[1] |
| All impact categories | Impact Variation (%) | 400 mm | 1300 | + 52.42 |
| | | 400 mm | 2405 | + 12.85 |
| | | 850 mm | 2571 | + 6.48 |
| | | 700 mm | 2860 | - 3.65 |
| | | 600mm | 2965 | - 7.47 |
| | | 650 mm | 3342 | - 21.15 |
| | | 650 mm | 3625 | - 32.73 |

[1] Impact variation referred to average grain production assumed in this study.

The impact variation due to increasing grain transport distances from 25 km to 100 km and to 500 km is shown in table V.10. The impact categories increase their impact contribution between (0.50 - 10.20%) when the grain transport distance became 100 km and (3.10 - 41.96%) when the distance is 500 km. These increments on the impact categories produce a poorer environmental performance for biodiesel in all categories analysed but do not invert the environmental results obtained in the case study. The three environmental categories where biodiesel has environmental benefits compared with diesel continue to be better when the distance analysed is 500 km

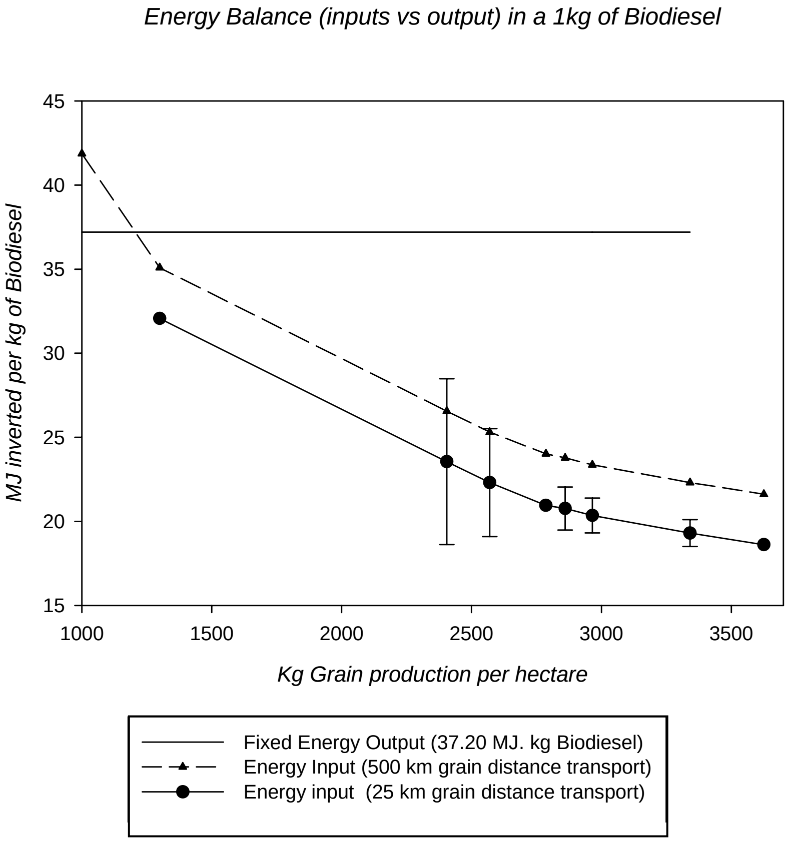
Table V.10 Environmental Balance variation according to the grain distance transported.

| Grain Production Variation | | | | |
|---|---|---|---|---|
| Categories analysed: | | AgroClimate | 100 km | 500 km |
| All impact categories And all grain productions | Impact Variation (%) | A.D. (kg Sb eq.) | 2.19 | 12.46 |
| | | GWP (kg CO2 eq.) | 2.52 | 14.11 |
| | | ODP (kg CFC 11 eq.) | 10.20 | 41.96 |
| | | HT (kg 1,4 -DB eq.) | 0.62 | 3.80 |
| | | FWAE (kg 1,4 -DB eq.) | 0.18 | 1.15 |
| | | MAE (kg 1,4 -DB eq.) | 0.88 | 5.35 |
| | | TE (kg 1,4 -DB eq.) | 0.50 | 3.10 |
| | | PO (kg $C_2H_4$ eq.) | 1.37 | 8.12 |
| | | A (kg SO2 eq.) | 3.16 | 17.19 |
| | | E (kg PO4--- eq.) | 4.74 | 24.05 |

The sensitivity analysis shows that the new energy investment range for each new situation is from 18.60 MJ invested in the lowest grain production case to 32.07 MJ invested in the highest grain production case when grain transport distance is 25 km and from 21.61 MJ invested in the lowest grain production case to 35.08 MJ invested in the highest grain production case when the transport distance is 500 km. All the new energy input are lower than the energy output obtained per kg of biodiesel (see figure V.4) and all the energy balance obtained present better results than conventional diesel.

The energy benefits of the biodiesel system are insignificant (see figure V.4) only when the grain production is almost 1,250 kg · ha$^{-1}$. In this unique case the energy invested is similar to the energy output obtained (only 2 or 5 MJ · kg biodiesel$^{-1}$ of energy benefit depends on the distance the transport considered); in the remaining production obtained in each agroclimate, the energy benefits are from 37% to 50% in local distance transport (25 km) and from 29% to 42% in regional distance transport (500 km).

Figure V.4 Relation of the energy input respect energy output obtained for each production and distribution grain scenario.



## V.5 Conclusions

The advantages detected in this study for biodiesel when compared with conventional diesel are in terms of a better energy balance, 16.25 or 35.10 MJ per kg of biodiesel when avoided impacts from rapemeal and glycerine are considered versus -9.96 MJ per the same equivalent quantity of conventional diesel. The greater part of the energy input associated with biodiesel production is incurred during the transesterification process (25.22% of the total energy input) and the industrial treatment of the seed in order to extract the oil (21.30% of the total energy input). However, the agricultural stage also has a high energy requirement such as for the diesel used throughout the agricultural phase and that used during transport (19.93% of the total energy input) and in the production of fertilizers (18.36%). In terms of environmental performance Biodiesel system presents smaller abiotic depletion resource impact and a lower contribution to global warming potential. Both categories currently have great political significance in Europe, these values therefore justify a final assessment favouring biodiesel in this case. On the other hand there are two categories in which biodiesel comes out markedly worse when compared to diesel, these are acidification and eutrofitzation 52% (0.0059 kg $SO_2 \cdot$ kg of biodiesel$^{-1}$) and 63% (0,00095 kg $PO_4{}^{-3} \cdot$ kg of biodiesel$^{-1}$) respectively. These impacts are mainly associated with the agricultural stage, necessary to produce the rapeseed production, where in order to assure minimum production intensive agricultural techniques such as mineral fertilizers are applied in the field.

Another conclusion of this study is that the use of coproducts from biodiesel process (glycerine and rapemeal) helps to improve the environmental performance of biodiesel. It appears to be necessary that these coproducts have an established capable market to absorb their production and that in this way allowing them to reduce the impact of the whole system.

On the other hand, the sensitivity analysis demonstrates that in environmental and energy terms, for agroclimates that ensure grain productions higher than 2000 kg · ha$^{-1}$ the biodiesel commercialization from *B. napus* energy crop is suitable for an energy local and regional production and distribution strategy. Otherwise when the grain productions is reduced to 1,250 kg · ha$^{-1}$ or less the energy benefit in both production and distribution strategies (25 km or 500 km) is not suitable in energetic and environmental terms.

Furthermore and based on the results obtained, the environmental and energy performance of the system could be improved by changing the mineral fertilizers used to alternative ones from agriculture, agribusiness, livestock waste, etc [11] and by reducing the energy-insensitive demand of the industrial process to obtain biodiesel.

The methodology described in this study allows us to determine which Mediterranean agroclimate regions are suitable from an energy and environmental point of view to be designated as agricultural areas to produce *B.napus* destined for biodiesel. Being agroclimates “C”, “D” and “B” the best for biodiesel production in the case studt area.

The present assessment should be integrated into the environmental evaluation of the Mediterranean bioenergy projects based on energy crops as a renewable energy source in order to ensure the sustainable performance not only of the power plant but also of the biomass that is used as a renewable source of energy.

## V.6 References to chapter V

[1] European Parliament, Directive 2003/30/EC on the production of the use biofuels or other renewable fuels for transport. European Parliament and the Council 2003. European Unión 2003.

[2] Civil Subchefia para Assuntos Jurídico PdRC. Lei No 11097, de 13 de Janeiro de 2005, Brasil 2005

[3] El Senado y Cámara de Diputados de la Nación Argentina. Ley 26.093 Régimen de Regulación y Promoción para la producción y usos sustentables de Biocombustibles. Autoridad de aplicación. Comisión Nacional Asesora. Habilitación de plantas productoras. Mezclado de biocombustibles con combustibles fósiles. Sujetos beneficiarios del régimen promocional. Infracciones y sanciones, Argentina, 2006

[4] Vicente G., Martínez M., Aracil J.A, A comparative study of vegetable oils for biodiesel production in Spain, Energy & Fuels 20 (1) (2006) 394-398.

[5] Mittelbach M., Remschmidt C., Biodiesel the comprehensive handbook, Boersedruck Ges.m.b.H, Viena (Austria), 2005.

[6] Talens L., Villalba G., Gabarrell X. Exergy analysis applied to biodiesel production, Resources, Consevation & Recycling 51 (2007) 397-407.

[7] AENOR, Gestión Medioambiental. Análisis de Ciclo de Vida. Evaluación de impacto de ciclo de Vida. ISO14042:2000, España, 2000.

[8] International Standardisation Organisation. ISO 14040: Environmental management - Life cycle assessment - Principles and Framework, Geneve (Switzerland), 2006.

[9] Boustead I., Hancock G.F., Handbook of industrial energy analysis, in: Frischknecht R., Jungbluth N. (Eds.), Implementation of life cycle assessment methods Ecoinvent Report, Swiss Centre for Life Cycle Inventories, Dübendorf. (Switzerland), 2003.

[10] Pimentel D. Food production and the energy crisis, in: Frischknecht R., Jungbluth N., (Eds.), Implementation of life cycle assessment methods Ecoinvent Report, Swiss Centre for Life Cycle Inventories, Dübendorf, (Switzerland), 2003.

[11] Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P., Solano M.L. & Rieradevall J. Life cycle assessment of a *Brassica carinata* bioenergy cropping system in southern Europe. Biomass & Bioenergy 31 (2007) 543-555.

[12] Frischknecht R., Jungbluth N., H.J. Althaus, G. Doka, T. Heck, S. Hellweg. Overview and Methodology, Swiss Center for Life Cycle Inventories, Dübendorf (Switzerland), 2004.

[13] Audsley E. Harmonisation of environmental life cycle assessment. Final Report Concerted action AIR-CT94-2028. European Commision DG VI Agriculture, 1997.

[14] Brentrup F., Kusters J., Kuhlmann H., Lammel J.. Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. European Journal of Agronomy 2001, 14 (1) (2001) 221-233.

[15] Braschkat J., Gärtner S.O., Reinhardt A. Life Cycle Assessment of Biodiesel: Update and New Aspects. IFEU- Institute for Energy and Environmental Research Heidelberg GmbH, Heidelberg (Germany), 2003.

[16] Bernesson S., Nilsson D., Hansson P.A.. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. Biomass & Bioenergy, 30 (1) (2006) 46-57.

[17] Koipesol Spain. Personal communication. 2007.

[18] Bernesson S., Nilsson D., Hansson P.A. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions . Biomass & Bioenergy 26 (2004) 545-559

[19] Lechón Y., Cabal H., de la Rúa C., Izquierdo L., Sáez R.M. & San Miguel M. Análisis de Ciclo de Vida de Combustible alternativos para el Transporte. Fase II. Análisis de Ciclo de Vida Comparativo del Biodiésel y del Diésel, Centro de Publicaciones Secretaría General Técnica Ministerio de Medio Ambiente, Madrid (Spain), 2006.

[20] Fertiberia Leader Entreprise of the sector of agrichemicals in Spain 2007. Available from <http://wwwfertiberiacom>. Accessed: April 2007.

[21] Castro M.B.G, Remmerswaal J.A.M., Reuter M.A., Life cycle impact assessment of the average passenger vehicle in the Netherlands. International Journal of Life Cycle Assessment 8 (5), (2003), 297-304.

[22] Faith W.L., Keyes D.B., Clark R.L., Industrial Chemicals, John Willey & Sons New York, 1957.

[23] Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S. & Blaser S., Life Cycle Inventories of Agricultural Production Systems. Final Report Ecoinvent 2000 FAI Reckenholz, Swiss Centre for Life Cycle Inventories, Dündendorf, Retrieved from: www.ecoinvent.ch , 2003 .

[24] Márquez L., Máquinaria para la preparación del suelo, la implantación de los cultivos y la fertilización VIII, Blake & Helsey, Madrid (España), 2001.

[25] Márquez L., Maquinaría Agrícola: preparación primaria , trabajo del suelo, siembra, plantación y transplante, Blake & Helsey, Madrid (España) 2004.

[26] Amman HiNT. Maschinenkosten 2000 - Kostenansatze Gebaudeteile und mechantsche Einrichtungen Life Cycle Inventories of agricultural production system, Dübendorf, 2003.

[27] Frischknecht R., Bollens U., Bosshart S., Ciot M., Ciseri L., Doka G., Dones R., Gantner U., Hirschier R., Martin A., in Nemecek T. (Ed.). Ökoinventare von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Life Cycle Inventories of agricultural production system, Dübendorf , 2003.

[28] Maibach M., Peter D., Seiler B., in Nemececk T., (Ed.) . Ökoinventar Transporte Grundlagen für den ökologischen Vergleich von Transportsystem und für den Einbezug von Transportsystemen in Ökobilanzen. Life Cycle Inventories of agricultural production systems, Dubendorf; 2003

[29] Volvo Truck. Emission from Volvo's Truck Emissions, standard diesel fuel. Available from: www.volvotruck.com, 2003.

[30] SAEFL in Nemecek T. (Ed.). Handbuch Offroad-Datebank, Life Cycle Inventories of agricultural production systems, 56, 2003..

[31] Davis J.H., Life Cycle Inventori (LCI) of Fertilize. Production-fertilizer products used in Sweden and Wester Europe. Life Cycle Inventories of agricultural production system, Dübendorf, 2003.

[32] Green M., Energy in pesticide manufacture, distribution and use. Life Cycle Inventories of agricultural production system, Dübendorf, 2003.

[33] Narain M., Singh B.P.N., Energy profile of a seed-processing plant . Applied Energy 30 (3) 1998 227-234.

[34] Brentrup F., Kusters J., Lammel J., Barraclough P., Kuhlmann H. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology - II. The application to N fertilizer use in winter wheat production systems. European Journal of Agronomy 20, (2004), 265-279.

[35] Heller M.C., Keoleian G.A., Volk T.A. Life cycle assessment of a willow bioenergy cropping system. Biomass & Bioenergy, 25 (2), (2003), 147-165.

[36] Brentrup F., Kusters J., Kuhlmann H. & Lammel J.. Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. European Journal of Agronomy, 14 (3) (2001); 221-233.

[37] Brentrup F., Küsters J., in Weidema B., & Meeusen M. (Eds.). Methods to estimate to potential N emissions related to crop production. Agricultural data for life cycle assessments. Agricultural Economics Research Insitute, The Hague, The Netherlands 2000 ,

[38] Ciria P., Mazón M.P., Carrasco J.E. *Populus spp.* productivity evolution on short rotation during three consecutive cycles in extreme continental climate. 2 nd World Conference on Biomass for Energy, industry and Climate Protection, 10-14 May 2004, Rome; Italy
2004.

[39] Hauschild B. in MZiW, & M. Meeusen (Eds), Estimating pesticide emissions for LCA of agricultural products. Agricultural data for life cycle assessments LCANet Food The Hague (Netherlands) 2000.

[40] Guinee J. Life Cycle Assessment An operational guide to the ISO standards, 1, 2 3. Centre of Environmental Science Leiden University, Leiden, 2001.

# Chapter VI. Feasibility assessment of *Populus spp.* bioenergy systems in the southern Europe

*Published as: Gasol CM. Martinez S., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P. and Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable & Sustainable Energy Reviews 13 (2009) 801-812.*

*Photografy by Carles Martinez Gasol. Italy 2008.*

# Abstract

A detailed reliability assessment of bioenergy production systems based on poplar cultivation was made. The aim of this assessment was to demonstrate the Economic feasibility of implementing poplar biomass production for power generation in Spain. The assessment considers the following chain of energy generation: cultivation and harvesting, and transportation and electricity generation in biomass power plants (10, 25 and 50MW). Twelve scenarios were analysed in accordance with the following: two harvesting methods (high density packed stems and chip production in the field), two crop distributions around the power plant and three power plant sizes. The results show that the cost of biomass delivered at power plant ranges from 18.65 to 23.96 €·Mg$^{-1}$ dry basis. According to power-plant size, net profits range from 3 to 22 million € per year.

Sensitivity analyses applied to capital cost at the power plant and to biomass production in the field demonstrate that they do not affect the feasibility of these systems. Reliability is improved if benefits through selling $CO_2$ emission credits are taken into account.

This study clears up the Economic uncertainty of poplar biomass energy systems that already has been accepted as environmentally friendlier and as offering better energetic performance.

*Keywords: energy crops, supply chain, power plant, final biomass cost.*

## VI.1 Introduction

Interest in the production of biomass by means of energy crops has increased over the last forty years in Europe. Northern and Central European countries began to promote energy crops after the oil crises of the mid-1970s mainly in an attempt to counteract escalating prices [1, 2]. Southern European countries such as Spain did not pay appropriate attention to the endeavour to produce additional renewable sources [2]. Currently, the promotion of biomass as a renewable energy is an important target for European policies, being incorporated within national policies [3-5]. Biomass-based electricity is promoted in the Renewable Electricity Directive, which aims to increase the use of renewable energy sources to 20% by 2020[4]. Spain, in common with many other countries in the European Union, does not have great reserves of petroleum or natural gas, and therefore needs to import around 75% of the total energy demand[6]. Biomass produced as energy crops on a national scale can be an opportunity to reduce external energy dependency.

The biomass from energy crops as a renewable energy source is seen as a significant contributor to the carbon dioxide abatement strategy aiming at an 8% reduction in Europe, as required by the Kyoto protocol. Within the European objective, Spain has been requested not to increase more than 15% over the 1990 emission levels by 2012. [7-10].

Some of the energy crops analysed in experimental and demonstration parcels for their implementation in Mediterranean areas are annual species such as Ethiopian Mustard (*Brassica carinata*) [11, 12], Cardoon (*Cynara cardunculus*)[13, 14], Sweet sorghum (*Sorghum bicolor L.*) [14, 15] as well as short rotation coppices (SRC) such as Poplar (*Populus sp.*)[16] or Eucalyptus (*Eucalyptus globulus*)[17] .

In accordance with the national Renewable Energy Plan, biomass must contribute 29.67% to the total renewable energy production for the year 2010 [5]. Energy crops are seen in the Spanish plan as a significant part of the strategy to achieve the expected energy objectives (3.35 Mtep) [5, 18].

The *Populus spp.* crop has been selected in this study because of its friendlier overall environmental performance and its high biomass-production yields per hectare in Mediterranean areas [3]. An environmental disadvantage of this crop is its high consumption of water, which is a limited resource in Spain and other Mediterranean countries[19]. Given this limitation, the implementation of *Populus spp.* as an energy crop competes with other crops in areas having sufficient water and land availability [20]. Currently in Spain, these areas are extensively occupied by woody crops aiming to produce wood for the paper and packaging industries. Additionally the implementation of this crop in unexploited marginal areas is also under consideration [21].

In this context, the main aim of this study is to examine the economic viability of the production of energy by means of biomass produced in poplar energy crops. The feasibility study also takes into account the marginal benefit of $CO_2$ emission reduction when substituting fossil fuel.

# VI.2 Methodology

In the following lines methodology applied to *Populus spp.* bioenergy system economic assessment is presented.

## *VI.2.1 The Populus spp. bioenergy system analysed*

The feasibility study analyses the three main subsystems of energy production with *Populus spp.* biomass in Spain: a) *Populus spp.* cultivation and harvesting, b) transport and c) energy conversion.

*Populus spp.* cultivation stages cover a 16-year period, including three five-year rotations. The best period considered for harvesting is during the autumn and winter, when leaves have fallen. This improves both the handling of poplar biomass and the efficiency of the harvesting operation [22]. Table VI.1 shows the agricultural labour covered throughout the entire cycle of the *Populus spp.* crop. Water irrigation and the associated energy consumption are not included in the analysis.

Table VI.1 *Populus spp*. field labours timeline.

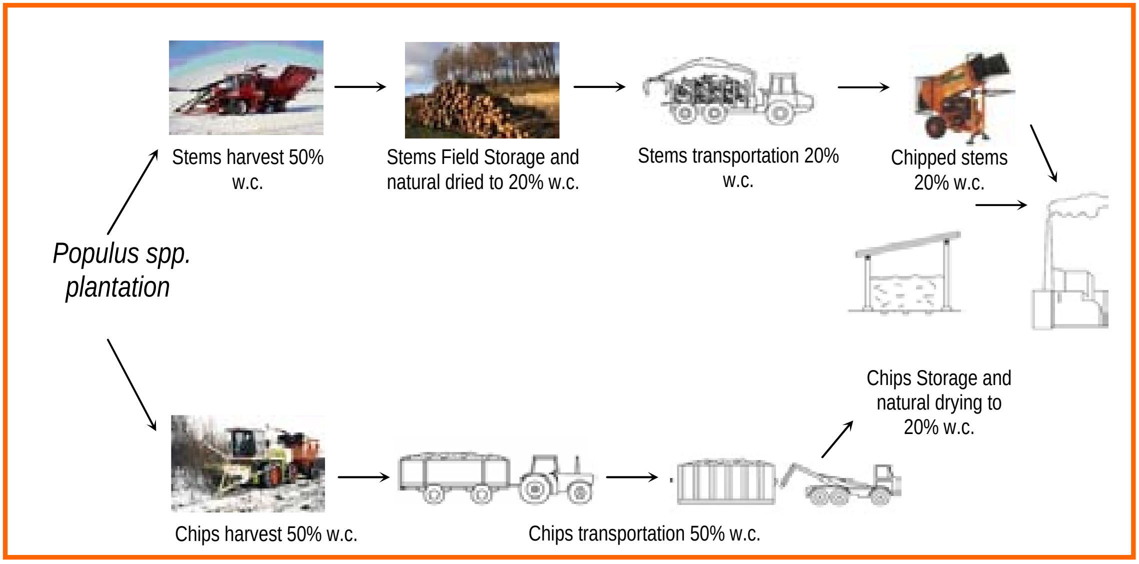
| Year | Activity |
|---|---|
| 0 | Plow, base fertilisation, herbicide, plant, first cut. |
| 1, 6, 7and 11,12 | Herbicide or insecticide application or no labour. |
| 2, 8 and 13 | Top fertilisation (during the first cycle) or Base fertilisation (during the rest). |
| 3, 9 and 14 | No labour (during the first cycle) or top fertilisation (during the rest). |
| 4, 10 and 15 | No labours |
| 5, 11 and 16 | Biomass harvest and Elimination of the poplar stools during the last cycle. |

*Populus spp.* biomass has an initial moisture content of about 50% at harvesting. Two alternatives for harvesting were analysed: production of high-density packed stems and chip production. In the case of packed-stem production, biomass fuel is left in the field to reduce water content to 20% through natural drying. Stems stored in the field are then transported to the power plant and chipped regularly according to the normal delivery schedule over the working period of the plant (333 days·yr$^{-1}$).

As regards the option of chip production, the poplar is immediately chipped in the harvesting period (150 days·yr$^{-1}$) [23] and is then directly transferred to the power plant for storage. A moisture content reduction has to be achieved at the plant, to about 20%, for better combustion.

In both cases, poplar biomass is assumed to be transferred by truck from the field to the combustion plant, applying the load limit authorized in Spain. Transport and disposal of ashes produced in the bioenergy conversion plant are included as a part of the system under study.

Figure VI.1 Sheme of the system under study.



### VI.2.1.1 Scenarios analysed

Twelve scenarios are defined for the economic poplar feasibility study. These assume an average *Populus spp.* production of 13.5 Mg.ha$^{-1}$ d.b., and include travel distance according to the occupancy of cropping area *(Cd)* area around the power plant. These scenarios are detailed in Table VI. 2.

Table VI.2 *Populus spp.* biomass base case scenarios definitions.

| Scenario | Biomass transported | Power | Pr (Mg ·ha $^{-1}$ · year $^{-1}$) | Crop Distribution Area *(Cd)* |
|---|---:|---|---:|---:|
| Sc. 1 | stems | 10 MW | 13.5 | 90 % |
| Sc. 2 | stems | 10 MW | 13.5 | 10 % |
| Sc. 3 | stems | 25 MW | 13.5 | 90 % |
| Sc. 4 | stems | 25 MW | 13.5 | 10 % |
| Sc. 5 | stems | 50 MW | 13.5 | 90 % |
| Sc. 6 | stems | 50 MW | 13.5 | 10 % |
| Sc. 7 | chips | 10 MW | 13.5 | 90 % |
| Sc. 8 | chips | 10 MW | 13.5 | 10 % |
| Sc. 9 | chips | 25 MW | 13.5 | 90 % |
| Sc. 10 | chips | 25 MW | 13.5 | 10 % |
| Sc. 11 | chips | 50 MW | 13.5 | 90 % |
| Sc. 12 | chips | 50 MW | 13.5 | 10 % |

## *VI.2.2 Supply and logistical aspects for the poplar bioenergy system*

Biomass required for the power plant, land-crop surface required to produce this quantity of poplar biomass and the logistical needs expressed in number of trucks required to transfer the biomass are calculated to determine the effect on the economic performance of the system.

### VI.2.2.1 *Populus spp.* biomass required as a fuel for a bioenergy conversion plant

Annual biomass requirements *(BF)* for biomass power plants are calculated taking into account the poplar's Low Heating Value (LHV) [18.2 MJ.kg$^{-1}$ (d.b.)] [24], the number of operation hours over a year (8,000 h) and plant efficiency (25, 28 and 30% for 10, 25 and 50 MW, respectively) [25]. Supply requirements for each plant are detailed in Table VI. 3.

Table VI.3 *Populus spp.* biomass supply for each plant.

| Power (MW) | *Populus spp.* requirement (Mg d.b.) | *Populus spp.* requirement (Mg 20% w.c.) |
|---:|---:|---:|
| 10 | 63,297 | 79,120 |
| 25 | 141,287 | 176,610 |
| 50 | 263,737 | 329,671 |

### VI.2.2.2 Cropping area required by a biomass power plant and transport distance

Considering the annual biomass fuel requirement *BF* (Mg) for a 10, 25 and 50 MW biomass power plant, the cropping area needed to supply a power plant *CA* (ha) is calculated through cropping productivity *Pr* (Mg ·ha $^{-1}$ · year $^{-1}$ ). See equation (VI.1).

$$CA = \frac{BF}{\mathrm{Pr}} \qquad \text{(eq. VI.1)}$$

A poplar-production yield variation of between 9 to 20 Mg (d.b.)·ha$^{-1}$.year$^{-1}$ was considered and a value of 13.5 Mg (d.b.)·ha$^{-1}$.year$^{-1}$ (see table 2) was assumed as average in the present study.

The area cultivated has a direct influence on the total distance of transport. Medium transport ratio to be appealed by biomass fuel supplier trucks *D* (km) is estimated, as follows:

$$D = \left( \frac{A}{2 \cdot \pi \cdot Cd \cdot 100} \right)^{0.5} \qquad \text{(eq. VI.2)}$$

Where A is the cultivation area, Cd is Crop distribution area and $\pi$ .

### VI.2.2.3 Number of trucks required for biomass poplar transportation

Number of trucks needed daily to supply a biomass power plant is defined from the total biomass fuel required for the power plant, the daily number of trips made by a truck and the daily biomass transported by a truck.

Table VI.4 shows the number of trips made by a 16 Mg truck per day, from the field to the power plant considering legal speed limits for a 16 Mg truck, loading and unloading time for poplar packed stems (high density) and chips, travel time by road and traffic incidents time. Trips per day made by a truck (*e*) were calculated by means of the truck driver's labour journey time (8 hours per day) divided by total travel time.

Table VI.4 Trips per day made by a truck transporting stems and chips from the field to the power plant.

| | Stem | Chip | Stem | Chip | Stem | Chip | Stem | Chip | Stem | Chip | Stem | Chip |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance from field to power plant (km) | *(a)* Going and return time by road (h) | | *(b)* Loading time for a truck (h) | | *(c)*Unloading time at plant (h) | | *(d)*Transport time lost by traffic (h) | | TOTAL TIME by travel *(e) =(a) + (b) + (c) + (d)* | | Travels per day made by a truck (Tpd) | |
| 1 – 5 | 0.16 | | 0.8 | 0.16 | 0.33 | 0.16 | 0.16 | 0.16 | 1.45 | 0.64 | 5.5 | 12.5 |
| 5 – 10 | 0.33 | | | | | | | | 1.62 | 0.81 | 5 | 9.5 |
| 10 – 20 | 0.58 | | | | | | | | 1.87 | 1.06 | 4.5 | 7.5 |
| 20 – 30 | 0.83 | | | | | | | | 2.12 | 1.31 | 4 | 6 |

The *Populus spp.* biomass transported daily by a truck was calculated according to the maximum weight and volume of a load per truck (16 Mg legal practical load for a Spanish regional transport truck)[26]. For a biomass density value higher than 340 kg.m$^{-3}$, load weight becomes a limiting factor in transport. On the other hand, for density values lower than these, the volume of biomass limits transport load. The assumed high density packed stem density is 310 kg·m$^{-3}$ (20% w.c), while harvested chip density is 280 kg (50% w.c).m$^{-3}$. Furthermore, the different intensity of transport necessities for both biomass fuels (stems and chips) were considered in order to calculate the total number of required trucks.

Table VI.5 Trucks needed to supply fuel to a power plant and total transport distance.

| | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 | Sc. 7 | Sc. 8 | Sc. 9 | Sc. 10 | Sc. 11 | Sc. 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity of biomass transported per day (Mg) | 238 | 238 | 530 | 530 | 990 | 990 | 844 | 844 | 1,884 | 1,884 | 3,516 | 3,516 |
| Trucks acquired to transport poplar biomass | 3 | 4 | 7 | 8 | 14 | 15 | 7 | 9 | 14 | 19 | 34 | 43 |

## VI.2.3 Cost and benefit analysis

In the following lines cost and benefit analysis applied to *Populus spp.* bioenergy system is presented.

### VI.2.3.1 *Populus spp.* cultivation and harvesting

Biomass-cultivation cost includes investment, depreciation and operational costs (the total cost for the agricultural machinery), agrichemical acquisition and use and maintenance of agricultural parcels, all of which influences the total cost of cultivation and harvesting [27].

#### VI.2.3.1.1 Total cost of agricultural machinery

Total cost of agricultural machinery (TCAM) considers the fixed costs (FCH) and variable cost per hectare (VCH). FCH include depreciation with an interest rate of 4.75% [28], and all insurance.

VCH includes fuel consumption by agricultural tractors and harvest as well as lubricants, grease, replacement of parts, repairs and maintenance. Table VI.6 shows the value of the components taken into account over the economic assessment of the agricultural subsystem.

Table VI.6 Economic values used to calculate the fixed and variables cost during the cultivation and harvesting subsystem (2006).

| Component | Cost |
|---|---|
| **Fixed Cost parameters** | |
| Tractor investment [27] | 71,560 € |
| Harvest investment (stems) [31] | 216,216 € |
| Harvest investment (chips) [31] | 225,225 € |
| Re-sell price of machinery[27] | 15% P |
| Machinery lifetime in hours[27] | 12,000 hours |
| **Variable Cost parameters** | |
| Diesel Agricultural Spanish price 2006 [43] | 0.67 €.$l^{-1}$ |
| Diesel consumption | 316-330 l.$ha^{-1}$ |
| Oil lubricant proportion cost respect diesel [27] | 4.50% |
| Grease lubricant proportion cost respect diesel [27] | 10% |
| Machinery material life time (replacement) [27] | 2500 hours |
| Pneumatic cost [27] | 3.364 € |
| Repairs and maintenance [27] | 85% of the acquisition price of machinery |
| *Labour cost [27]* | *14.43 €.hour*$^{-1}$ |

Where possible, the use of common agricultural equipment is assumed (e.g., a tractor). For prototype equipment, information from the literature is used. Large machines are assumed to be operated by contractors because the machines are usually too expensive for one farmer only. To enable a relevant comparison, cost calculations of machines that can only be used for poplars are based on full utilization.

### VI.2.3.2 Transportation Cost.

Economic evaluation of poplar transport to the power plant was based on:

- Investment related to trucks and loading systems;
- Maintenance and reparation costs related to trucks;
- Operating costs related to labour cost and diesel consumption.

In order to model the long-term costs for transport machinery, contractor costs based on prices from [29, 30] were used. Labour cost was assigned from the bibliography [27, 31]. Input data used to describe transportation cost are shown in table VI.7.

Table VI.7 Component of total transport cost evaluation (2006).

| Component | Factor | Cost (€/truck) |
|---|---|---|
| Truck investment (chips transport) | Ic | 70000 [29] |
| Truck investment (stems transport)* | Is | 98000 [29] |
| Truck driver labour cost (chips transport) | Lc | 21080 ·year$^{-1}$ [29] |
| Truck driver labour cost (stems transport) | Ls | 25960 ·year$^{-1}$,[29, 30] |
| Annual Maintenance and Reparation cost (chips transport) | Mc | 0.5 · Ic · lifetime $^{-1}$ (7 yr) [30] |
| Annual Maintenance and Reparation cost (stems transport) | Ms | 0.5 · Is · lifetime $^{-1}$ (7 yr) [30] |

### VI.2.3.3 Operating-cost calculation for transport at power plant site

Assuming both the same number of truck drivers as the daily trucks used to supply the power plant and driver salary (Table VI.7), labour cost was calculated according to the transportation periods.

Diesel cost by trucks is directly calculated from the distance needed to be covered between the biomass power plant and the cultivations, number of trips made by a truck during the transportation period and the trucks needed daily to supply the power plant. In addition, a diesel consumption of 0.335 litres·km$^{-1}$ [32] and a Spanish diesel cost of 0.9751 €·litre$^{-1}$ were assumed, based on the average cost for 2006 [33].

## *VI.2.4 Chipping Cost at Plant*

When biomass in the form of stems arrives at the plant, the chipping process has to be made in order to introduce the biomass to the boiler. Assumed chipping cost at the power plant is 2.83 €·Mg$^{-1}$ *Populus spp*. stems[31].

## *VI.2.5 Ash transportation and disposal cost*

Ash transportation and disposal cost was calculated from the quantity of ash generated per Mg of biomass burned at the plant (0.02 Mg of ash · Mg biomass burned$^{-1}$) [34] These costs include total transportation costs for the ash generated, assuming a distance of 25 km and disposal taxes in Catalan landfills (72 €·Mg$^{-1}$).

## *VI.2.6 Power plant*

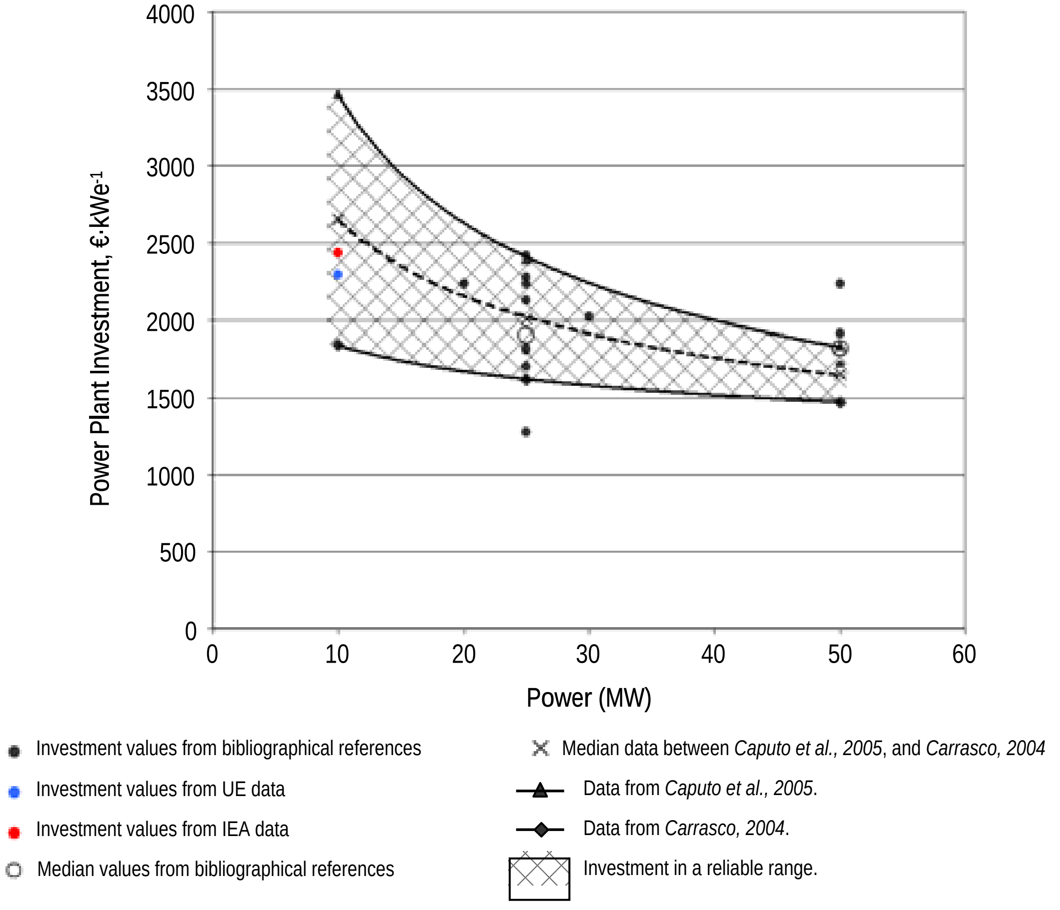
Power plant costs of 10, 25 and 50 MW were analysed with the purpose of obtaining economic reliability using *Populus spp*. as a biomass fuel.

### VI.2.6.1 Power plant investments

A range of investments for each power plant was considered as generalisable to the Spanish case, selecting average data to obtain an approximation of realistic economic values. Figure VI.2 shows investment data range considered to the economic study. Expression VI.3 shows a mathematical correlation between power and the investment carried out (€·kWe $^{-1}$):

$$\text{Biomass Power Plant Capital} = 5217 \cdot MW^{0.2946} \quad \text{(VI.3)}$$

Figure VI.2 Biomass power plant investments, data considered in the study.



Source: [24,35, 35-40]

### VI.2.6.2 Plant Maintenance and operating costs

Plant Maintenance costs was calculated as 1.5% of total plant investment according to the bibliography [25]. Table 8 shows the number of plant workers considered in order to estimate power plant operating costs [24, 25]. Insurance and other minor plant costs were calculated as 1% of total plant investment [25].

Table VI.8 Number of workers and labour cost at 10, 25 and 50 MW biomass power plants.

| Power Plant | Plant Workers |
|---:|---:|
| 10 MW | 8 |
| 25 MW | 12 |
| 50 MW | 19 |

### *VI 2.7 Annual benefits and economic feasibility indicators used*

Annual benefits earned were calculated according to the current electric tariffs for biomass energy plants, as established by Spanish Royal Decree 661/2007 [41].

To define the economic feasibility for each scenario, economic indicators such as Simple Payback Period (SPP), Net Present Value (NPV) and Internal Rate of Return (IRR) were used. An interest rate of 4.75% [28] and a 20-year period were considered for NPV calculation.

### *VI.2.8 Sensitivity analysis*

Three independent sensitivity analyses were carried out using the following variables: investment cost, $CO_2$ benefits from selling emissions credits and biomass crop yield.

A plant investment cost variation of 10% was studied and a $CO_2$ price range per Mg from 5 to 50 €·Mg $CO_2^{-1}$ with a $CO_2$ generating factor from coal (0.95 Mg $CO_2 \cdot MWh^{-1}$) [9] was analysed. Finally, new economic feasibility rates were calculated, taking into account crop-yield variation from 9 to 20 Mg (d.b.) $\cdot ha^{-1}$.

## VI.3. Results

In the following lines the results obtained of *Populus spp.* bioenergy system economic assessment are presented.

### *VI.3.1 Biomass production and harvesting cost.*

The total cost production for *Populus spp.* biomass reached 3.065 or 3.342 € · $ha^{-1}$ over the 16 crop years depending on whether biomass was harvested in stems or chips. This implies a yearly production cost of poplar biomass of 197 €$\cdot ha^{-1} \cdot yr^{-1}$ when the poplar is harvested as stems and 209 €$\cdot ha^{-1} \cdot yr^{-1}$ when harvested as chips. Biomass production cost will vary according to total biomass production obtained during the different harvesting periods.

Table VI.9 shows the variability of *Populus spp.* biomass cost · $Mg^{-1}$ according to the different biomass productions and harvesting methods considered.

Table VI.9 *Populus spp*. production and harvesting biomass tonne cost (€. Mg$^{-1}$ d. b. · yr$^{-1}$).

| | | *Biomass production (Mg d.b . ha$^{-1}$· yr$^{-1}$)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *9.00* | | *13.50* | | *15.00* | | *20.00* | |
| | | *Stems* | *Chips* | *Stems* | *Chips* | *Stems* | *Chips* | *Stems* | *Chips* |
| Total Machinery Cost | Fixed costs | 3.89 | 4.98 | 2.79 | 3.32 | 2.33 | 2.99 | 1.75 | 2.24 |
| | Variable costs | 2.15 | 2.33 | 1.43 | 1.55 | 1.29 | 1.40 | 0.97 | 1.05 |
| Labour cost | | 2.41 | 3.06 | 1.81 | 2.04 | 1.45 | 1.84 | 1.09 | 1.38 |
| *Agrochemicals acquisition* | | *7.85* | *7.85* | *5.24* | *5.24* | *4.71* | *4.71* | *3.53* | *3.53* |
| *Use and maintenance of the parcel* | | *4.98* | *4.98* | *3.32* | *3.32* | *2.99* | *2.99* | *2.24* | *2.24* |
| *Total Cost production* | | *21.89* | *23.22* | *14.59* | *15.48* | *12.77* | *13.93* | *9.58* | *10.45* |

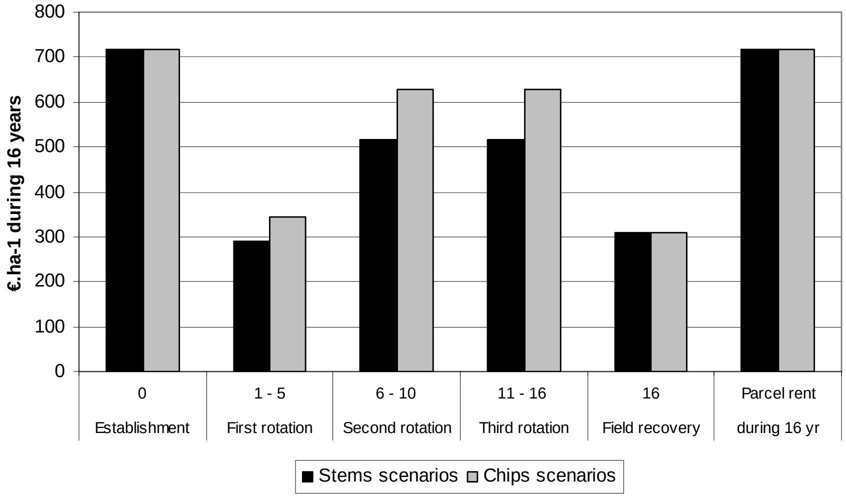
In the case of poplar stems, the cost of dry biomass production per tonne and of harvesting oscillates from 9.58 to 21.89 €.Mg$^{-1}$ d.b. · yr $^{-1}$ depending on the total biomass production obtained per hectare. For chip production, the maximum cost obtained is 23.22 €.Mg$^{-1}$ d.b. yr $^{-1}$ with a minimum of 10.45 €.Mg$^{-1}$d.b. yr $^{-1}$. These ranges are comparable with the values obtained in other studies that analyse the cost production and harvest for short rotation crops aimed at biomass production. In these studies the specie selected was willow. The biomass cost in the field after harvesting was 13.88 €.Mg$^{-1}$ d.b. for stem production and 14.76 €.Mg$^{-1}$ d.b. for chip production. Both cases consider an average biomass production of 8 to 12 Mg dry matter with an overall cultivation period of 20 years [31]. According to other studies where poplar is cultivated for 8 years [42], poplar biomass cost is 56 €.Mg$^{-1}$ d.b. The main reason for this variability is the total cultivation period of the crop under exploitation. When short-rotation crops are cultivated over large periods (16 - 20 years), the final biomass cost is less in comparison with shorter rotation times.

Chip production in the field has higher costs compared with stem production due to fixed and variable costs for major machinery as well as to the higher labour costs involved.

For both biomass types (stem and chip), the agrochemical acquisition and parcel-land rent are the main cost that the farmer has to assume. Both represent between 55.31 - 60.31% of the total biomass production cost.

When total cropping cost is grouped in periods, the results obtained show that the most expensive period is the crop implementation year. The two next most expensive periods are the second and third rotation. First rotation and land-restoration work are the lowest cost periods for labour. In contrast, parcel-rent cost is one of the most expensive costs that the farmer has to face in the conditions studied. (see figure VI.3).

Figure VI.3 Contributioin of the agricultural labours to total biomass cost production.



## VI.3.2 Transportation cost

Results in table VI.10 show that chip-transportation cost are, in certain cases, 65% higher than stem-transportation cost for the same quantity of biomass supply (in terms of energy values).

For stem transportation, labour cost is the most expensive factor in the final transportation cost. This represents from 40 to 50% of total transportation cost.

On the other hand, depreciation is the most expensive factor in the final chip transportation cost, representing from 20 to 30% of total transportation cost.

Table VI.10 Total biomass transport cost to the biomass power plant.

| Scenario | | Transport depreciation ($10^3$ €·$y^{-1}$) | Operating costs | | Maintenance costs ($10^3$ €·$y^{-1}$) | TOTAL ($10^3$ €·$y^{-1}$) |
|---|---|---|---|---|---|---|
| | | | Labor cost ($10^3$ €·$y^{-1}$) | Diesel Fuel cost ($10^3$ €·$y^{-1}$) | | |
| Stems | Sc. 1 | 42 | 77 | 10 | 21 | 150 |
| | Sc. 2 | 56 | 84 | 31 | 23 | 193 |
| | Sc. 3 | 112 | 171 | 34 | 46 | 349 |
| | Sc. 4 | 112 | 209 | 102 | 56 | 479 |
| | Sc. 5 | 196 | 352 | 87 | 95 | 730 |
| | Sc. 6 | 210 | 391 | 260 | 105 | 966 |
| Chips | Sc. 7 | 70 | 51 | 49 | 31 | 201 |
| | Sc. 8 | 90 | 67 | 146 | 41 | 343 |
| | Sc. 9 | 140 | 113 | 162 | 69 | 484 |
| | Sc. 10 | 190 | 149 | 486 | 91 | 916 |
| | Sc. 11 | 340 | 278 | 413 | 170 | 1201 |
| | Sc. 12 | 430 | 353 | 1239 | 215 | 2237 |

The final biomass cost related to transport mainly depends on the truck driver labour cost and diesel costs when the distances involved are important. The results obtained allow us to assume that a truck depreciation variation will not notably affect biomass transportation cost.

### *VI.3.3 Final biomass cost*

Biomass production, transportation and chipping costs (for stems only) are aggregated, giving the final biomass cost up to the biomass power plant [€·Mg$^{-1}$ d.b.] (Table VI.11).

Chip costs at plant were calculated to be from 18.65 to 23.96 €·Mg$^{-1}$, thus attaining higher costs than for stems transported and chipped at the plant, where the final biomass cost calculated varies from 19.79 to 21.09 €·Mg$^{-1}$ d.b..

Table VI.11 Biomass fuel cost at plant.

| Scenario | | Biomass production and harvesting cost (€·Mg$^{-1}$ d.b. biomass) | Transportation cost (€·Mg$^{-1}$ d.b. biomass) | Chipping cost (€·Mg$^{-1}$ d.b. biomass) | TOTAL cost (€·Mg$^{-1}$ d.b. biomass chips) |
|---|---|---|---|---|---|
| Stems | Sc. 1 | 14.59 | 2.37 | 2.83 | 19.79 |
| | Sc. 2 | 14.59 | 3.05 | 2.83 | 20.48 |
| | Sc. 3 | 14.59 | 2.47 | 2.83 | 19.89 |
| | Sc. 4 | 14.59 | 3.39 | 2.83 | 20.82 |
| | Sc. 5 | 14.59 | 2.77 | 2.83 | 20.19 |
| | Sc. 6 | 14.59 | 3.66 | 2.83 | 21.09 |
| Chips | Sc. 7 | 15.48 | 3.17 | - | 18.65 |
| | Sc. 8 | 15.48 | 5.43 | - | 20.91 |
| | Sc. 9 | 15.48 | 3.43 | - | 18.91 |
| | Sc. 10 | 15.48 | 6.48 | - | 21.96 |
| | Sc. 11 | 15.48 | 4.55 | - | 20.03 |
| | Sc. 12 | 15.48 | 8.48 | - | 23.96 |

Comparing the results of final biomass cost obtained with others studies, we observe that SRF crops such as poplar or willow have a similar final cost in a local or regional scenario. In the case of this comparative study [31], the supply cost of stems and chips had a range of 17.6 to 26.1 €. Mg$^{-1}$ d.b.

## VI.3.4 Economic results of biomass power plants

As biomass cost is the factor contributing most to total plant cost, excepting 10 MW power plants, depreciation weight decreases as power plant size increases. Table VI. 12 shows the economic results for biomass power plants defined in each scenario.

Net Present Values calculated vary from 27.7 to 28.9 million € for 10 MW power plants, from 95.5 to 99.1 million € for 25 MW and from 232.3 to 240.8 million € for 50 MW power plants. For all the scenarios under study, SPP are less than 6 years, achieving values of 3 years for 50 MW power plants. IRR calculated for 10 MW power plants is higher than 15.6%; for 25 MW, IRR is higher than 23.0% and for 50 MW, IRR exceeds the value of 30.9%.

Table VI.12 Economic study of biomass power plants presented as scenarios.

| Item | Units (·1000) | Scenario | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 | Sc. 7 | Sc. 8 | Sc. 9 | Sc. 10 | Sc. 11 | Sc. 12 |
| Capital cost | € | 26470 | | 50530 | | 82390 | | 26470 | | 50530 | | 82390 | |
| *Depreciation* | *€. yr$^{-1}$* | *1320* | | *2520* | | *4120* | | *1320* | | *2520* | | *4120* | |
| O&M cost | | | | | | | | | | | | | |
| Biomass cost | *€. yr$^{-1}$* | 1250 | 1300 | 2810 | 2940 | 5320 | 5560 | 1180 | 1320 | 2670 | 3100 | 5280 | 6320 |
| Operating labor | *€. yr$^{-1}$* | 210 | | 310 | | 490 | | 210 | | 310 | | 490 | |
| Maintenance cost | *€. yr$^{-1}$* | 400 | | 760 | | 1240 | | 400 | | 760 | | 1240 | |
| ***Total O+M costs*** | ***€. yr$^{-1}$*** | *1860* | *1910* | *3880* | *4010* | *7050* | *7390* | *1790* | *1930* | *3740* | *4170* | *7010* | *8050* |
| Other costs | | | | | | | | | | | | | |
| Ash disposal cost | *€. yr$^{-1}$* | 350 | | 770 | | 1420 | | 350 | | 770 | | 1420 | |
| Insurance and others | *€. yr$^{-1}$* | 260 | | 500 | | 820 | | 260 | | 500 | | 820 | |
| *Total Other costs* | *€. yr$^{-1}$* | *610* | | *1270* | | *2240* | | *610* | | *1270* | | *2240* | |
| ***TOTAL plant cost*** | ***€. yr$^{-1}$*** | *3790* | *3840* | *7670* | *7800* | *13410* | *13650* | *3720* | *3860* | *7530* | *7960* | *13370* | *14410* |
| Income from energy production | *€. yr$^{-1}$* | 9970 | | 24920 | | 51600 | | 9970 | | 24920 | | 51600 | |
| Gross profit | *€. yr$^{-1}$* | 6180 | 6130 | 17250 | 17120 | 38190 | 37950 | 6250 | 6110 | 17390 | 16960 | 38230 | 37190 |
| Net profit | *€. yr$^{-1}$* | 3160 | 3130 | 9570 | 9490 | 22150 | 21990 | 3200 | 3110 | 9670 | 9390 | 22170 | 21500 |
| Cash Flow | *€. yr$^{-1}$* | 4480 | 4450 | 12090 | 12010 | 26270 | 26110 | 4520 | 4430 | 12190 | 11910 | 26290 | 25620 |
| Simple Payback Period (SPP) | years | 5.9 | 5.9 | 4.2 | 4.2 | 3.1 | 3.2 | 5.9 | 6.0 | 4.1 | 4.2 | 3.1 | 3.2 |
| Net Present Value (NPV) | million € | 28.3 | 28.0 | 97.8 | 96.8 | 240.5 | 238.5 | 28.9 | 27.7 | 99.1 | 95.5 | 240.8 | 232.3 |
| Internal Rate of Return (IRR) | % | 15.8 | 15.7 | 23.4 | 23.3 | 31.7 | 31.5 | 16.0 | 15.6 | 23.6 | 23.0 | 31.7 | 30.9 |

## VI.3.5 Sensitivity analysis about plant investment

Results presented in table VI.13 shows cash flow and NPV variations for all the scenarios when invested capital cost varies 10% from the initial value selected in the study.

Table VI.13 Sensitivity analysis modifying investment value into a range of 10%.

| Scenario | Capital Cost (thousand $€\cdot y^{-1}$) | Depreciation (thousand $€\cdot y^{-1}$) | Cash Flow (thousand $€\cdot y^{-1}$) | Net Present Value (million €) |
|---|---|---|---|---|
| Sc. 1 | 23820 - 29120 | 1190 - 1450 | 4,520 – 4,600 | 26.9 - 31.5 |
| Sc. 2 | | | 4,490 – 4,570 | 26.5 - 31.1 |
| Sc. 3 | 45480 - 55580 | 2270 - 2770 | 12,170 – 12,440 | 96.3 - 103.9 |
| Sc. 4 | | | 12,090 – 12,350 | 95.2 - 102.9 |
| Sc. 5 | 74150 - 90630 | 3710 - 4530 | 26,390 – 27,000 | 239.7 - 250.3 |
| Sc. 6 | | | 26,230 – 26,840 | 237.3 - 248.3 |
| Sc. 7 | 23820 - 29120 | 1190 - 1450 | 4,560 – 4,650 | 27.5 - 32.0 |
| Sc. 8 | | | 4,470 – 4,560 | 26.3 - 30.9 |
| Sc. 9 | 45480 - 55580 | 2270 - 2770 | 12,260 – 12,530 | 97.5 - 105.1 |
| Sc. 10 | | | 11,980 – 12,250 | 93.9 - 101.5 |
| Sc. 11 | 74150 - 90630 | 3710 - 4530 | 26,410 – 27,030 | 240.1 - 250.6 |
| Sc. 12 | | | 25,740 – 26,350 | 231.5 - 242.0 |

The assessment carried out demonstrates that a fluctuation of 10% in plant investment implies a variation of NPV from 4.73 to 11.40 % for 10 MW plants, from 1.56 to 6.25% for 25 MW plants and from 0.29 to 4.32% in the case of 50 MW plants.

## VI.3.6 Benefits by selling $CO_2$ credits

Additional gross benefits for plants attained through selling $CO_2$ emission credits can substantially increase economic reliability in all cases (Table VI 14).

Table VI.14 NPV (million €) obtained by selling $CO_2$ credits at determined $CO_2$ Mg prices.

| Power (MW) | Scenario | Million $€\cdot Mg^{-1}$ $CO_2$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 20 | 50 | 100 |
| 10 | Sc. 1 | 28.3 | 31.0 | 33.7 | 39.0 | 55.1 | 81.8 |
| | Sc. 2 | 28.0 | 30.5 | 33.3 | 38.5 | 54.7 | 81.4 |
| | Sc. 7 | 28.9 | 31.5 | 34.3 | 39.5 | 55.6 | 82.3 |
| | Sc. 8 | 27.7 | 30.4 | 33.2 | 38.4 | 54.4 | 81.2 |
| 25 | Sc. 3 | 97.8 | 104.6 | 111.3 | 124.6 | 164.8 | 231.5 |
| | Sc. 4 | 96.8 | 103.5 | 110.2 | 123.5 | 163.7 | 230.5 |
| | Sc. 9 | 99.1 | 105.7 | 112.4 | 125.7 | 165.9 | 232.7 |
| | Sc. 10 | 95.5 | 102.2 | 108.8 | 122.3 | 162.4 | 229.1 |
| 50 | Sc. 5 | 240.5 | 254.3 | 268.2 | 295.8 | 378.8 | 517.2 |
| | Sc. 6 | 238.5 | 252.3 | 266.1 | 293.9 | 376.9 | 515.3 |
| | Sc. 11 | 240.8 | 254.7 | 268.4 | 296.2 | 379.2 | 517.6 |
| | Sc. 12 | 232.3 | 246.0 | 259.9 | 287.5 | 370.5 | 508.9 |

According to the values showed in Table VI.14, for 10MW plants, an increase from 9.1 to 190 % of NPV is attained when the price of $CO_2$ varies from 5 to 100 €·Mg $CO_2$ $^{-1}$, respectively. For 25 and 50 MW plants, this range varies from 6.9 to 137 %, and 5.8 to 116 % for the same $CO_2$ price deviation, respectively.

## VI.3.7 *Populus* spp. production variation

Average poplar production yields can vary yearly, thus influencing the final cost of biomass produced on the crop. From this premise, an economic analysis was carried out to determin feasibility in electrical production from poplar production variation in cultivation from 9 to 20 Mg d.b.per hectare (Table VI.15).

Table VI.15 Biomass final cost according to poplar production yield variation in the cultivation and power economic reliability.

| | | | 10 MW | | | | 25 MW | | | | 50 MW | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Concept | Units | Sc.1 | Sc.2 | Sc.7 | Sc.8 | Sc.3 | Sc.4 | Sc.9 | Sc.10 | Sc.5 | Sc.6 | Sc.11 | Sc.12 |
| 9 $Mg\cdot ha^{-1}$ | BC at plant | $€\cdot Mg^{-1}$ | 27.12 | 28.08 | 26.56 | 29.94 | 27.50 | 28.27 | 27.67 | 31.22 | 27.56 | 28.95 | 28.13 | 33.71 |
| | Cash Flow | $10^6$ € | 4.20 | 4.10 | 4.20 | 4.10 | 11.40 | 11.30 | 11.40 | 11.00 | 25.00 | 26.80 | 24.90 | 23.90 |
| | NPV | $10^6$ € | 24.40 | 23.90 | 24.80 | 23.00 | 89.00 | 88.10 | 88.80 | 84.60 | 224.4 | 221.3 | 223.1 | 210.9 |
| 15 $Mg\cdot ha^{-1}$ | BC at plant | $€\cdot Mg^{-1}$ | 18.32 | 18.99 | 17.06 | 19.24 | 18.42 | 19.32 | 17.30 | 20.98 | 18.71 | 19.58 | 18.41 | 22.17 |
| | Cash Flow | $10^6$ € | 4.50 | 4.50 | 4.60 | 4.50 | 12.20 | 12.10 | 12.30 | 12.00 | 26.50 | 26.40 | 26.60 | 25.90 |
| | NPV | $10^6$ € | 29.10 | 28.70 | 29.70 | 28.60 | 99.60 | 98.60 | 100.9 | 96.70 | 243.7 | 241.1 | 244.4 | 236.1 |
| 20 $Mg\cdot ha^{-1}$ | BC at plant | $€\cdot Mg^{-1}$ | 15.02 | 15.65 | 13.48 | 15.46 | 15.11 | 15.76 | 13.67 | 17.06 | 15.18 | 16.17 | 14.02 | 18.09 |
| | Cash Flow | $10^6$ € | 4.70 | 4.60 | 4.70 | 4.60 | 12.50 | 12.50 | 12.70 | 12.30 | 27.10 | 26.90 | 27.30 | 26.60 |
| | NPV | $10^6$ € | 30.80 | 30.5 | 31.70 | 30.50 | 103.5 | 102.7 | 105.2 | 101.2 | 251.4 | 249.2 | 253.9 | 245.0 |

For all power plants analysed, the final biomass cost variation with respect to the costs obtained assuming the average production yield mentioned above sees an average increase of 39.8% when production yield decreases to 9 Mg·ha$^{-1}$; this decreases at an average rate of 7.4% when production yield increases to 15 Mg·ha$^{-1}$ and decreases by 25.2% when production yield increases to 20 Mg·ha$^{-1}$.

As regards NPV, when biomass yield production decreases to 9 Mg·ha$^{-1}$, the value of this economic indicator decreases by an average of 10.8 % for all analysed scenarios. When biomass yield production reaches 15 Mg·ha$^{-1}$, NPV increases by an average of 1.9%; and finally, when the production obtained is 20 Mg·ha$^{-1}$, NPV also increases, to 6.8%.

## VI.4 Conclusions

The main conclusion of this study is that biomass power-plant implementation is an economically viable option in a regional or local scenario. This study complements others that consider the positive environmental and energetic reliability of the use of poplar as biofuel for energy production. Economic feasibility can be supported if the new benefits of selling $CO_2$ emissions are added.

The new electrical tariffs (established in Spanish legislation via Royal Decree 611/2007) paying 14.659 c€·kWh produced$^{-1}$using biomass energy crops as fuel, help to achieve economic reliability for small and medium biomass power plants.

According to the economic results, costs of the cultivation subsystem are the main contributor to the final cost of biomass at plant (72 -75% for chip production at plant). Stem or chip production at the harvesting stage must be a logistical decision depending on similar final biomass cost at plant. This variation in final cost reaches a maximum of 2.87 € Mg$^{-1}$ for the same power size.

Stem transportation over the period of a year is made by fewer trucks than in chip transportation. Important drawbacks to be taken into account are truck availability for chip transportation and biomass storage volume needed by the power plant in order to guarantee a water-content reduction in biomass during non-harvesting periods.

Loss of water produced by stems in the field optimises the number of kilometres travelled by trucks. As a consequence, chip transportation costs are higher than stems transportation costs, due to the following factors:

- Chip density is lower than for stems.
- Chips are transported with more water content, so more trips are required to transport the same biomass energy (d.b) to the power plant.
- A greater number of trips per day imply higher transportation depreciation and maintenance costs, and an increase in diesel consumption and labour costs.

In contrast, the effect of crop distribution on the territory does not represent a great disadvantage for final biomass cost, although diesel fuel costs are trebled in all scenarios where the crop distribution area varies from 10 to 90%. When biomass fuel availability is guaranteed at local and regional scales, this study has demonstrated that larger power plants become more economically feasible than small power plants.

The sensitivity assessment carried out allows us to observe that the power size of a given plant is a key variable when considering the possible cost fluctuations in the final biomass cost and in the adjustment of plant investment. This fact is attributable to a lower energy auto-consumption and greater energy conversion efficiency by larger biomass power plants. The benefits obtained by selling $CO_2$ credits have shown themselves to be an important tool in fostering the economic reliability of all biomass plants in comparison with non-renewable power-generation systems.

However, the implementation of biomass energy systems should be based on real biomass production potential in the territory and within the infrastructural characteristics facilitating the system's overall logistics.

## VI.5 References to chapter VI

[1] Rosenqvist H., Dawson M. Economics of willow growing in Northern Ireland. Biomass & Bioenergy. 28 (1) (2005) 7-14.

[2] Venendaal R., Jorgensen U. & Fosters C.A.European Energy Crops: A synthesis. Biomass & Bioenergy. 13 (3) (1997) 147-185.

[3] Faaij A.P.C. Bio-energy in Europe: changing technology choices. Energy Policy. 34 (3) (2006) 322-342.

[4] Council EPa. Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market. Brussels, 2001.

[5] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversifiacación y Ahorro de la Energía (IDAE). Resumen Plan de las Energías Renovables en España, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspx

[6] IDAE. Instituto de Diversificación y Ahorro de la Energía. Available from : http://www.idae.es; Accessed in: March 2007.

[7] European Comission. Council Decision 2002/358/EC: Council Decision of 25 April 2002 concerning the approval on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments there under, 2002. Available from: http://unfccc.int/resource/docs/convkp/kpeng.pdf .Accessed in: April 2007

[8] Generalitat de Catalunya. Pla de l'energia de Catalunya 2006-2015. Generalitat de Catalunya; Barcelona 2005.

[9] Ministerio de la Presidencia. Real Decreto 1370/2006, Plan nacional de asignación de derechos de emisión de gases de efecto invernadero 2008-2012. Madrid 2006.

[10] Mirasgedis S., Sarafidis Y., Georgopoulou E., Lalas D.P. The role of renewable energy sources within the framework of the Kyoto Protocol: the case of Greece. Renewable & Sustainable Energy Reviews. 6 (3) 2002 247-269.

[11] Cardone M., Mazzoncini M., Menini S., Rocco V., Senatore A., Seggiani M. & Vitolo S. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass & Bioenergy 25 (6) 2003 623-636.

[12] Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P., Solano M.L. & Rieradevall J. Life Cycle Assessment of a *Brassica carinata* bioenergy system in southern Europe. Biomass & Bioenergy 31 (8) 2007 543-555.

[13] Raccuia S.A., Melilli M.G. Biomass and grain oil yields in Cynara cardunculus L. genotypes grown in a Mediterranean environment. Field Crops Research 101 (2) 2007 187-197.

[14] Groscurth, H. M., Almeida, A. de, Bauen, A., Costa, F. B., Ericson, S. O., Giegrich, J., Grabczewski, N. von, Hall, D. O., Hohmeyer, O., Jörgensen, K., Kern, C., Kühn, I., Löfstedt, R., Mariano, J. da S., Mariano, P. M. G., Meyer, N. I., Nielsen, P. S., Nunes, C., Patyk, A., Reinhardt, G. A., Rosillo-Calle, F.,

Scrase, I., Widmann, B. Total costs and benefits of biomass in selected regions of the European Union. Energy (Oxford), 2000.

[15] Fernandez J., Curt M.D. New energy crops for bioethanol production in the Mediterranean region. International Sugar Journal. Agra Europe (London), 2005.

[16] Ciria P. Efecto del turno de corta y de la densidad de plantación sobre la productividad de diversos clones de chopo en condiciones de corta rotatcion. Tesis doctoral Universidad Politecnica de Madrid, Madrid,1998.

[17] Perez S., Renedo C.J., Ortiz A., Manana M., Silio D. Energy evaluation of the Eucalyptus globulus and the Eucalyptus nitens in the north of Spain (Cantabria). Thermochimica Acta 451 (1-2) 2006 57-64

[18] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversifiacación y Ahorro de la Energía (IDAE). Resumen Plan de las Energías Renovables en España, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspx

[19] Linares P, Leal J, Sáez R. Assessment of the Externalities of Biomass Energy for Electricity Production. . Informes Técnicos CIEMAT, 1996.

[20] Nonhebel S. Renewable energy and food supply: Will there be enough land? Renewable & Sustainable Energy Reviews 9 (2005) 191-201.

[21] Varela M, Saez R, Audus H. Large-scale economic integration of electricity from short-rotation woody crops. Solar Energy 70 (2) 2001 95-107.

[22] Kathryn R. Mechanised Harvesting and Comminution of Short Rotation Coppice. Biobase_European Energy Crops InterNetwork, 1998.

[23] Rushton K. BioBase, Mechanised Harvesting and Comminution of Short Rotation Coppice.: http://www.eeci.net/; 1998.

[24] Ciria P., Mazón M.P., Carrasco J.E. Poplar productivity evolution on short rotation during three consecutive cycles in extreme continental climate. 2 nd World Conference on Biomass for Energy, industry and Climate Protection, 10-14 May 2004, Rome 2004.

[25] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass & Bioenergy 28 (1) 2005 35-51.

[26] Ministerio de Fomento. Observatorio del transporte de mercancías del transporte por carretera, Nº4. Ministerio de Fomento, Madrid, España, 2003. Available from: http://wwwfomentoes 2003.

[27] Masip A. Cost horari de la Maquinaria Forestal. . 1er Quadern d'Informació Tècnica Área d'Infraestructures, Urbanisme i Habitatge Oficina Técnica de Prevenció Municipal d'Incendis Forestals Diputació de Barcelona, Xarxa de Municipis; Barcelona, España 2003.

[28] European Central Bank. Available from: http://www.ecbint/home/html/indexen.html.

[29]Volvo Truck from Spain. Personal Communication.

[30 ]Transgruas SA. Personal Communication..

[31] Gigler JK, Meerdink G, Hendrix EMT. Willow supply strategies to energy plants. Biomass & Bioenergy 17 (3) 1999 185-198.

[32] Volvo Truck. Emission from Volvo's Truck Emissions, standard diesel fuel. Available from: www.volvotruck.com , 2003.

[33] Ministerio_de_Industria TyC. Precio carburantes comparación entre 2005-2006. Available from: http:// www.mityces/petroleo/seccion/precios/informes/informesanuales. Accessed in: September 2006.

[34] Gasol C.M. ACV del Cultivo Energético: Brassica carinata. Master tesis. Universitat Autònoma de Barcelona (UAB). Barcelona 2006..

[35] European Commission. Biomass Conversion Technologies, Achievement and Prospects for Heat and Power Generation. Brussels, 1998.

[36] vandenBroek R, Faaij A, vanWijk A. Biomass combustion for power generation. Biomass & Bioenergy 11 (4) 1996 271-281.

[37] vandenBroek R, Faaij A, vanWijk A. Biomass combustion, Power Generation Technologies.. Department of Science, Technology and Society. Utrecht University. The Netherland, 1995. Available from: http://www.chem.uu.nl/nws/www/publica/95029.htm.

[38] International Energy Agency. Renewables for Power Generation. Status and Prospects, 2003.

[39] Engineering Chemical. Marshall & Swift Equipment Cost Index. 2007;Volme.

[40] Carrasco J. Análisis Económico de Centrales de Generación Eléctrica con Biomasa.: CIEMAT, 2004, p. 10.

[41] Ministerio de Industria, Turismo y Comercio. Real Decreto 661/2007. BOE número 126 de 26/5/2007, por el que se regula la actividad de producción de energía eléctrica en régimen especial. Madrid, 2007.

[42] Brun F, Mosso A. Profitability comparison between short rotation forestry and agricultural crops in Piedmont Region, Italy. 15 th European Biomass Conference & Exhibition. Berlin, Germany; 2007.

# Chapter VII. Feasibility Assessment of *Brassica carinata* bioenergy Systems in the southern Europe

---

*Published as: Martinez-Lozano S. Gasol C.M., Rigola M. Rieradevall J. Anton A. Carrasco J. Ciria P. & Gabarrell X. Feasibility Assessment of Brassica carinata bioenergy system in southern Europe. Renewable Energy Journal. (Accepted).*

---

*Photografy by Carles Martinez Gasol. Caldes de Malavella (Girona,) 2007.*

# Abstract

A detailed reliability assessment was made of electricity generation systems that are based on *B.carinata* cultivation. The assessment considers the following chain of energy generation: biomass cultivation and harvesting, transportation and electricity generation in biomass power plants (10, 25 and 50MW). Flue gas desulphurization systems have been included for larger plants following the criteria of the Spanish legislation framework. Six scenarios were analysed in accordance with the following aspects: two crop distributions around the power plant and three power plant sizes. The results show that the cost of biomass delivered at power plant ranges from 107.81 to 112.54 €·Mg$^{-1}$ d. b..

Sensitivity analysis shows that a biomass production variation in the field demonstrates that biomass cost delivered at plant is notably affected and consequently so is the system's feasibility.

Furthermore, the increase of the price of $CO_2$ emission credits, also considered in sensitivity, can help to improve the reliability of systems because of the increase of gross profit for each scenario.

This study clears up the economic uncertainty of *B.carinata* biomass energy systems based on the single use of this renewable energy resource. Higher crop productivities are needed to ensure an economical reliability of analysed systems. On the other hand biomass mix can solve $SO_2$ emission cleaning cost for large power plants, improving the reliability of *B.carinata* application as fuel.

*Keywords: energy crops, supply chain, power plant and final biomass cost.*

## VII.1 Introduction

Substituting biomass for fossil fuels in the generation of energy is an important strategy for the EU in order to mitigate climate change and enhance security of supply. For this purpose bioenergy is being promoted in the Renewable Electricity Directive[1], as well as national policies[2, 3]. According to the Spanish national Renewable Energy Plan biomass has to contribute 29.67% to the total renewable energy production for the year 2010 [3].

Biomass is considered to be an attractive option for energy production for a number of fundamental agricultural, industrial and rural development reasons [4]. In particular energy crops show higher production per land unit than conventional counterparts. Crops such us: Ethiopian Mustard (*B. carinata*)[5, 6], Rape (*B. napus*), Cardoon (*Cynara cardunculus*)[7, 8], Sweet sorghum (*Sorghum bicolour L.*) [8, 9] and also short rotation coppices (SRC) as Poplar. (*Populus spp.*)[10, 11] and Eucalyptus (*Eucalyptus globulus*) have been proposed in Europe as possible energy crops. Energy crops are established in the Spanish plan as a significant strategy to achieve the expected energy objectives (3.35 Mtep) [3]. Furthermore, the biomass from energy crops as renewable source is seen as an important contributor to the carbon dioxide abatement strategy to achieve the 8% reduction in Europe required in the Kyoto protocol. Within the European objective, Spain has been assigned an increase of no more than 37% on the 1990 emission levels by 2012, emission level largely over-phased by 2006[12-15].

Until now, the introduction of bioenergy schemes under the existing financial and legislative frameworks was still rather uncertain and in may cases seemed to be uneconomical [16]. In the Spanish case, new legislation (Spanish Royal Decree 63 661/2007)[2] has recently appeared with the intention of promoting electricity production using energy crops with economical guarantees.

Bearing in mind the aforementioned facts, this study uses the new Spanish legislation framework to calculate economic performance of *B. carinata* energy crops destined for the production of electricity in Spain.

The main reason for selecting *B. carinata* in this study has been its respectful environmental performance and its high adaptability to Spain's climatic areas and unexploited marginal areas [5, 6]. Furthermore it can be cultivated without irrigation, key factor in its possible application in a large scale scenario.

The results obtained will help to decide if *B. carinata* as an energy crop is adequate for implementation in the current legislative framework and the factors that determine its performance. Furthermore, the methodology applied highlights the main economic factors to be considered in the economic viability studies of bioenergy schemes. The conclusions from the study can be extended to similar geographical areas in Southern Europe.

## VII.2 Methodology

In the following lines methodology applied to *B. carinata* bioenergy system economic assessment is presented.

### VII.2.1 The B. carinata bioenergy system analysed

The feasibility study analyses the three main subsystems of energy generation with B. carinata biomass in Spain: a) B. carinata cultivation and harvesting, b) transport and c) energy conversion.

*B. carinata* cultivation stage covers a 1 year period. Table VII.1 shows the agricultural labour covered throughout the entire cycle of the crop.

Table VII.1 *B.carinata* field labours timeline.

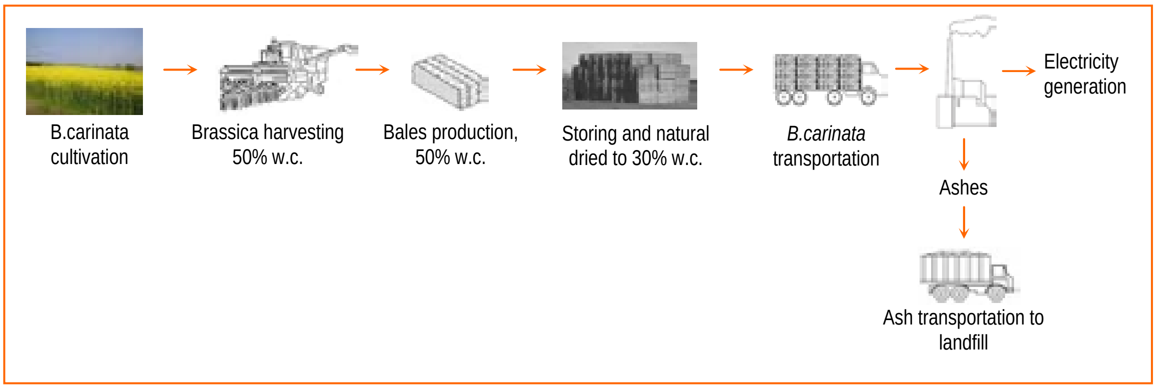
| Month | Type of Labours |
|---|---|
| September | Herbicide treatment |
| September | Base fertilisation |
| September | Sowing |
| December | Cultivation |
| January | Top fertilisation |
| June | Harvesting |
| June | Raking |
| June | Baling |
| September | Transport to energy plant |

Small bales of *B. carinata* with an initial moisture content of about 50% are produced at harvesting. The biomass fuel is left in the field to reduce water content (w.c.) to 30% through natural drying during the summer period for better combustion at the power plant. Bales accumulated at the roadside are then transported to the power plant according to the normal delivery schedule over the working period of the plant (333 days·yr$^{-1}$).

Bales of *B. carinata* are assumed to be transferred by truck from the field to the combustion plant. Bales are loaded onto the truck by an elevator action through a tractor-mounted forklift. Downloading the *B. carinata* bales at the plant is carried out by electric forklift trucks.

Combustion of *B. carinata* bales is carried out in power plants for electrical generation. Transport and disposal of ashes produced in the bioenergy conversion plant are also included as part of the system under study. The entire system under study is schematically shown in Figure VII.1.

Figure VII.1 Scheme of the system under study.



### VII.2.1.1 Scenarios analysed

Six scenarios are defined for the economic *B. carinata* feasibility study. From 3 to 10 Mg d.b.$\cdot$ha$^{-1}\cdot$year$^{-1}$ can be reached from several cultivation conditions (water availability, fertilization procedures, etc). For the scenarios analysed, productivity in the field of 4.72 Mg (d.b.)$\cdot$ha$^{-1}$.year$^{-1}$ has been considered according to obtained results into cropping experimental areas located in northeast Spain during 2003. These scenarios include different travel distance according to the occupancy of cropping area distribution (Cd) around the power plant. The considered values for (Cd) are 10% and 90% for each power plant size. These scenarios are detailed in Table VII.2.

Table VII.2 *B.carinata* biomass base case scenarios defintions.

| | Units | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 |
|---|---|---|---|---|---|---|---|
| Cropping productivity | Mg (d.b)$\cdot$ha$^{-1}\cdot$year$^{-1}$ | 4.72 | 4.72 | 4.72 | 4.72 | 4.72 | 4.72 |
| Power | MW | 10 | 10 | 25 | 25 | 50 | 50 |
| Cropping Area Distribution *(Cd)* | % | 10 | 90 | 10 | 90 | 10 | 90 |

## *VII.2.2 Supply and logistical aspects for the B. carinata bioenergy system*

Biomass as fuel required for the power plants, land-crop surface associated withproducing this biomass quantity and the logistical needs expressed in the number of trucks required to transfer the biomass are calculated to determine the effect on the economic performance of the system.

### VII.2.2.1 *B.carinata* biomass required as a fuel for a power plant

Annual biomass requirements (BF) for biomass power plants are calculated taking into account the *B. carinata's* Lower Heating Value (LHV) (Table VII.3)[6], the number of operation hours over a year (8,000 h) and the power plant efficiency (25, 28 and 30% for 10, 25 and 50 MW, respectively) [17].

Table VII.3 Physical and chemical characterisation of *B.carinata.*

| | $kJ \cdot kg\ d.b^{-1}$. |
|---|---:|
| Net calorific value | 17,730 |
| | Weight (wt.) % d.b. |
| Carbon | 46.30 |
| Hydrogen | 6.10 |
| Nitrogen | 0.70 |
| Sulphur | 0.49 |
| Chlorine | 0.41 |
| Oxygen | 38.30 |
| Ashes | 7.70 |

Source: [18]

Supply requirements for each power plant are detailed in Table VII.4.

Table VII.4 *B.carinata* biomass supply for each power plant.

| Power (MW) | Mg, d.b. (*BF*) | Mg, 30% water content |
|---|---|---|
| 10 | 64,980 | 81,220 |
| 25 | 145,030 | 181,290 |
| 50 | 270,730 | 338,410 |

### VII.2.2.2 Cropping area required by a biomass power plant and transport distance

Considering the annual biomass fuel requirement *BF* (Mg) for a 10, 25 and 50 MW biomass power plant, the cropping area needed to supply a power plant *A* (ha) is calculated through cropping productivity *Pr* (Mg d.b. $\cdot ha^{-1} \cdot year^{-1}$). See equation (VII.1).

$$CA = \frac{BF}{\Pr} \qquad \text{(eq. VII.1)}$$

The area cultivated has a direct influence on the total distance of transport. Medium transport ratio to be appealed by biomass fuel supplier trucks *D* (km) is estimated, as follows:

$$D = \left( \frac{A}{2 \cdot \pi \cdot Cd \cdot 100} \right)^{0.5} \qquad \text{(eq. VII.2)}$$

Where *A* is the cultivation area*,* and *Cd* is Crop distribution area.

### VII.2.2.3 Number of trucks required for *B.carinata* transportation to the power plant

Number of trucks needed daily to supply a biomass power plant is defined from the total biomass fuel required for the power plant, the daily number of trips made by truck and the daily biomass transported by truck.

Table VII.5 shows the number of trips made by a 16 Mg truck per day, from the field to the power plant considering legal speed limits for a 16 Mg truck, loading and unloading time for *B. carinata* small bales [19], travel time by road and traffic incidents time. Preliminary calculations discarded other tonnage options. Trips per day made by a truck *(e)* were calculated by means of the truck driver's working journey time (8 hours per 146 day) divided by total travel time.

Table VII.5 Trips per day made by a truck transporting dried bales from the field to the power plant.

| Distance from field to power plant (km) | *(a)* Going and return time by road (h) | *(b)* Loading time for a truck (h) | *(c)* Unloading time at plant (h) | *(d)*Transport time lost by traffic (h) | TOTAL TIME by travel (h). *(e)=(a)+ (b)+ (c)+ (d)* | Travels per day made by a truck (Tpd) |
|---|---|---|---|---|---|---|
| 1 – 5 | 0.16 | 0.42$^A$ | 0.28$^B$ | 0.16 | 1.02 | 8 |
| 5 – 10 | 0.33 | | | | 1.19 | 6.5 |
| 10 – 20 | 0.58 | | | | 1.44 | 5.5 |
| 20 – 30 | 0.83 | | | | 1.69 | 4.5 |

A – It is assumed two tractors loaders by truck.

B – It is assumed two tractor-mounted forklift per truck.

The *B. carinata* biomass transported daily by a truck was calculated according to the authorised maximum weight and volume of a load per truck (16 Mg legal practical load for a Spanish regional transport truck) [20] and the assumed *B. carinata* bales density (150 kg·m-3 (30% w.c)). Table VII.6 shows trucks needed to supply power plants as considered over a year for each scenario.

Table VII.6 Trucks needed to supply biomass fuel to a power plant and total transport distance.

| | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 |
|---|---|---|---|---|---|---|
| Distance from field to power plant (km) | 1-5 | 10-20 | 5-10 | 20-30 | 10-20 | 20-30 |
| Quantity of biomass transported per day (Mg) | 240 | 240 | 540 | 540 | 1,020 | 1,020 |
| Trucks required to transport *B.carinata* biomass | 4 | 6 | 12 | 17 | 26 | 32 |

## *VII.2.3. Cost and benefit analysis*

In the following lines cost and benefit analysis applied to *B.carinata.* bioenergy system is presented.

### VII.2.3.1 *B.carinata* cultivation and harvesting

Biomass-cultivation cost includes: a) investment, b) depreciation and operational costs (the total cost for the agricultural machinery), c) agrochemical acquisition and use, and d) maintenance of agricultural parcels, all of which influences the total cost of cultivation and harvesting.

### VII.2.3.1.1 Total cost of agricultural machinery

Total cost of agricultural machinery (TCAM) considers the fixed costs (FCH) and variable cost per hectare (VCH). FCH include depreciation with an interest rate of 4.75% [21], and insurance.

VCH includes: a) fuel, lubricants, and grease consumption by agricultural tractors and harvester and also b) replacement of parts, repairs and maintenance. Table VII.7 shows the values of the abovementioned components considered in the economic assessment of the agricultural subsystem. These costs were checked and partially compared to local data in bibliography [22-25].

Table VII.7 Economic values used to calculate the fixed and variables cost during the cultivation and harvesting subsystem, 2006.

| Component | Cost |
|---|---|
| *Fixed Cost parameters* | |
| Tractor investment | 71,560 € |
| Harvest investment | 216,216 € |
| Re-sell price of machinery | 15% P |
| Machinery lifetime in hours | 12,000 hours |
| *Variable Cost parameters* | |
| Diesel Agricultural Spanish price 2006 | 0.67 €.l$^{-1}$ |
| Diesel consumption | 316-330 l.ha$^{-1}$ |
| Oil lubricant proportion cost respect diesel | 4.50% |
| Grease lubricant proportion cost respect diesel | 10% |
| Machinery material life time (replacement) | 2,500 hours |
| Pneumatic cost | 3,364 € |
| Repairs and maintenance | 85% of the acquisition price of machinery |
| *Labour cost* | *14.43 €.hour$^{-1}$* |

### VII.2.3.2 Loading, transportation and downloading cost

Economic evaluation of biomass logistical operation was based on: a) investment related to machinery; b) maintenance and reparation costs and c) operating costs related to labour cost and diesel consumption.

In order to model the long-term costs for transport machinery, contractor costs based on prices from [26-28] were used. Labour cost was assigned from local sources and bibliography [24,26,27]. Input data used to describe loading, transportation and downloading cost may be extended to other areas for crops (Table VII.8).

Table VII.8 Components of biomass logistical cost evaluation

| Component | Units | Cost |
|---|---|---|
| Loading investment | € · tractor$^{-1}$ | 72,000 |
| Loading labor cost | € · hour$^{-1}$ | 12.82 |
| Truck investment | € · truck$^{-1}$ | 70,000 |
| Truck driver labor cost | € · year$^{-1}$ | 21,080 |
| Annual Maintenance and Reparation cost | € · year$^{-1}$ | 0.5 · truck investment · lifetime $^{-1}$ (7 yr) |
| Electric forklift truck investment | € · electric forklift truck$^{-1}$ | 27,000 |
| Electric forklift truck labor cost | € · year$^{-1}$ | 9,480 |

Number of loader operators has been calculated through the time need to load a truck (see Table VII.5) and the quantity of biomass transported per day for each scenario (see Table VII.6). Operating cost was determined as the hourly operating cost for loaders operators (Table VII.8). Diesel consumption at loading stage has been calculated according to the time spent on this operation.

Assuming the same number of truck drivers as the daily trucks used to supply the power plant and driver salary (Table VII.8), labour cost was calculated according to the transportation needs.

Diesel cost by trucks is directly calculated from the average distance *(D)* between the power plant and the cultivation areas *(A)*, number of trips made by a truck during the transportation period and the trucks needed daily to supply the power plant. A truck diesel consumption of 0.335 litres·km$^{-1}$ [29] and a Spanish diesel cost of 0.9751 €·litre$^{-1}$ were assumed, based on the average cost for 2006 [25].

Number of *B. carinata* downloaders (electric forklift trucks at plant) and operators, has been calculated through the time needed to download a truck (see Table VII.5) and the quantity of biomass transported per day for each scenario (see Table VII.6). Number of electric forklift truck operators was assigned according to the downloaders needed at plant and the 8 hours per day as labour journey time.

### VII.2.3.3 Ash transportation and disposal cost

Ash transportation and disposal cost was calculated from the quantity of ash generated per tonne (Mg) of biomass burned at the plant (0.08 Mg of ash · Mg biomass burned$^{-1}$) [30]. These costs include operation and investment costs based on ash generated transportation. It was assumed a distance of 25 km from the power plant to the landfill and disposal costs from Catalan disposal taxes (72 €·Mg$^{-1}$).

Ash returned to the field as fertilizer has not been studied. Fertilization properties of ashes could improve cultivation cost reducing the biomass cost at plant.

## *VII.2.4 Power plant*

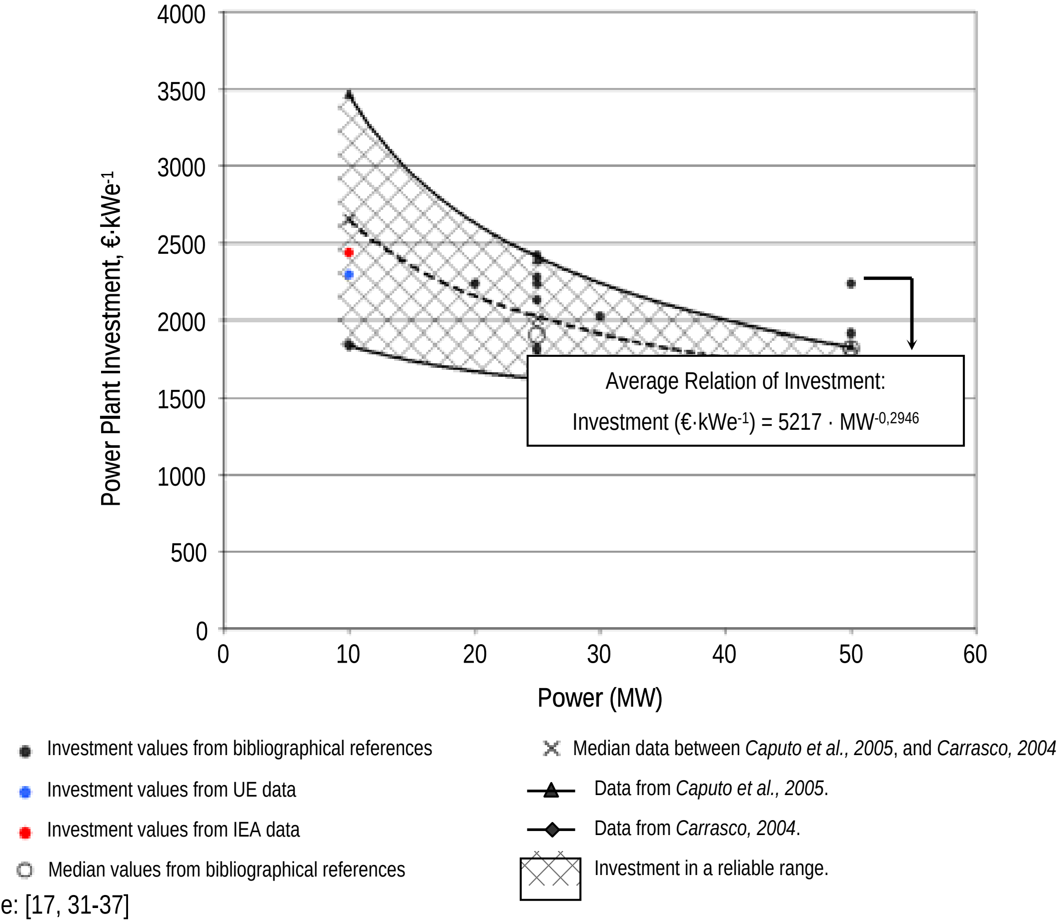
Power plant costs of 10, 25 and 50 MW were analysed with the purpose of obtaining economic reliability using *B. carinata* as a biomass fuel.

### VII.2.4.1. Power plant investments

A range of investments for each power plant was considered as standard to the Spanish case, selecting average data to obtain an approximation of realistic economic values. Figure VII.2 shows investment data range considered to the economic study. Equation VII.3 shows a mathematical correlation between power and the investment carried out (€·kWe$^{-1}$):

$$Biomass\ Power\ Plant\ Capital = 5217 \cdot MW^{0.2946} \qquad \text{(eq. VII.3)}$$

Figure VII.2 Biomass power plant investments data considered in the study



Source: [17, 31-37]

### VII.2.4.2 Power plant maintenance and operating costs

Plant Maintenance costs was calculated as 1.5% of total plant investment according to the bibliography [17]. Table VII.9 shows the number of plant workers considered in order estimate plant operating costs [17, 36]. Insurance and other minor plant costs were calculated as 1% of total plant investment [17].

Table VII.9 Number of power plant workers at 10,25 and 50 MW biomass power plants

| Power Plant | Number of Plant Workers |
|---|---|
| 10 MW | 8 |
| 25 MW | 12 |
| 50 MW | 19 |

### VII.2.4.3 Desulphurization plant investment

*B. carinata* biomass contains an average 0.5 wt.% of sulphur content dry basis (Table VII.3). When this is combusted for power generation a fraction of sulphur content (55 to 70%) is oxidised to sulphate remaining in ashes. However, other sulphur fraction (30 to 45%) is oxidised as $SO_2$ being emitted to the stack [18, 38].

Two alternatives can be used to reduce the average $SO_2$ emissions: cleaning the gas using a desulphurization process or mixing the *B. carinata* with other fuels enough to reach the emission limits. In this last case, burning the same amount of *B. carinata* does not exclude the total emission of $SO_2$.

Considering sulphate production in the combustion system and sulphur emission to the stack, an average of 595 mg $SO_2/Nm^3$ is assumed to be emitted (6% $O_2$, dry gas).

According to the current Spanish sulphur emission limitation on electricity generation[39], 50MW power generation plants using biomass as fuel may emit 200 mg $SO_2/Nm^3$ as maximum (6% $O_2$, dry gas). $SO_2$ emission treatment is not enforced for smaller plants.

The EPA desulphurisation modelling cost has been used to calculate desulphurisation system cost need to 50 MWe power plants with *B. carinata* as fuel [40]. Limestone Forced Oxidation is the Flue Gas Desulphurisation system evaluated due to its adjusted desulphurisation yields required in the scenarios under study (58 – 72 %). Economic data have been actualized using cost indexes [37].

#### VII.2.4.4 Desulphurisation plant maintenance and operating costs

Desulphurisation plant maintenance and operating costs were calculated using the same methodology [40].

### *VII.2.5 Annual benefits and economic feasibility indicators used*

Annual profits earned were calculated according to the current electric tariffs for biomass energy plants, as established by Spanish Royal Decree 661/2007[2], which guarantees a price of 14.659 c€·kWh$^{-1}$ for 15 a year period, and 12.347 c€·kWh$^{-1}$ for the next 5 years, being revised and updated annually in function of the CPI (Consumer Price Index) increment minus 25 basic points until December 2013 and 50 basic points from that date on.

To define the economic feasibility for each scenario, economic indicators such as Simple Payback Period (SPP), Net Present Value (NPV) and Internal Rate of Return (IRR) were used. An interest rate of 4.75% [21] and a 20-year period were considered for NPV calculation.

### *VII.2.6 Sensitivity analysis*

Two independent sensibility analyses were carried out using the following variables: crop productivity variation and addition of $CO_2$ benefits from selling emissions credits by fossil fuel substitution in a power plant burning coal. New economic feasibility rates were calculated. Because of the very low yield reached in the experimental cropping area of *B.carinata*, higher productivity yields delivered in other areas were considered to the sensibility analysis (8 to 10 Mg (d.b.) ·ha$^{-1}$). Finally, a $CO_2$ price range per Mg from 5 to 50 €·Mg $CO_2$ $^{-1}$ with a $CO_2$ generating factor from coal (0.95 Mg $CO_2$·MWh$^{-1}$) [14] was analysed. The influence of an investment cost variation at plant level compared to the influence of a crop productivity variation [41]. For this reason, this variable has not been considered in this sensibility analysis.

# VII.3 *Results*

In the following lines the economic assessment results obtained are presented.

## *VII.3.1 Biomass production and harvesting cost*

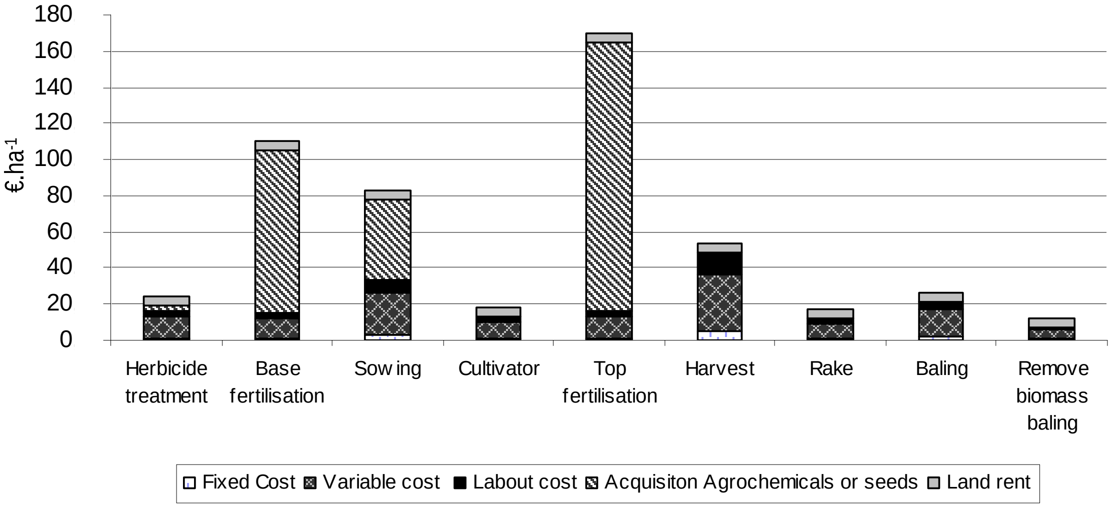
The total production cost of *B. carinata* biomass in the field is 474 € · ha$^{-1}$ over the 1 crop year. Production cost per tonne will vary according to total biomass production obtained during the harvesting period. Table VII.10 shows the variability of *B. carinata* biomass cost per tonne according to their biomass productivity.

Table VII.10 *B.carinata* production and harvesting biomass tonne cost (€.Mg$^{-1}$.yr $^{-1}$)

| | | Biomass production (Mg d.b . ha$^{-1}$· yr$^{-1}$) | | |
|---|---|---|---|---|
| | | *4.72* | *8* | *10* |
| Machinery Cost | Fixed costs | 3.70 | 2.18 | 1.75 |
| | Variable costs | 18.01 | 10.63 | 8.50 |
| Labour cost | | 8.57 | 5.05 | 4.04 |
| Acquisition Agrochemicals | | 60.81 | 35.88 | 28.70 |
| Land rent | | 9.50 | 5.61 | 4.49 |
| Total Cost production (€ . Mg$^{-1}$) | | 100.59 | 59.35 | 47.48 |

The cost of biomass production per tonne including harvesting is 100.59 €.Mg$^{-1}$ (d.b.) · yr$^{-1}$ assuming a productivity of 4.72 Mg (d.b.) · ha$^{-1}$. Agrochemical acquisition is the highest cost that *B.carinta* producers have to assume, reaching up 60.45% of the total agricultural production cost. Following, variable machinery cost supposes 17.90% of the total agricultural production cost. The parcel land rent represents 9.45%, labour cost is 8.52% and finally the fixed machinery cost supposes 3.68%. When the total cropping costs are distributed for each annual labour, the most expensive cost is associated to agrochemicals application (mainly fertilizers). The next two most expensive labours are sowing and harvesting (see Figure VII.3).

Figure VII.3 Contribution of the agricultural labours to total biomass cost production.



## VII.3.2 Loading, transportation and downloading cost

The most costly logistical stage is the biomass transportation to the power plant (40 – 64% of total biomass logistic cost) (see Table VII.11). The transportation cost is increased in relation to other stages because of the truck driver labour cost and the diesel costs when the distances involved are large. Biomass loading contributes to 32 – 54% of total biomass logistic cost. Labour during this stage is the most costly factor.

Finally, biomass downloading represents a minor percentage over the biomass logistical cost (4 – 6%). The results obtained allow us to assume that a truck depreciation variation will not notably affect the biomass transportation costs.

Table VII.11 Total biomass logistical cost to the biomass power plant ($10^3$ € · year$^{-1}$)

| | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 |
|---|---|---|---|---|---|---|
| Loading Cost | | | | | | |
| Tractor depreciation | 60 | 60 | 130 | 130 | 250 | 250 |
| Labor cost | 130 | 130 | 280 | 280 | 520 | 520 |
| Diesel fuel cost | 70 | 70 | 150 | 150 | 270 | 270 |
| TOTAL Loading cost | 260 | 260 | 560 | 560 | 1040 | 1040 |
| Transportation Cost | | | | | | |
| Transport depreciation | 40 | 60 | 120 | 170 | 260 | 320 |
| Maintenance cost | 20 | 30 | 60 | 90 | 130 | 160 |
| Labor cost | 90 | 130 | 250 | 360 | 550 | 670 |
| Diesel fuel cost | 40 | 110 | 120 | 370 | 320 | 950 |
| TOTAL transportation cost | 190 | 330 | 550 | 990 | 1260 | 2100 |
| Downloading Cost | | | | | | |
| Elec. forklift truck depreciation | 10 | 10 | 20 | 20 | 40 | 40 |
| Labor cost | 20 | 20 | 50 | 50 | 100 | 100 |
| TOTAL downloading cost | 30 | 30 | 70 | 70 | 140 | 140 |

## VII.3.3 Final biomass cost

Biomass production, loading, transportation and downloading costs are aggregated, giving the final biomass cost delivered to the biomass power plant (Table VII.12).

Results show that the loading, transportation and downloading of biomass bales contribute from 7 to 12% over the final biomass cost per tonne at the plant. Biomass cultivation cost is a critical factor to the final biomass cost.

Table VII.12 Biomass fuel cost at plant (€ · Mg *B.carinata* in dry basis $^{-1}$)

| | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 |
|---|---|---|---|---|---|---|
| Biomass production and harvesting | 100.42 | 100.42 | 100.42 | 100.42 | 100.42 | 100.42 |
| Loading | 4.00 | 4.00 | 3.86 | 3.86 | 3.84 | 3.84 |
| Transportation | 2.92 | 5.08 | 3.79 | 6.83 | 4.65 | 7.76 |
| Downloading | 0.46 | 0.46 | 0.48 | 0.48 | 0.52 | 0.52 |
| FINAL BIOMASS COST AT PLANT | 107.81 | 109.97 | 108.56 | 111.59 | 109.44 | 112.54 |

## VII.3.4 Economic results of basic scenarios

Table VIII.13 shows the economic results for each scenario analysed. For all scenarios, electricity generation from *B. carinata* is non-reliable: SPP are greater than 3 or 4 years, NPV are less than the investment cost needed by the plant, and IRR values are less than 7.90%, and in smaller plant this last indicator is negative.

The main cause for these negative results is the low biomass productivity reached in the cropping area and the corresponding high biomass cost. This is the factor which has the highest contribution to the energy production cost. For 50 MW plants, economy of scale does not help to increase the reliability of the system because of desulphurisation investment and operating costs in addition to the costs of the power plant itself.

Table VII.13 Economic study of biomass power plants presented as scenarios

| Item | Units (·1000) | Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| | | Sc. 1 | Sc. 2 | Sc. 3 | Sc. 4 | Sc. 5 | Sc. 6 |
| Power Plant Capital cost | € | 26,470 | | 50,530 | | 82,390 | |
| Desulphurisation Plant Capital Cost | € | - | | - | | 40,200 | |
| *Income from energy production* | | | | | | | |
| From year 1 to 15 *(a)* | €. yr$^{-1}$ | 9,970 | | 24,920 | | 51,600 | |
| From year15 *(a')* | €. yr$^{-1}$ | 8,400 | | 20,990 | | 43,460 | |
| O&M cost at plant | | | | | | | |
| Biomass cost | €. yr$^{-1}$ | 7,010 | 7,150 | 15,740 | 16,180 | 29,630 | 30,470 |
| Operating labour | €. yr$^{-1}$ | 210 | | 310 | | 490 | |
| Maintenance cost | €. yr$^{-1}$ | 400 | | 760 | | 1,240 | |
| O&M cost at desulphurisation plant | €. yr$^{-1}$ | - | | - | | 950 | |
| *Total O+M costs (b)* | *€. yr$^{-1}$* | *7,620* | *7,760* | *16,810* | *17,250* | *32,310* | *33,150* |
| Other costs | | | | | | | |
| Ash disposal cost | €. yr$^{-1}$ | 380 | | 850 | | 1590 | |
| Insurance and others | €. yr$^{-1}$ | 260 | | 500 | | 820 | |
| Total Other costs *(c)* | *€. yr$^{-1}$* | *640* | | *1350* | | *2410* | |
| *TOTAL plant cost (d) = (b+c)* | *€. yr$^{-1}$* | *8,260* | *8,400* | *18,160* | *18,600* | *34,720* | *35,560* |
| Power plant Depreciation | €. yr$^{-1}$ | 1320 | | 2520 | | 4120 | |
| Desulphurisation plant depreciation | €. yr$^{-1}$ | - | | - | | 2010 | |
| Total Depreciation *(e)* | *€. yr$^{-1}$* | *1320* | | *2520* | | *6130* | |
| From year *1 to 15* | | | | | | | |
| Gross profit *(f) = (a-d)* | €. yr$^{-1}$ | 1710 | 1570 | 6760 | 6320 | 16880 | 16040 |
| Taxes *(g)* = ( 0.35 · [(f) – (e)]) | €. yr$^{-1}$ | 140 | 90 | 1480 | 1330 | 3760 | 3470 |
| Net profit *(h)* =( 0.65 · [(f) – (e)]) | €. yr$^{-1}$ | 250 | 160 | 2750 | 2460 | 6990 | 6440 |
| Cash Flow *(i) = (h) + (e)* | €. yr$^{-1}$ | 1570 | 1480 | 5280 | 4990 | 13120 | 12570 |
| From year 15 | | | | | | | |
| Gross profit *(f') = (a'-d)* | €. yr$^{-1}$ | 140 | 0 | 2830 | 2390 | 8740 | 7900 |
| Taxes *(g')* = ( 0.35 · [(f') – (e)]) | €. yr$^{-1}$ | 0 | 0 | 100 | 0 | 910 | 620 |
| Net profit *(h')* =( 0.65 · [(f') – (e)]) | €. yr$^{-1}$ | -1180 | 0 | 200 | -140 | 1700 | 1150 |
| Cash Flow *(i') = (h') + (e)* | €. yr$^{-1}$ | 140 | 0 | 2730 | 2390 | 7830 | 7280 |
| Simple Payback Period (SPP) | years | 16.9 | 17.9 | 9.6 | 10.1 | 9.3 | 9.8 |
| Net Present Value (NPV) | million € | -9.6 | -10.8 | 11.1 | 7.3 | 32.9 | 25.9 |
| Internal Rate of Return (IRR) | % | -1.0 | -2.1 | 7.4 | 6.6 | 7.9 | 7.3 |

## *VII.3.5 Sensitivity analysis results*

In the following lines the results obtained of *B.carinata* sensitivity analysis are presented.

### VII.3.5.1 *B.carinata*'s production variation

*B. carinata* average production yields can vary yearly influencing final biomass cost of biomass produced from the crop. From this premise, an economic analysis has been carried out determining feasibility in electrical production from increasing *B. carinata* productivity in cultivation to 8 and 10 Mg (d.b.) per hectare (Table VII.14).

Table VII.14 Biomass final cost according to *B.carinata's* production yield variation in the cultivation and power plant economical reliability

| | | | 10 MW | | 25 MW | | 50 MW | |
|---|---|---|---|---|---|---|---|---|
| | Concept | Units | Sc.1 | Sc.2 | Sc.3 | Sc.4 | Sc.5 | Sc.6 |
| 8 Mg·ha$^{-1}$ | BC at plant | €·Mg$^{-1}$ | 65.97 | 67.97 | 66.67 | 68.53 | 66.94 | 70.00 |
| | SPP | years | 7.9 | 8.1 | 5.5 | 5.6 | 6.0 | 6.1 |
| | NPV | $10^6$ € | 13.8 | 12.8 | 61.4 | 59.1 | 128.2 | 121.3 |
| | IRR | % | 10.6 | 10.2 | 17.2 | 16.8 | 15.6 | 15.1 |
| 10 Mg·ha$^{-1}$ | BC at plant | €·Mg$^{-1}$ | 54.63 | 56.48 | 55.26 | 56.98 | 55.53 | 58.41 |
| | SPP | years | 6.9 | 7.1 | 4.9 | 5.0 | 5.4 | 5.5 |
| | NPV | $10^6$ € | 19.9 | 18.9 | 75.1 | 73.0 | 153.8 | 147.3 |
| | IRR | % | 12.9 | 12.5 | 19.6 | 19.3 | 17.5 | 17.0 |

Under these conditions, the final biomass cost delivered at the plant decreases by an average of 38% when the biomass production yield in the field is 8 Mg·ha$^{-1}$ and decreases an average of 49% when the production yield is increased to 10 Mg·ha$^{-1}$.

Values shown in Table VII.14 demonstrate how economic reliability begins to be achieved when the crop productivity is increased from 10 Mg (d.b.) · ha$^{-1}$ for 25 MW power plants.

When desulphurisation is obligatory for 50 MW power plants or superior, high desulphurisation costs makes the production of electricity non-reliable although crop productivity was 10 Mg (d.b.)·ha$^{-1}$.

### VII.3.5.2 Benefits by selling $CO_2$ credits

Additional plant gross benefits by selling $CO_2$ emission credits can largely increase the economic reliability for all the cases (Table VII.15).

Table VII.15 SPP (years); NPV (million €) and IRR (%) obtained selling $CO_2$ credits at determined $CO_2$ Mg prices

| Power (MW) | Scenario | Concept | Units | €·$Mg^{-1}$ $CO_2$ | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 0 | 5 | 10 | 20 | 50 |
| 10 | Sc. 1 | SPP | Years | 16.9 | 14.9 | 13.2 | 11.0 | 7.2 |
| | | *NPV* | *million €* | *-9.6* | *-6.7* | *-3.6* | *2.0* | *18.0* |
| | | IRR | % | -1.0 | 1.1 | 2.9 | 5.7 | 12.2 |
| | Sc. 2 | SPP | Years | 17.9 | 15.7 | 13.9 | 11.4 | 7.4 |
| | | *NPV* | *million €* | *-10.8* | *-7.9* | *-4.9* | *0.8* | *16.9* |
| | | IRR | % | -2.1 | 0.2 | 2.2 | 5.1 | 11.7 |
| 25 | Sc. 3 | SPP | Years | 9.6 | 8.7 | 8.0 | 6.8 | 4.8 |
| | | *NPV* | *million €* | *11.1* | *17.9* | *24.5* | *37.9* | *78.0* |
| | | IRR | % | 7.4 | 8.9 | 10.3 | 12.9 | 20.1 |
| | Sc. 4 | SPP | Years | 10.1 | 9.2 | 8.4 | 7.1 | 4.9 |
| | | *NPV* | *million €* | *7.3* | *14.2* | *20.9* | *34.2* | *74.4* |
| | | IRR | % | 6.6 | 8.1 | 9.6 | 12.2 | 19.5 |
| 50 | Sc. 5 | SPP | Years | 9.3 | 8.6 | 8.0 | 7.0 | 5.1 |
| | | *NPV* | *million €* | *32.9* | *46.7* | *60.6* | *88.3* | *171.3* |
| | | IRR | % | 7.9 | 9.2 | 10.3 | 12.6 | 18.7 |
| | Sc. 6 | SPP | Years | 9.8 | 9.0 | 8.3 | 7.2 | 5.2 |
| | | *NPV* | *million €* | *25.9* | *39.8* | *53.6* | *81.3* | *164.3* |
| | | IRR | % | 7.3 | 8.6 | 9.8 | 12.0 | 18.2 |

Furthermore, current $CO_2$ credits prices are not so high and economic reliability is not guaranteed.

# VII.4 Conclusions

The main conclusion of this study is that biomass power-plant implementation from *B.carinata* as energy crop is a non-economically viable option for the initial scenarios under study.

According to the economic results, the low productivity yield of *B. carinata* in the field and corresponding final biomass cost when *B. carinata* is delivered at plant is the main contributor to the non-reliability of all scenarios. Transport system is not a limiting economic factor in compromising the reliability of bioenergy systems with *B. carinata* in a national scenario.

Furthermore, desulphurisation investment and operation costs at 50 MW power plants contribute to the non-reliability of the generation of electricity. Under Spanish legislation (via Royal Decree 430/2004) 50 MW power plants have to reduce their sulphur emissions to under 200 mg $SO_2/Nm^3$. Desulphurisation investment required for power plants higher than 50MW with *B. carinata* as fuel increase the costs applied to these plants, making the benefits obtained from electricity generated insufficient. To resolve this cost increment for 50MW power plants, the mixing of *B.carinata* with others low content sulphur biomasses (i.e. *Populus spp. biomass*) is recommended. In this way, flue gas cleaning cost and also solid biofuel cost can be reduced making *B. carinata* part of the Spanish energy crop mosaic for power generation.

The sensitivity assessment carried out allows us to observe that crop productivity increments can solve economic reliability for 25 and 50MW when production yields in the field are higher than 10 Mg (d.b.)·$ha^{-1}$. The benefits obtained by selling $CO_2$ credits have shown themselves to be an important tool for promoting the economic reliability of all biomass plants in comparison with non-renewable power-generation systems.

This paper demonstrates that the single use of *B.carinata* biomass is economically nonreliable to electricity production at power plant considering current crop productivities. An agronomic investigation is needed to obtain higher productivities for *B.carinata* crops.

## VII.5. References to chapter VII

[1] Council EPa. Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market. Brussels, 2001.

[2] Ministerio de Industria Turismo y Comercio. Real Decreto 661/2007. BOE número 126 de 26/5/2007 382 de mayo, por el que se regula la actividad de producción de energía eléctrica en régimen especial. Madrid, 2007.

[3] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversifiacación y Ahorro de la Energía (IDAE). Resumen Plan de las Energías Renovables en España, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspx

[4] Maniatis K, Millich E. Energy from biomass and waste: The contribution of utility scale biomass gasification plants. Biomass & Bioenergy 15 (3) 1998195-200.

[5] Cardone M., Mazzoncini M., Menini S., Rocco V., Senatore A., Seggiani M. & Vitolo S. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass & Bioenergy 25 (6) 2003 623-636.

[6] Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P., Solano M.L. & Rieradevall J. Life Cycle Assessment of a *Brassica carinata* bioenergy system in southern Europe. Biomass & Bioenergy 31 (8) 2007 543-555.

[7] Raccuia S.A., Melilli M.G. Biomass and grain oil yields in *Cynara cardunculus L*. genotypes grown in a Mediterranean environment. Field Crops Research 101 (2) 2007 187-197.

[8] Groscurth, H. M., Almeida, A. de, Bauen, A., Costa, F. B., Ericson, S. O., Giegrich, J., Grabczewski, N. von, Hall, D. O., Hohmeyer, O., Jörgensen, K., Kern, C., Kühn, I., Löfstedt, R., Mariano, J. da S., Mariano, P. M. G., Meyer, N. I., Nielsen, P. S., Nunes, C., Patyk, A., Reinhardt, G. A., Rosillo-Calle, F., Scrase, I., Widmann, B. Total costs and benefits of biomass in selected regions of the European Union. Energy (Oxford), 2000.

[9] Fernandez J., Curt M.D. New energy crops for bioethanol production in the Mediterranean region. International Sugar Journal. Agra Europe (London), 2005.

[10] Ciria P. Efecto del turno de corta y de la densidad de plantación sobre la productividad de diversos clones de chopo en condiciones de corta rotatcion. Tesis doctoral Universidad Politecnica de Madrid, Madrid,1998.

[11] Ciria P., Mazón M.P., Carrasco J.E. Poplar productivity evolution on short rotation during three consecutive cycles in extreme continental climate. 2 nd World Conference on Biomass for Energy, industry and Climate Protection, 10-14 May 2004, Rome 2004.

[12] European Comission. Council Decision 2002/358/EC: Council Decision of 25 April 2002 concerning the approval on behalf of the European Community, of the Kyoto Protocol to the United Nations

Framework Convention on Climate Change and the joint fulfilment of commitments there under, 2002. Available from: http://unfccc.int/resource/docs/convkp/kpeng.pdf .Accessed in: April 2007

[13] Generalitat de Catalunya. Pla de l'energia de Catalunya 2006-2015. Generalitat de Catalunya; Barcelona 2005.

[14] Ministerio de la Presidencia. Real Decreto 1370/2006, Plan nacional de asignación de derechos de emisión de gases de efecto invernadero 2008-2012. Madrid 2006.

[15] Mirasgedis S., Sarafidis Y., Georgopoulou E., Lalas D.P. The role of renewable energy sources within the framework of the Kyoto Protocol: the case of Greece. Renewable & Sustainable Energy Reviews. 6 (3) 2002 247-269.

[16] European Comission. Biomass and energy resource for the European Union. Luxembourg: Office for official publications of the European Communities, 2000. Available from: http://www.cordis.lu/eesd/

[17] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass & Bioenergy 28 (1) 2005 35-51.

[18] Llorente MJF, Cuadrado RE, Laplaza JMM, Garcia JEC. Combustion in bubbling fluidised bed with bed material of limestone to reduce the biomass ash agglomeration and sintering. Fuel 85 (2006) 2081–2092

[19] Serup, H., Falster, H. et al. Straw for energy production (technology, environment, economy), Centre for Biomass Technology (for the Danish Energy Agency, 1998.

[20] Ministerio de Fomento. Observatorio del transporte de mercancías del transporte por carretera, Nº4. Ministerio de Fomento, Madrid, España. Available from: http://www.fomento.es.

[21] European Central Bank. Available from: http://www.ecbint/home/html/indexen.html.

[22] Ministerio_de_Industria TyC. Precio carburantes comparación entre 2005-2006. Available from: http://www.mityces/petroleo/seccion/precios/informes/informesanuales. Accessed in: September 2006.

[23] Masip A. Cost horari de la Maquinaria Forestal. . 1er Quadern d'Informació Tècnica Área d'Infraestructures, Urbanisme i Habitatge Oficina Técnica de Prevenció Municipal d'Incendis Forestals Diputació de Barcelona, Xarxa de Municipis; Barcelona, España 2003.

[24] Gigler JK, Meerdink G, Hendrix EMT. Willow supply strategies to energy plants. Biomass & Bioenergy 17 (3) 1999 185-198.

[25] Ministerio_de_Industria TyC. Precio carburantes comparación entre 2005-2006. Available from: http://www.mityces/petroleo/seccion/precios/informes/informesanuales. Accessed: September 2006.

[26] Volvo Truck from Spain. Personal Communication. Personal details available from: http://wwwv.volvocom/group/spain/es-es

[27] Transgruas SA. Personal Communication. Personal details available from: http://www.transgruas.com

[28] Todaew Equipos_ ndustriales. Toyota from Spain. In: www.todaew.com, editor. 2007.

[29] Volvo Truck. Emission from Volvo's Truck Emissions, standard diesel fuel. Available from: www.volvotruck.com ,2003

[30] Gasol C.M. Análisis de Ciclo de Vida del cultivo energético *Brassica carinata*. Master thesis. Universitat Autònoma de Barcelona. Barcelona 2006.

[31] European_Commission. Biomass Conversion Technologies, Achievement and Prospects for Heat and Power Generation. . Brussels, 1998.

[32] vandenBroek R, Faaij A, vanWijk A. Biomass combustion for power generation. Biomass & Bioenergy 11 (4) 1996 271-281.

[33] vandenBroek R, Faaij A, vanWijk A. Biomass combustion, Power Generation Technologies.. Department of Science, Technology and Society. Utrecht University. The Netherland, 1995. Available from: http://www.chem.uu.nl/nws/www/publica/95029.htm.

[34] International Energy Agency. Renewables for Power Generation. Status and Prospects. OECD/IEA France 2003.Available from: http://www.iea.org/textbase/nppdf/free/2000/renewpower_2003.pdf

[35] Carrasco JE, Esteban LS. Análisis económico de centrales de generación eléctrica con biomasa. Curso de biomasa de CIEMAT. Àvila 2004.

[36] Carrasco J. Análisis Económico de Centrales de Generación Eléctrica con Biomasa.: CIEMAT; 2004, p. 10.

[37] Engineering C. Marshall & Swift Equipment Cost Index. 2007.

[38] Llorente MJF, Laplaza JMM, Cuadrado RE, Garcia JEC. Ash behaviour of lignocellulosic biomass in bubbling fluidised bed combustion. Fuel 85 (9) 2006 1157-1165.

[39] Ministerio_de_la_Presidencia. Real Decreto 430/2004. _Nuevas normas sobre limitación de emisiones a la atmósfera de determinados agentes contaminantes procedentes de grandes instalaciones de combustión, y condiciones para el control de las emisiones a la atmósfera de las refinerías de petróleo. 2004.

[40] Srivastava, R. K. CONTROLLING SO2 EMISSIONS: A REVIEW OF TECHNOLOGIES (EPA/600/R-00/093). U.S. Environmental Protection Agency, Washington, D.C., 2000.

[41] Gasol CM., Martinez S., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P. and Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable & Sustainable Energy Reviews 13 (2009) 801-812.

# Chapter VIII. Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale

---

*Manuscript draft: Gasol C.M., Rigola M. Rieradevall J. & Gabarrell X. Environmental assessment (LCA) and spatial modelling (GIS) of energy crops implementation at local scale.*
*Environmental Science & Technology. (Under Revision).*

---

*Photografy by Carles Martinez Gasol, Italy 2008.*

# Abstract

This paper provides an integrated methodology combining LCA and GIS able to determine suitable areas for cultivating *Brassica spp. (B. carinata and B.napus)* and *Populus spp.* and propose a local and decentralised energy production and consumption scenario. The methodology is verified and applied in a Catalonia (southern Europe) case study area but it can be extrapolated to other mediterranean regions with similar agroclimates.

The study aims to: a) Develop a methodology estimating the potential areas for cultivating energy crops (*Brassica spp. and Populus spp*.) and the potential power and biodiesel production. b) Analyse whether local-level territorial planning enables the implementation of a local energy production and consumption biomass system which renewable fuel - biomass - is not transported more than 25 km. c) Analyse the sustainability at local and regional level of the local biomass energy systems in terms of their potential global warming category ($CO_2$ eq.).

Integration of GIS and LCA tools, has led to a proposal in the Catalonia case study of a scenario where 189,814 ha could be cultivated annually, mainly with *Brassica spp.*, obtaining suitable biomass yields. *Brassica spp.* would be cultivated every three years in a crop rotation system with wheat and barley

The results obtained show that a high impact reduction in potential global warming category can be achieved annually (annual reduction of 1,954,904 Mg of $CO_2$ eq.) in a local scale scenario. It has also been confirmed that increasing the power plant size (> 25 MW) increase the biomass transport distance without reducing the environmental benefits.

*Keywords: biomass, LCA, GIS, potencial global warming, Brassica spp., Populus spp., Catalonia*

# VIII.1 Introduction

The electrical biomass energy sector in Spain and Europe in general has started to import solid biomass from countries in South America, East Europe and Asia to achieve the biomass quote necessary to meet the demand of their power plants at the lowest cost [1,2]. Biomass production and transportation usually account for a significant part of total bioenergy environmental and economical costs [3, 4].

This has been extensively criticised by ecology organizations and some environmental researchers, who consider that energy systems based on imported biomass areneither sustainable, environmental nor economical at a local social level. [5-7]. As example of the impact of this controversy was the European Commission president Jose Manuel Durao Barroso's call for a new study to analyse the impact of agrofuels on the environment and food market after the European Environmental Agency expert group had published a letter demanding the suspension of the 10 percent biofuels target [8]. However, this new assessment took place, and the aim of 10% of European transport fuels coming from biomass by 2020 has been reaffirmed by the president of the European Commission. Considering the background of biodiesel case, Europe, Spain and Catalonia, as other regions, should try to produce the maximum quantity of solid biomass in a local scenario, optimizing its environmental performance.

Agricultural land use has declined over the last four decades by about 38% in Europe [9] and 12.64% in Spain [9]. At the same time, crop productivity has increased considerably in Europe (40.5% for cereal and 20% for fruit in the last 20 years) [9].

Changes in agricultural productivity, and changes in the economic policies supporting agriculture (e.g. reform of the Common Agricultural Policy; CAP), mean that more cropland will be surplus to food production in the coming decades [10]. An analysis of European Commission data suggested that the EU15 is currently oversupplying agricultural goods by about 10% (although this figure has been larger in the past) [11].

Although it is difficult to anticipate how this land would be used in the future, it seems that continued urban expansion, recreational areas and forest land use would all be likely to account for at least some of the surplus. However, this surplus land would provide further opportunities for the cultivation of energy crops. Considering that the amount of land available for agriculture in Spain and Europe is limited, it is necessary to define the proportion of farmland that could be used for the production of agrofuels, or solid biomass to produce power or biofuels (biodiesel or bioethanol). In order to promote the use of local resources, in a local scenario and reduce the global environmental impact, there must be guaranteed biomass production areas available, and local consumers/users such as industrial areas or facilities in the surrounding areas capable of consuming it.

These types of challenges can be analysed by combining several environmental and planning tools such as Geographical Information Systems (GIS) and Life Cycle Assessment (LCA) tools, in an attempt to undertake the assessment with the greatest possible interdisciplinarity.

Within this context, this paper presents a work that aims:

a) To develop and apply a methodology that analyses potential biomass energy crop production (*Brassica spp.* and *Populus spp.*) and potential consumers in a case study in Catalonia, applying GIS.

b) To determine the cultivation level aptitude and its potential crop production.

c) To ascertain whether a local production and consumption energy crops scenario (<25 km) is feasible in the Catalonia case study area.

d) To analyse the sustainability of the local biomass energy systems in terms of their potential global warming category ($CO_2$ eq.) by applying LCA.

### *VIII.1.1 Energy crops analysed in the Catalonia case study*

The energy crops analysed are *Brassica spp.* (*B.carinata and B. napus*) and *Populus spp.* *Brassica spp.* is an annual alotetraploid herbaceous species with a large number of varieties. It has gained a high profile as an energy crop in southern Europe due to its adaptation to and productivity in Mediterranean areas such as Spain, Italy and France [12,13]. This crop can be cultivated every 3 years in a rotating system, after 2 years of cereals. It has also been confirmed that cereal production is higher ini the years after one year of *Brassica spp*. cultivation.

*Populus spp*. is a lignocellulosic forest species cultivated as an energy crop. This crop is cultivated in periods of 10 or 15 years and biomass is obtained every 2 or 5 years, depending on the agricultural technique used [4,14]. As an energy crop, *Populus spp.* could compete for land where it is currently cultivated, but for wood production mainly for economical reasons [15,16].

## VIII.2. Methods and Tools

In the following lines methods and tools applied in the case study area are presented.

### *VIII.2.1 Case study area*

The geographical area analysed is Catalonia in north-eastern Spain (minimum longitude: 0° 4' 2.4906'', maximum longitude: 3° 20' 10.81746'', minimum latitude: 40° 30' 59.0622'' and maximum latitude: 42° 53' 7.25376'') as a representative area of the Mediterranean Southern European zones. Its area of 31,895 km$^2$ is divided into 41 administrative counties, where the production of cereal is predominant and the presence of *Brassica spp*. (3,000 ha) is superior to very other regions in Spain. [17]. *Populus spp*. is also common as a crop producing wood in Catalonia (there are approximately 13,000 ha )[17].

### *VIII.2.2 Tools -Geographic Information System (GIS) and Life Cycle Assessment (LCA)*

A Geographic Information System (GIS) is composed of digital geographic data (digital maps and tables of attributes linked to map identities) and the hardware and software needed to manipulate and display data in a mapped format [18,19]. In our case, the software applied was Miramon [20]. This study uses GIS to understand the geographic context of a wide range of issues pertinent to bioenergy, especially energy demand, biomass supplies and transport distance.

LCA is a tool that analyses the environmental and energy impact of all inputs and outputs within a system, process or product from a cradle-to-grave perspective [21]. The boundaries of the system take into account the $CO_2$ eq. emitted during the biomass production, transportation and energy conversion stages. The environmental assessment of the location of bioenergy facilities has been analysed in order to calculate whether a local biomass production and consumption system as proposed in this study ensures a reduction in greenhouse gases ($CO_2$ eq.) compared to non-renewable energy systems such as natural gas in power production plants, and diesel in decentralised heat production. It has been applied previous results calculated at unit functional level in order to extrapolate the environmental impact in terms of global warming of the biomass production and transportation at territorial level [12,14, 22]. Ecoinvent and BUWAL databases have been used for the estimated emission of natural gas combustion in a power plant and diesel combustion in small boilers [23, 24]. The energy production values used as a reference to compare the greenhouse impact of the biomass production applied are shown in table VIII.2.

### VIII.2.2.1 Application of GIS

For the *Brassica spp. (B.carinata and B.napus)* crops, GIS has been applied to combine various digital agronomic data and to mark the areas with the most feasible energy crop production in each layer. Very suitable agroclimate conditions received the highest score (4 points), suitable conditions received 3 points, moderate conditions received 2 points, low conditions received 1 point and areas with non-availability received 0 points (see figure VII.1). Digital layers were subsequently combined according to hierarchical factors of contribution to the correct growth of the crop (see chapter VIII.2.2.2 and figures VIII.1 and VIII.2). The agroclimate variables applied in the assessment were those that had the most influence on the correct development of the *B.carinata and B.napus* crops [12]. They are as follows:

**Slope of the land** [25]. Agricultural tractors were assumed not to work correctly on gradients greater than 10%. Furthermore, erosion in this land would suppose an increase in the soil lost. Flatlands (0-2.5% gradient) therefore scored 4 points, whereas those ranked between 2.5-5% scored 3 points, those between 5-7.5% scored 2 points, those with gradients between 7.5-10% scored 1 point, and land with gradients higher than 10% scored 0 points.

**Orientation** [25]. The most suitable areas (4 points) are those oriented to north, north-east and north-west because they receive more radiation than the rest. However, the areas oriented south, south-east and south-west were the most penalized (0 points). East- and west-facing areas scored 3 and 2 points respectively.

**Direct Irradiation** [25]. Irradiation was also considered in terms of whether it was direct. Lands that receive direct irradiation scored 4 points. The increase in the percentage of irradiation deviation was deemed to reduce potential crop growth progressively from 3 to 1 point.

**Precipitation between September and March** [25]. This variable scored 4 points in areas where total precipitation is between 300 and 450 mm. Precipitation between 150-300 mm scored 3 points, between 0-150 mm scored 2 points and between 450-600 mm scored 1 point. Areas above 600 mm, where the accumulated precipitation can lead to flooding, scored 0 points.

The criteria used was that the flooding lands is detrimental to the correct development of the crop in its initial growth phase, although moderate total precipitation is beneficial to the crop [10].

**Precipitation between April and June** [25]. Precipitation during these months is beneficial to the final development of the crop to enable it to attain maximum grain production. Areas with the most total precipitation during that time (more than 300 mm) therefore scored 4 points, those with more than 150 mm scored 3 points, those with more than 100 mm scored 2 points, those with more than 50 mm scored 1 point, and dry areas (less than 5mm) scored 0 points.

**Frost risk until December** [25]. Frosts between September (the sowing month of the crop) and December (the month the rosette develops) are very harmful to the crop, and causes most production losses. Land suffering 20 frost days or more scored 0, land with between 19 and 15 days' frost scored 1, land with between 14-10 days' frost scored 2, land with between 9-5 days' frost scored 3 and land with less than 4 days' frost scored 4 points.

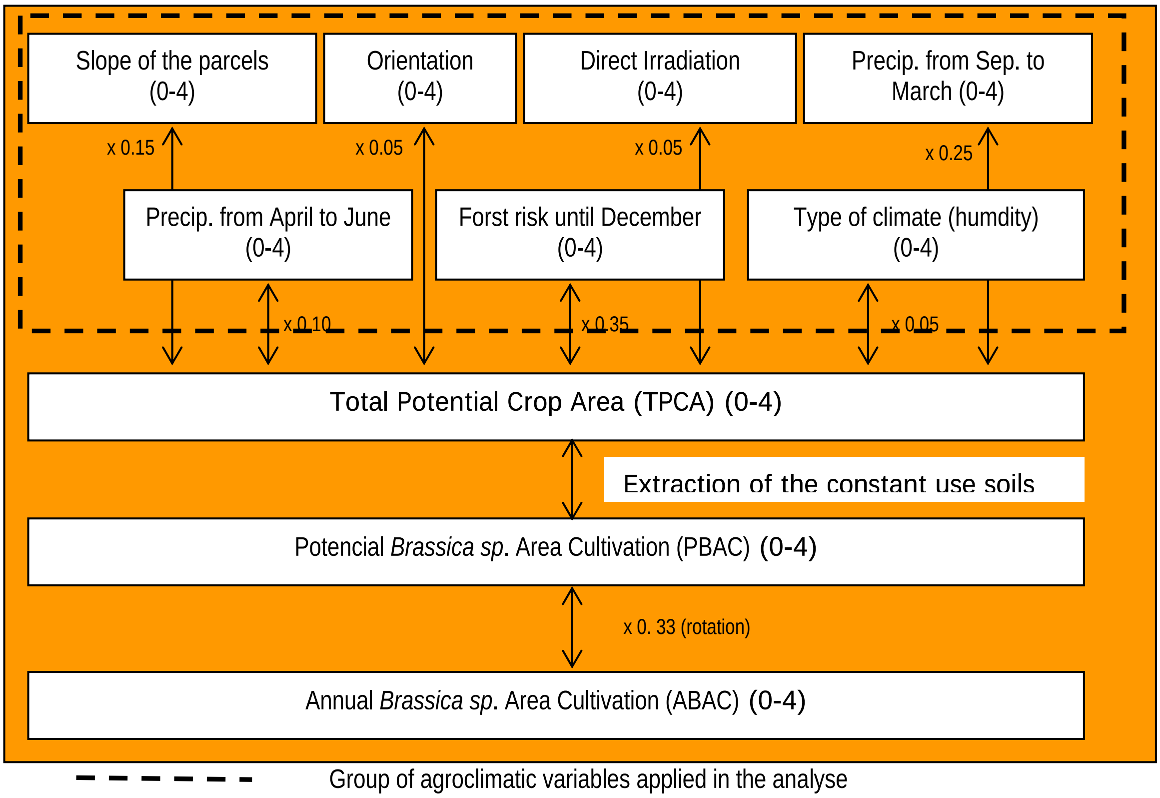
**Type of climate (humidity) according to the Thornthwaite index** [25]. The climates with the highest humidity scored 4 points, and the driest (continental climate) scored 0 points. The range of points between 3 and 1 was applied according to the reduction in climate humidity.

### *VIII.2.3 Prioritization of the agroclimatic variables for Brassica spp. energy crop*

Not all agroclimatic variables were considered in the same way, as shown in figure VIII.1. According to our field experience, the variables for frost risk until December scored 0.35 and the precipitation from September to March scored 0.25 are the most important of these [12,13,26]. The other variables also contribute to the correct development of the crop, but to a lesser extent. Those was scored between 0.05 and 0.15, see figure VIII.1

The maps obtained from this methodological process are Total Potential Crop Area (TPCA), which means the total surface and its suitability for cultivatation of Brassica spp. (*B.carinata and B.napus).*, without considering that these soils may be occupied by other pre-existent land uses and Potential *Brassica spp.* Area Cultivation (PBAC). This latter map enables us to ascertain the various degrees of suitability of the potential land for cultivation of the *Brassica spp.* energy crops, considering that this crop could be cultivated on land with non-existent or scarce vegetation or on unirrigated agricultural land. Other land uses, such as a) continental water, b) infrastructures, c) housing, d) Urban areas, e) Industrial area and facilities, f) irrigated crops, g) irrigated and non-irrigated orchards, f) vineyards, h) grasslands, i) forests j) wetlands, k) beaches and l) burnt soils, have been removed from the TPCA map (see figure VIII.1).

Figure VIII.1 Agroclimate variables considered and ther assumed contribution to the correc development of *Brassica carinata and Brassica napus*.



The mathematical formula that emergese from this methodology is shown below:

$$TPCA = 0.15 \cdot \text{gradient of the slopes} + 0.05 \cdot \text{orientation} + 0.05 \cdot \text{direct irradiation} + 0.25 \cdot \text{Precipitation between September and March} + 0.10 \cdot \text{Precipitation between April and June} + 0.35 \cdot \text{Frost risk until December} + 0.05 \cdot \text{Type of climate (Humidity)}$$

Table VIII.1 shows the various possible scores obtained for each county and the subsequent biomass or grain production [12, 14, 22, 26].

Table VIII.1 Biomass production attributed to each type according its suitability

| | | *B.carinata* | *B.napus* |
|---|---|---|---|
| Score | Aptitude to cultivate energy crops | Productions (Mg. d.b. ha$^{-1}$) | Grain Productions (Mg. ha$^{-1}$) |
| 0 | Not recommended | 0 | 0 |
| 1 | Low | 4.72 | 0.60 |
| 2 | Moderate | 6.00 | 1.20 |
| 3 | Suitable | 8.07 | 1.80 |
| 4 | Very suitable | 10.00 | 2.40 |

Source: [12, 14,22,26]

### VIII.2.3.1 Determination of the agricultural production areas for *Populus spp.*

For *Populus spp*. crops the areas where this crop has been cultivated in the last 20 years were been considered potential production areas. The digital data were provided for the Spanish Agricultural Ministry of Agriculture [27] and were added to the PBAC and ABAC maps. A constant annual average production of 13.5 Mg d.b. · $ha^{-1}$ · $yr^{-1}$ was assumed for this study [14]. A single level of aptitude has been assumed for *Populus spp.* while *B.carinata and B.napus* present a range of aptitudes depending of the suitability of the climate for its cultivation.

### VIII.2.3.2 Determination of the number of power plants and biodiesel production level that could be implemented in each county of the studied area

In order to calculate the number of power plants and their power production in the case study scenario, the potential available biomass in 41 counties in the area studied and the biomass requirement for each plant expressed in oven dry tonnes of biomass must be considered.

In order to calculate the potential number of biomass power plants in each county, we assumed that:

*B.carinata* low production areas will not considered when calculating the potential biomass production. They have been excluded due to their low contribution to total production, and their poor environmental and energy balance compared with other production areas

The annual *B.carinata* and *B.napus* area for cultivating (ABAC) biomass will be PBAC · $3^{-1}$ of the estimated total, due to its crop rotation system with wheat and barley. Priority will be given to crops producing solid biomass (*B.carinata*) instead of biodiesel (*B.napus*), due to their higher energy efficiency conversion rate and better energy balance of their energy production systems [12-14, 22].

Power plants will be projected inside or near consumption areas, such as industrial estates and facilities, and only the biomass generated inside the administrative boundaries of the counties will be consumed (<25 km). Priority will be given to larger power plants when biomass production enables them to be supplied. See table VIII.2 for the biomass requirement for each power plant analysed.

Table VIII.2 Biomass input requirement for each energy plant in the study.

| Power (MW electric) | Biomass requirement (Mg d.b. · $yr^{-1}$) | Power production (MJe · $yr^{-1}$) |
|---|---|---|
| 50 | 270,272 | 1,293,819,091 |
| 25 | 145,000 | 694,129,500 |
| 10 | 64,975 | 288,000,000 |
| 5 | 35,312 | 144,000,000 |
| 2 | 14,125 | 57,600,000 |

Source: [4]

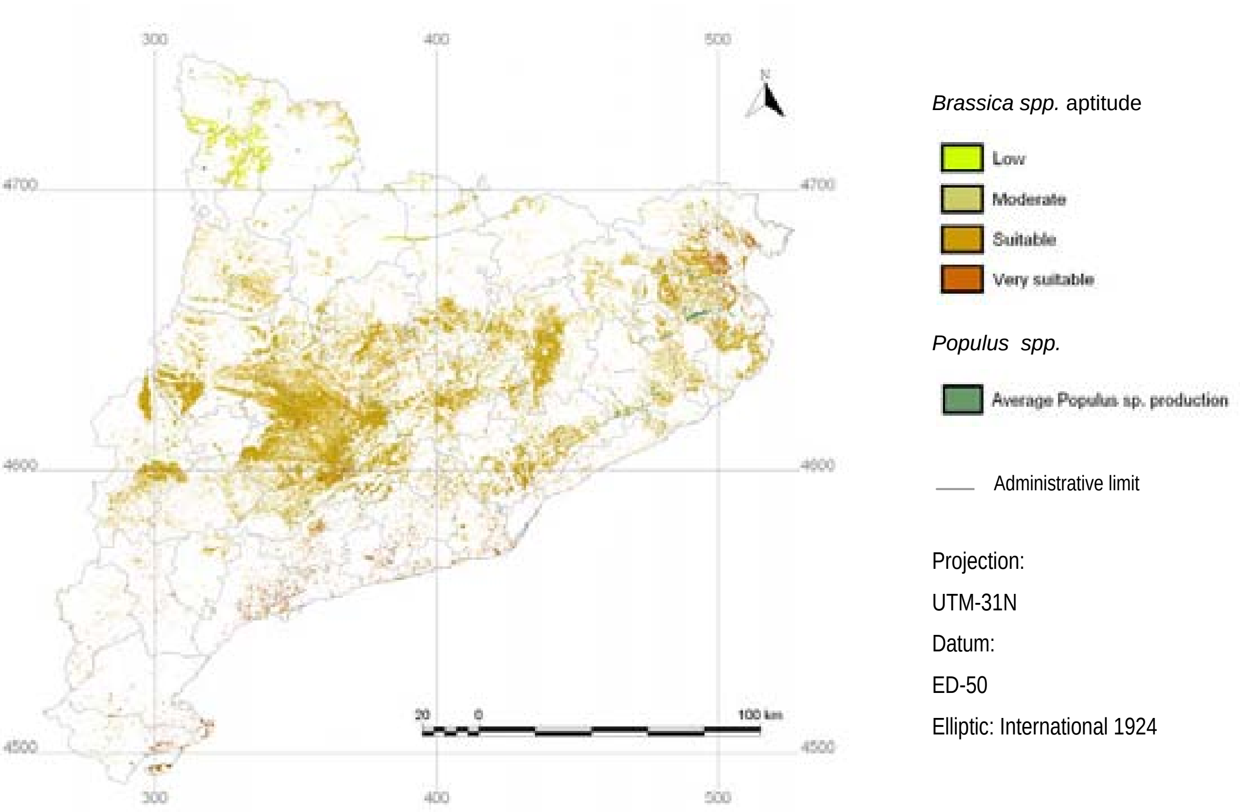
Biodiesel will be produced in counties where biomass production will be insufficient to feed any power plants or in counties where extra land will be available.

## VIII.3 Results

### VIII.3.1 Potential Land for Brassica spp. and Populus spp. cultivation in the Catalonia case study area

Figure VIII.2 shows the potential land that could be cultivated with *Brassica spp*. and *Populus spp*.in the case study area.

Figure VIII.2 Potential land for *Brassica spp*. and *Populus spp.* cultivation. PBAC layer plus annual *Populus spp.* cultivation area



Projection:
UTM-31N
Datum:
ED-50
Elliptic: International 1924

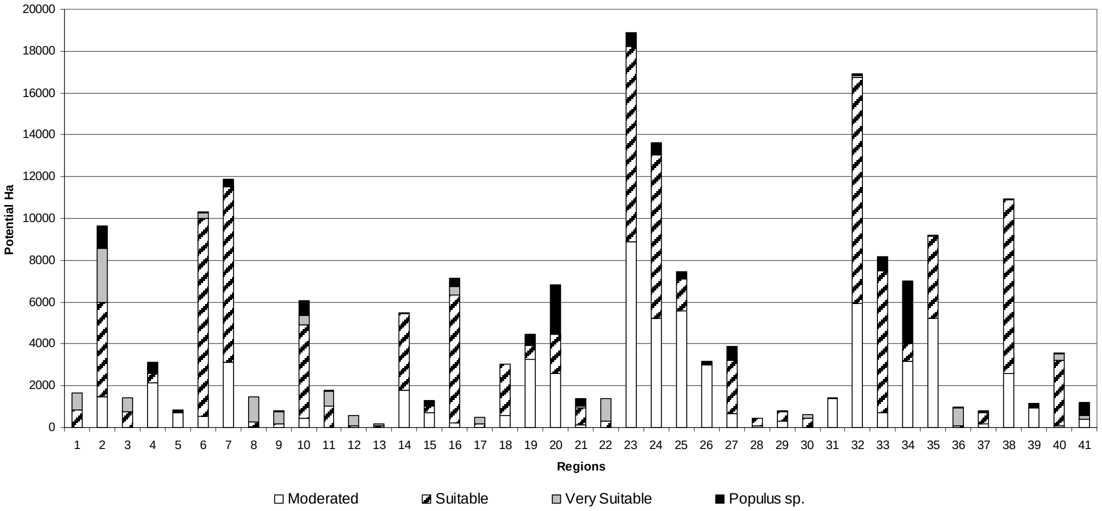
According to our results, 54.46% of the potential showed in figure VIII.2 is suitable for *Brassica spp*. (*B.carinata and B.napus*) cultivations. The area with moderate *Brassica spp.* aptitude is 31.21%, area that are very suitable amount to 5.79%, low aptitude is only 4% and annual areas occupied by *Populus spp.* are 4.89% of the potential annual area. The potential number of hectares where *Brassica spp.* and *Populus spp.* could be cultivated would be 191,559 ha, i.e a 59-fold increase in the current area occupied by *Brassica spp.*, and current levels of *Populus spp.* maintained.

## *VIII.3.2 Potential biomass production for counties in Catalonia case study area*

As mentioned in section VIII.2.1, *B.carinata an B.napus* are crops that are cultivated every 3 years after the cultivation of cereal for 2 years. This agronomic aspect reduces the potential area for producing *Brassica spp.* biomass by a third (ABAC) of the total shown in figure VIII.2. For this reason, the results shown in figure VIII.3 refer to the annual number of hectares in each county for three *Brassica spp*. cultivation aptitude areas (very suitable, suitable and moderate) and P*opulus spp.* areas.

The results in figure VIII.4 are taken from figure VIII.3, which show the potential production of biomass and its cultivation aptitude (shown as different types of bars) and/or marginal grain production for biodiesel (shown as a line on the graph) for each county in the case study area.

Figure VIII.3 Annual potential land cultivated in the counties of the case study are with Brassica spp. and Populus spp.

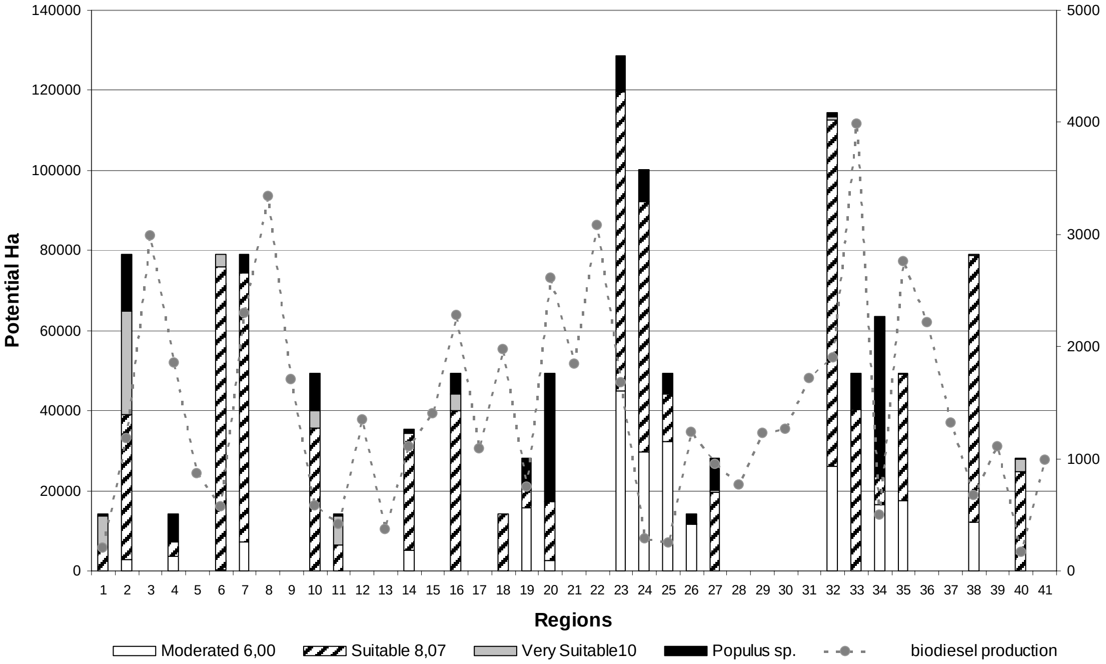


The potential annual area allocated to *B.carinata* as an energy crop was 141,614 ha, and for *Populus spp*. it was 12,186 ha. However, the land that will produce biodiesel covers 36,014 ha (*B.napus*). That means a total energy crop area of 189,814 ha in 41 counties of a total area of 3,189,500 ha.

Based on our assumption, *Populus spp*. would occupy the same area as it does at present, and *Brassica spp.* would have to be implemented in rotation system in lands with non-existent or scarce vegetation, with an area of 88,508 ha, or in unirrigated agricultural lands with an area of 479,363 ha. This means that 65.5% of the proposed area for *Brassica spp*. can be implemented in land with non-existent or scarce vegetation, while 34.5% would be implemented in unirrigated agricultural lands. This implies repleacing 11.08% of the unirrigated agricultural land, assuming that a small proportion of it (less than 2%) is disused land [17].

Other considerations can be taken into account in this discussion, such as the change in land use in the case study area between 2001 and 2006, in order to contextualize these initial results. In the case of land with non-existent or scarce vegetation, approximately 49,500 ha became to scrubland, and 16,700 ha of unirrigated land also changed its use, both due to lack of management [17]. However, forest areas increased by 140,200 ha [17], which was clearly due to the gradual decline in management of the territory. New scrubland or abandoned unirrigated agricultural land, that was considered as forest land in this study, have great potential for providing land for biomass energy crop production without reducing their biomass yield.

Figure VIII.4 *Brassica spp*. and *Populus spp*. average annual biomass and grain production for counties in Catalonia

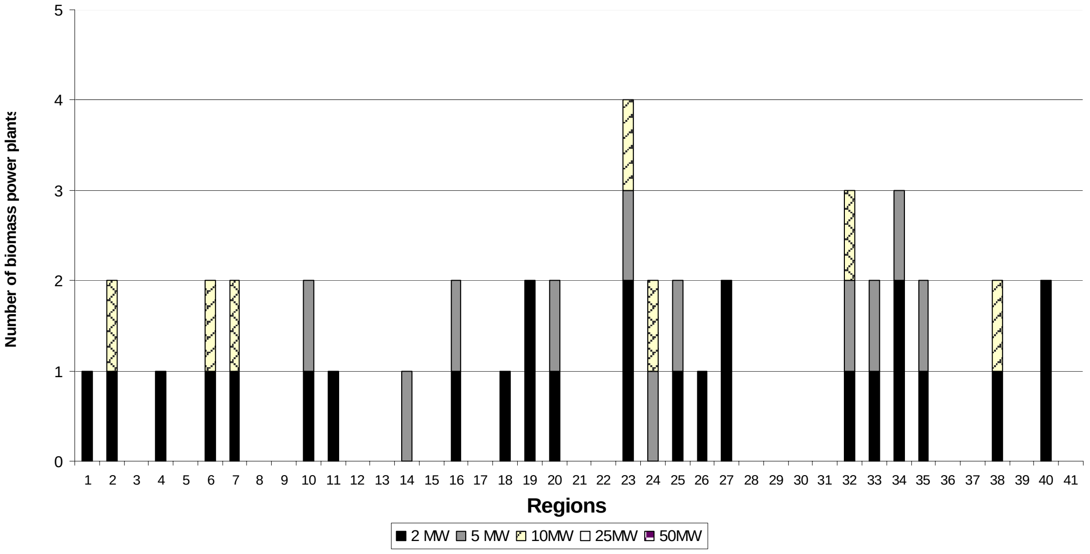


As shown in figure VIII.4, 18 of 41 counties that do not have enough biomass to feed the smallest power plant considered (2MW) just produce biodiesel; there is also marginal biodiesel production in counties where solid biomass is the main product. The total solid biomass production and consumption in power plants would be 1,210,513 Mg of dry matter (30% water content) and the marginal grain for biodiesel production would be 58,837 Mg of tht total grain. Potential solid biomass production has been applied to calculate the number of power plants that could be implemented in each county.

## *VIII.3.3 Potential energy production in each county: number of power plants and marginal biodiesel production*

In order to demonstrate that a decentralised and local biomass energy system can be implemented in each county of the case study area, the total number of biomass power plants for each county has been calculated assuming that only the biomass cultivated within the administrative county boundaries will be consumed by the power plant (see figure VIII.5).

Figure VIII.5 Potential number of biomass power plants to be implemented in each county in the case study area



Assessment at local level has shown that a local strategy would make implementation of local and adapted power plants lower than 10 MWe possible. Only 16% of these power plants would be 10 MW. These power plants have several advantages compared to implementation of high power plants (higher than 25 MWe) in terms of local social benefits, e.g.: a) lower investment costs than high power plants and more accessibility for local entrepreneurs, b) less biomass requirements, reducing the potential importation or extraction of biomass from distant locations and/or c) More job creation locally.

According to our results, see figure VIII.5, 44 power plants with a total installed power of 177 MW could be implemented in Catalonia, with these only consuming biomass strictly within the administrative boundaries of each county.

Furthermore, figures VIII.5 and VIII.6 show that solid biomass energy crop production and power plant implementation does not occur in most counties near Pyrenean mountainous areas (northern Catalonia). Counties like numbers 5, 15, 31 and 39 may have great potential for implementing biomass power plants applying forest biomass, but we did not focus our attention on biomass energy crop production in these counties. Other counties, such as 13, 17, 21, 36 and 41 have little capacity for implementing biomass power plants, due to the lack of non-developed land. However, counties such as 2, 6, 7, 23, 24, 32 and 38, with a lond tradition of agricultural land use, have the most power plants and power installed.

Marginal biodiesel production (24,536 Mg of biodiesel) would be focused in the counties where solid biomass is not produced in large quantities. This involves a potential diesel substitution of 21,319 Mg of diesel applied to produce heat in decentralized and local boilers.

### VIII.3.4 Relationship between production crop areas and consumption areas

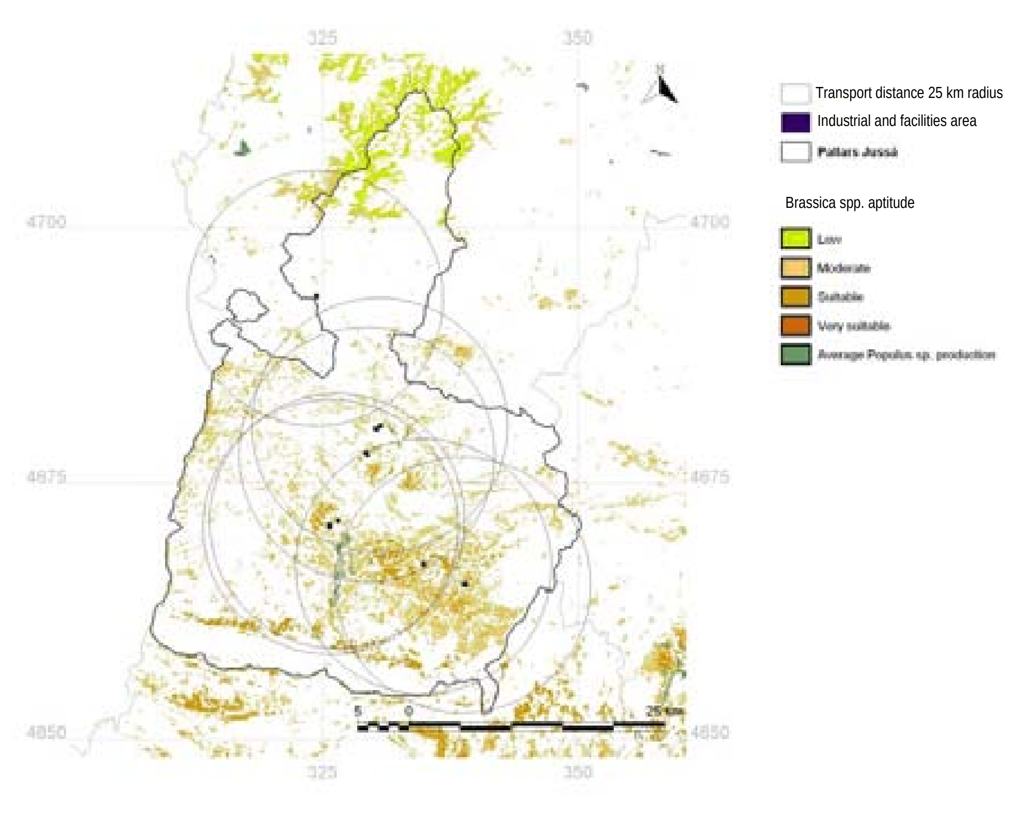
In table VIII.3 are caracterized the 41 counties analysed to carry out a second assessment in one of the counties with lowest density of industrial or facility consumption points and limited biomass production.

Table VIII.3. Biomass consumption and production county's typologies.

| Counties | Name | Energy crops (ha) | Biomass production Mg d.b | Biodiesel production Mg grain | Power Plants (MW) | | | Nº Industrial and facilities consumption points | Population density (Pop. km2) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2 | 5 | 10 | | |
| 1 | A. Camp | 1,666 | 14,133 | 201 | 1 | - | - | Low | 82.11 |
| 2 | A. Empordà | 9,623 | 79,100 | 1,181 | 1 | - | 1 | Low | 99.75 |
| 3 | A. Penedes | 1,437 | 0 | 2,989 | - | - | - | Moderate | 171.67 |
| 4 | A. Urgell | 3,109 | 14,125 | 1,850 | 1 | - | - | Low | 15.16 |
| 5 | A.Ribagorça | 719 | 0 | 863 | - | - | - | Low | 10.15 |
| 6 | Anoia | 10,292 | 79,100 | 569 | 1 | - | 1 | Moderate | 132.53 |
| 7 | Bages | 11,858 | 79,100 | 2,294 | 1 | - | 1 | Moderate | 139.60 |
| 8 | Baix Camp | 1,476 | 0 | 3,341 | - | - | - | Moderate | 268.84 |
| 9 | Baix Ebre | 761 | 0 | 1,711 | - | - | - | Low | 81.08 |
| 10 | B.Empordà | 6,055 | 49,435 | 579 | 1 | 1 | - | Moderate | 186.32 |
| 11 | B.Llobregrat | 1,795 | 14,125 | 414 | 1 | - | - | High | 1,609.53 |
| 12 | B.Penedès | 582 | 0 | 1,347 | - | - | - | Moderate | 322.86 |
| 13 | Barcelonés | 174 | 0 | 369 | - | - | - | High | 15,447.61 |
| 14 | Berguedà | 5,513 | 35,312 | 1,108 | - | 1 | - | Low | 35.01 |
| 15 | Cerdanya | 1,017 | 0 | 1,404 | - | - | - | Low | 34.14 |
| 16 | C.Barberà | 7,153 | 49,437 | 2,282 | 1 | 1 | - | Low | 32.54 |
| 17 | Garraf | 501 | 0 | 1,088 | - | - | - | Moderate | 757.84 |
| 18 | Garriques | 3,057 | 14,125 | 1,975 | 1 | - | - | Low | 25.51 |
| 19 | Garrotxa | 4,456 | 28,250 | 745 | 2 | - | - | Low | 74.02 |
| 20 | Gironès | 6,828 | 49,437 | 2,612 | 1 | 1 | - | Moderate | 304.39 |
| 21 | Maresme | 1,035 | 0 | 1,847 | - | - | - | High | 1,054.18 |
| 22 | Montsia | 1,362 | 0 | 3,078 | - | - | - | Moderate | 96.63 |
| 23 | Noguera | 18,883 | 128,537 | 1,676 | 2 | 1 | 1 | Low | 22.14 |
| 24 | Osona | 13,613 | 100,287 | 290 | - | 1 | 1 | Moderate | 119.15 |
| 25 | P. Jussà | 7,471 | 49,437 | 247 | 1 | 1 | - | Low | 10.21 |
| 26 | P. Sobirà | 3,173 | 14,125 | 1,237 | 1 | - | - | Low | 5.40 |
| 27 | P. l'Estany | 3,865 | 28,250 | 949 | 2 | - | - | Moderate | 112.79 |
| 28 | P. d'Urgell | 458 | 0 | 767 | - | - | - | Moderate | 118.21 |
| 29 | Priorat | 783 | 0 | 1,230 | - | - | - | Low | 19.79 |
| 30 | R. d'Ebre | 643 | 0 | 1,267 | - | - | - | Low | 28.82 |
| 31 | Ripollès | 1,415 | 0 | 1,712 | - | - | - | Low | 28.06 |
| 32 | Segarra | 16,907 | 114,412 | 1,902 | 1 | 1 | 1 | Low | 30.91 |
| 33 | Segria | 8,190 | 49,437 | 3,983 | 1 | 1 | - | Moderate | 141.33 |
| 34 | Selva | 7,002 | 63,562 | 499 | 2 | 1 | - | Moderate | 165.46 |
| 35 | Solsonès | 9,197 | 49,437 | 2,762 | 1 | 1 | - | Low | 13.67 |
| 36 | Tarragonès | 947 | 0 | 2,216 | - | - | - | Moderate | 757.54 |
| 37 | Terra Alta | 771 | 0 | 1,316 | - | - | - | Low | 17.33 |
| 38 | Urgell | 10,937 | 79,100 | 669 | 1 | - | 1 | Low | 62.21 |
| 39 | Val D'aran | 925 | 0 | 1,110 | - | - | - | Low | 16.09 |
| 40 | V.Occidental | 3,562 | 28,250 | 162 | 2 | - | - | High | 1,478.76 |
| 41 | V. Oriental | 603 | 0 | 987 | - | - | - | High | 454.14 |
| Total | Catalonia | 189,814 | 1,210,513 | 58,837 | 26 | 11 | 7 | - | 229.36 |

This second assessment took place in one of the counties with the lowest density of industrial or facility consumption points, Pallars Jussà county (no. 25). Figure VIII.6 shows that even in biomass production areas where the consumption points are disperse, it will be possible to implement a local biomass energy system where this renewable fuel would not be transported more than 25 km (see figure VIII.6).

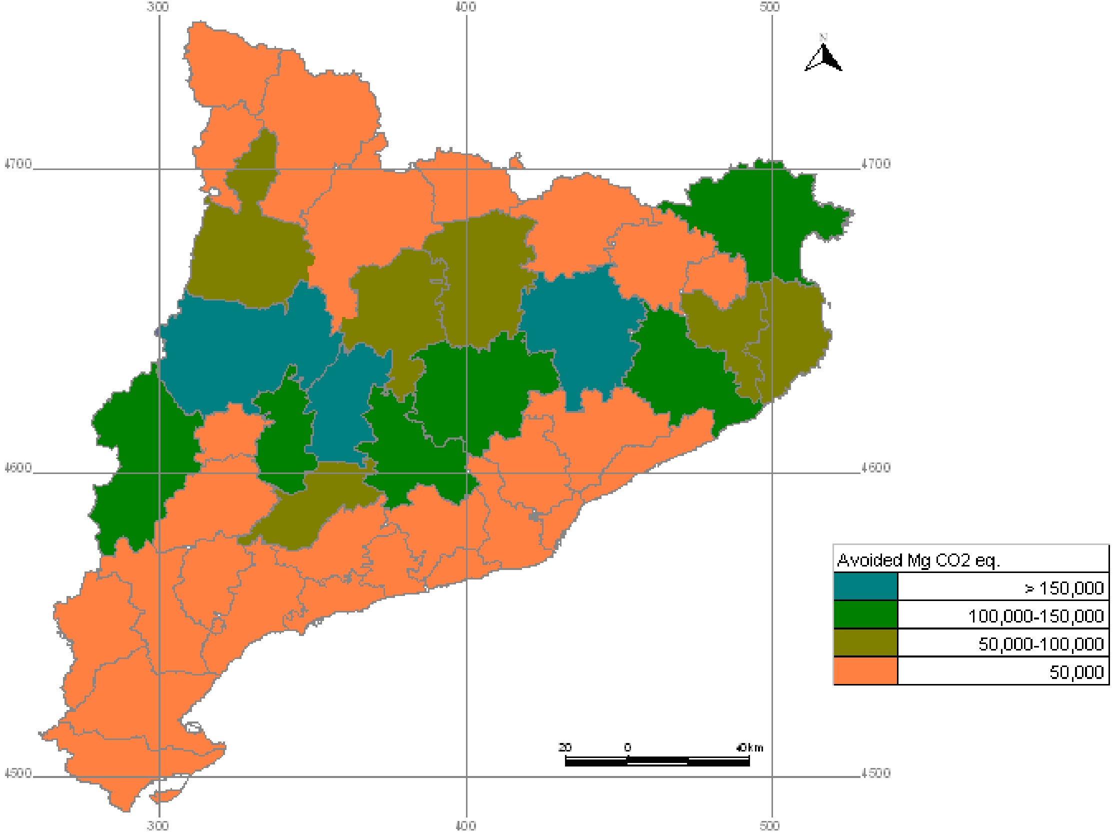
Figure VIII.6 Example of a biomass production county with a low density of consumption point density: the industry or facilities where biomass as a renewable energy source is transported is less than 25 km away



## VIII.3.4 Avoided global warming potential Impact (CO$_2$ eq.); LCA of the potential biomass energy generation in the Catalonia area case study

The annual reduction of CO$_2$ eq. emissions that could be attained has been calculated based on the results obtained for the potential generation of power when applying local biomass production. Figure VIII.7 shows the distribution of total CO$_2$ eq. reduction for each county in the case study area. Table VIII.3 shows the quantification of CO$_2$ eq. emission reduction organized in four groups of counties.

Figure VIII.7 Potential $CO_2$ reduction in a local strategy of energy crop implementation strategy for energy production.



The total annual reduction in the Potential Global Impact category will be 1,954,904 Mg of $CO_2$ eq. annually, or 36.66% of the objective of the Catalonia Climate Change Mitigation plan which anticipates a total $CO_2$ eq. reduction of 5.33 Mg [28].

Table VIII.4 Potential Global Warming (PGW) annual reduction in the Catalonia case study

| | Electricity Bioenergy system | | Electricity non-renewable system | | Heat bioenergy system | Heat non-renewable system | |
|---|---|---|---|---|---|---|---|
| | Emission (Mg $CO_2$ eq.) | | | | Emission (Mg $CO_2$ eq.) | | |
| Number of Group of counties | *Brassica spp.* | *Populus spp.* | Gas Natural | Reduction | *Brassica sp.* | Diesel | Reduction |
| 3,6,7,11,13,14,17, 21,24,40,41 | 44,612 | 525 | 586,058 | 540,921 | 6,505 | 14,784 | 8,279 |
| 2,10,15,19,20, 27,31,34 | 27,049 | 4,073 | 504,010 | 472,887 | 5,198 | 11,813 | 6,615 |
| 4,5,18,23,25,26,28, 32,33,35,38,39 | 71,942 | 1,241 | 879,087 | 805,904 | 10,223 | 23,234 | 13,011 |
| 1,8,9,12,16,22 ,29,30,36,37 | 7,641 | 210 | 105,490 | 9,658 | 9,658 | 21,949 | 12,291 |
| All counties | 151,244 | 6,049 | 2,074,645 | 1,917,352 | 31,584 | 71,780 | 40,196 |

The application of biomass as a solid fuel obtained from *Populus spp*. or *Brassica spp.* makes a contribution of 97.83 % of the total potential reduction in the global warming potential category when compared to the use of natural gas in power plants. Replacing 25,320 Mg of biodiesel with local production of 20,334 Mg of diesel reduces the impact in the global warming category by 40,196 Mg $CO_2$ eq. or 2.17 % of the total attained in the territory covered in this paper.

### *VIII.3.5 Sensitivity assessment in $CO_2$ eq. avoided impact*

A brief analysis at regional level shows that if biomass potential production is transported 100 km and converted into energy in high power plants (> 25 MW) with high energy factor conversion (0.31) [4] the impact generated would be 117,123 Mg $CO_2$ eq. instead of 157,293 Mg $CO_2$ eq. The impact reduction in a local biomass strategy with 100 km of biomass transport distance would be 1,997,718 Mg $CO_2$ eq. instead of 1,957,548 Mg $CO_2$ eq. (base case scenario, 25 km of biomass transport distance). Increase the size of power plants in a local strategy leads to compensatea the higher impact related to longer biomass distances transport. The energy conversion factors enable less biomass to be consumed and the total energy crop production stage to be reduced. Of course, the impact related to transport distance increases but this is not relevant in the final comparison results.

## VIII.4 Conclusions

Environmental integration such as GIS and LCA provide a methodology capable of giving enough information and results to determine an energy crop implementation strategy for reducing energy consumption and $CO_2$ eq. emissions.

Furthermore, GIS also enables energy crop production areas and energy consumption areas such as industrail estates and facilities calculating potential biomass energy crop production and transport distance to be coordinated. Integration of environmental tools that analyse various aspects of the environment is essential for the inclusion of environmental assessment. GIS and LCA can thereby perfectly obtain environmental results from energy and materials flows based on territorial organization proposed by the GIS results.

The results obtained show that the proposed potential energy crop production enables a local biomass energy system to be designed in which biomass production and power plants are at least 25 km apart.

The results show that in the case study area, a decentralised power system based on biomass would be possible with power plants lower than 10 MW. Furthermore, a marginal biodiesel quantity would undertake production together with power production.

Local biomass production would be consumed in local consumption areas, reducing their energy dependency and this would help to attain global targets for $CO_2$ eq. impact reduction, and in the implementation of renewable energies.

In terms of preventing Global Warming Impact, a local biomass energy system could contribute to reaching 36.6% of the aims stipulated in the Catalan climate change plan in just one year. It allows affirming that biomass can reduce significantly the environmental impact of the energy sector.

Local implementation strategy (< 25 km or < 100 km) assessment has shown similar environmental benefits. The higher energy conversion factors of power plants enable the biomass transport distance to be increased from 25 km to 100 km without increasing the total environmental impact of bioenergy sytems.

Energy crops as a renewable energy resource lead to an annual implementation of 141,614 ha of *Brassica spp.* in a rotation system with cereal. Of this extension 65.5% of the proposed *Brassica spp.* areas would be on land with non-existent or scarce vegetation. The remaining 34.5% would be on unirrigated agricultural lands, implying a substitution of 11.08% of this land use.

The 12,186 ha proposed for *Populus spp*. would be cultivated in the same areas as at present

Furthermore, the current lack of territorial management has led to a large number of hectares becoming incipient forest (scrubland). Appropriate management of this area could reduce the minimum competition of our energy crop proposal with agricultural lands and at same time help with maintenance and prevention of forest fires.

Other studies are necessary to complete this assessment, in order to determine the economical feasibility of this proposal and to analyse the benefit to the farmer and the economic and social performance of this proposal on a national level.

## VIII.5 References

[1] Ministerio de Industria, Turismo y Comercio e Instituto para la Diversifiacación y Ahorro de la Energía (IDAE). Resumen Plan de las Energías Renovables en España, 2005. Available from: http://www.mityc.es/energia/desarrollo/EnergiaRenovable/Plan/Paginas/planRenovables.aspx The Spanish renewable energies plan, 2005-2010 (PER). Ministry of Industry, Tourism and Trade; August 2005.

[2] Eixkhout B., Van Meijl H., Tabeau A. and Van Rheenen T. Economic and ecological consequences of four European land-uses scenarios. Land Use Policy (2007) (24) 562-575.

[3] Zhan F.B., Chen X., Noon C.E., Guangyu W. A GIS-enabled comparison of fixed and discriminatory pricing strategies for potential switchgrass-to-ethanol conversion facilities in Alabama. Biomass and Bioenergy 28 (2005) 295-306.

[4] Gasol CM., Martinez S., Rigola M., Rieradevall J., Anton A., Carrasco J., Ciria P. and Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable & Sustainable Energy Reviews 13 (2009) 801-812.

[5] Russi D. An integrated assessment of a large-scale biodiesel production in Italy:
Killing several birds with one stone? Energy Policy 36 (2008) 1169–1180.

[6] Oxfam International. Another Inconvenient Truth, Oxfam Briefing Paper, June 2008. Available from: www.oxfam.org.uk/resources/policy/climate_change/downloads/bp114_inconvenient_truth.pdf

[7] FOE. New draft law exposes weak EU standards for agrofuels. Safeguards fail to protect poor or environment. Press release of Friend of Earth Europe.
http://www.foeeurope.org/giant_eu_energy_flag/FoEE_EU_Council_media_bref_March07.pdf . 2007.

[8] European Environmental Agency. (2008). Suspend 10 percent biofuels target, says EEA's scientific advisory body. Available from:
http://glossary.eea.europa.eu/terminology/sitesearch?term=Opinion+of+the+EEA+Scientific+Committee+on+the+environmental+impacts+of+biofuel+utilisation+in+the+EU+

[9] FAOSTAT. 2009. Available from:
http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377#ancor

[10] Rousevell M.D.A, Ewert F., Reginster I., Leemans R., Carter T.R. Future scenarios of European Agricultural land use. II. Projecting changes in cropland and grassland. Agriculture Ecosystems & Environment 107 (2005) 117-135.

[11] European Commission, 2001 Agriculture in the European Union: statistical and economic information 2000. http://europa.eu.int/comm/agriculture/agrista/2000/table-en/index.htm

[12] Gasol C, M. , Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P, Solano M.L. and Joan Rieradevall. Life Cycle Assessment of a *Brassica carinata* bioenergy system in southern Europe. Biomass & Bioenergy 31 (2007) 543-555.

[13]Cardone M, Mazzoncini M, Menini S, Rocco V, Senatore A, Seggiani M, et al. Brassica carinata as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass & Bioenergy 25 (2003); 623-636.

[14] Gasol C.M., Gabarrell X., Anton A., Rigola M., Carrasco J., Ciria P, and Rieradevall. LCA o Populus spp bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario. Biomass and Bioenergy 33 (2009); 119-129.

[15] Gasol C.M., Brun Filippo, Mosso A., Rieradevall J. and Gabarrell X. Economic assessment and comparison of some bioenergy short rotation coppices with annual traditional crops in southern Europe. Journal: Energy Policy. Draft document. It was send it in October 2008.

[16] Brun F. and Mosso A. Profitability comparison between short rotation forestry and agricultural crops in Piedmont Region, Italy, in. K.Maniatis, H.-P. Grimm, P. Helm, A. Grassi (eds.) 15th European Biomass Conference, From Research to Market Deployement, 07-11 May 2007, Berlin, Germany, ISBN 978-88-89407-X, pp. 2594-2599, 2007.

[17] Web de l'estadística oficial de Catalunya. Available from:
http://www.idescat.cat/dequavi/Dequavi?TC=444&V0=11&V1=9

[18] Tomlison R.F. Geographic Information 1992/3 (Yearbook of association for geographic information) - Cadouxhudson, J, Heywood, I. 1993. Volume 45 480-481.

[19] Graham RL, English BC, Noon CE. A Geographic Information System-based modelling system for evaluating the cost of delivered energy crop feedstock. Biomass & Bioenergy (2000)18 (4) 309-329.

[20] Pons, X., 2004. MiraMon. Geographic Information System and Remote Sensing software.Centre de Recerca Ecològica i Aplicacions Forestals, Barcelona.

[21] Consoli F., Allen D., Boustead I., de Oude N., Fava J., Franklin W., Quay B., Parrish R., Perriman R., Postlethwaite D., Seguin J., Vigon B. 1993. Guidelines for Life-Cycle Assessment: A Code of Practice. Setac: Pensacola (USA).

[22] Gasol C.M., Salvia J., Serra J., Anton A., Rieradevall J. and Gabarrell X. Comparative of winter rape (*Brassica napus*) cultivation as energy crop to produce Biodiesel in a southern Europe. Fuel. Draft Document.

[23] Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N. and Röder A. (2004) Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, 2004

[24] HABERSATTER, K., (1991). “Ecobalance of packaging materials. State of 1990”. Study on behalf of the Federal Office of Environment, Forests and Landscape (BUWAL). Environmental Series Nº132. Swiss Federal office of Environment, Forest and Landscape (FOEFL). Berna (Swiss).

[25] Agroclimate digital data. Atles Climàtic de la Generalitat de Catalunya. Available from:http://mediambient.gencat.net/cat/el_departament/cartografia/docs/cartografia_referencia.jsp?ComponentID=7169&SourcePage=3351#1

[26] Personal Comunication with Jordi Salvia. Agronomic Engineering of the Institut de Recerca i Tecnologia Agroalimentaria (IRTA-Mas Badia).

[27] Agricultural Spanish Ministry.Dirección General de la Producción Agraria. Mapa de Cultivos y Aprovechamiento (1980). Available in:
http://mediambient.gencat.net/cat/el_departament/cartografia/fitxes/mca-a.jsp?ComponentID=5560&SourcePageID=6463#1.

[28] Pla marc de mitigació del canvi climàtic a Catalunya 2008-2012. (2008) Generalitat de Catalunya. Departament de Medi Ambient i Habitatge. Available from:
http://mediambient.gencat.cat/cat/el_medi/C_climatic/nov/aprovat_pla_marc_mitigacio_cc.jsp?ComponentID=158882&SourcePageID=112595#1

# Chapter IX. General conclusions and future research

Each chapter in this thesis ends with a discussion of its results and subsequent conclusions, here we summarize the main points. According to the objectives presented in chapter I, the conclusions are grouped in five areas: methodology, energy balance of the studied bioenergy systems, environmental performance, economic feasibility and territorial planning.

# IX.1 Methodology and tools

- There is a lack of environmental, energetic, agronomic and economic data about energy crop production in Spain. This thesis presents agronomic inventory data on three bioenergy systems in Spain: *Brassica carinata* annual crop for solid biomass production, *Brassica napus* for biodiesel production and *Populus spp*. pluri-annual lignocellulosic crop for solid biomass production.
- Life Cycel Assessment has proved to be a useful tool for establishing the global environmental impact and energy balance of the bioenergy systems analyzed (*B.carinata, B.napus & Populus spp*.).
- The application of economic indicators enables the financial performance of bioenergy systems to be calculated based on local biomass production and determine their feasibility as generators of electricity.
- Geographic Information System is a useful tool for coordinating energy crop production areas and energy consumption demand areas such as industrial estates and facilities; it calculates potential biomass crop production and transportation distances.
- Together the Geographic Information System and Life Cycle Assessment tools provide enough information to determine the most sustainable energy crop implementation strategy to reduce energy consumption and $CO_2$ eq. emissions.

# IX.2 Energy Balance

Energy balance of the bioenergy systems studied: *Brassica carinata, Populus spp. and Brassica napus*

- All the bioenergy systems analyzed – *Brassica carinata*, *Populus spp.* and *Brassica napus* – present a better energy balance than their counterpart non-renewable energy sources, such as natural gas and diesel.

| Units: MJ | *Populus spp.* bioenergy system | *Brassica carinata* bioenergy system | Natural Gas production and distribution system | Biodiesel from *Brassica Napus* | Diesel production and distribution system |
|---|---|---|---|---|---|
| Energy input | 0.02 | 0.12 | 0.18 | 0.56 | 1.20 |
| Energy output[1] | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Net balance | 0.98 | 0.88 | 0.82 | 0.44 | -0.20 |

[1] The energy output of *Brassica carinata* and *Populus spp.* refers to their biomass; for *Brassica napus*, it refers to biodiesel LHV.

- *Populus spp.* is the bioenergy system with the best energy balance: it has the highest biomass production at 13.5 Mg. d.b · $ha^{-1}$ · $yr^{-1}$ and lower input requirements compared to other energy crops.
- The net energy ratios (output – input / output) for all the bioenergy systems studied were always positive irrespective of the final type of energy (heat, electricity or biodiesel). However, using direct combustion to produce heat has proved to be the most efficient conversion technology studied.

| Type of energy production | *Brassica carinata* Net energy ratios | *Populus spp.* Net energy ratios | *Brassica napus* (biodiesel) Net energy ratios |
|---|---|---|---|
| Direct energy stored in biomass | 0.88 | 0.98 | - |
| Heat energy production | 0.86 | 0.97 | - |
| Electric energy production | 0.55 | 0.91 | - |
| Biodiesel production | - | - | 0.44 |

<u>Life cycle stages with high energy consumption in the *Brassica carinata* and *Populus spp* bioenergy systems</u>

- Diesel use and fertilizer production consume the most energy in both bioenergy systems. Diesel represents 47% of the energy input for the *B.carinata* system and 53% for the *Populus spp*. Fertilizer production represents 35% of the energy input for *B.carinata* and 41% for *Populus spp*.

<u>Life cycle stages with higher energy consumption in the *Brassica napus bioenergy systems*</u>

- Transesterification, oil extraction and diesel use are the three stages with high energy consumption in the *Brassica napus* system, representing 25%, 21% and 20% respectively of total energy consumption.

## IX.3 Global environmental impacts

<u>Environmental impact of the *Brassica carinata* and *Populus spp.* bioenergy systems compared to natural gas</u>

- The environmental impact of *Populus spp.* and *Brassica carinata* solid biofuel production is smaller than that of the non-renewable energy source, natural gas, with the exception of the Photochemical Oxidation Potential (POP), Acidification Potential (AP) and Eutrofization Potential (EP) of *Brassica carinata*; these were greater mainly due to the production and application of fertilizers in fields.

- The global impact of *Populus spp.* on the environment is between 48-99% less than natural gas in all environmental categories analyzed, with its Global Warming Potential (GWP) 94% lower.

- The global impact of *Populus spp.* on the environment is between 79-90% less than *Brassica carinata* in all environmental categories analyzed.

### Environmental impact of *Brassica napus* biodiesel compared to diesel

- The environmental impact of *Brassica napus* biodiesel is smaller than conventional diesel in the Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) categories; in all other categories, the environmental impact of this energy crop system was greater than conventional diesel mainly due to the use of non-renewable fuels (diesel, hexane and methanol) in several life cycle stages.

- Glycerine is the unavoidable by-product of biodiesel production systems. When the impact of by-products such as glycerine and meal are discounted from the environmental balance of biodiesel, the environmental performance of the *Brassica napus* system improves in all categories analyzed.

### Life cycle stages with high global environmental impact in the *Brassica carinata* and *Populus spp.* bioenergy systems

- In six of the categories analyzed – Global Warming Potential (GWP), Fresh Water Aquatic Ecotoxicity Potential (FWAEP), Marine Aquatic Ecotoxicity Potential (MAEP), Terrestrial Ecotoxicity Potential (TEP), Acidification Potential (AP) and Eutrofization Potential (EP) – the emissions from fertilizer production and application have the highest environmental impact in both bioenergy systems. For the *Brassica carinata* bioenergy system, fertilizer production contributes 60-68% of the global environmental impact in these six categories; for the *Populus spp.* bioenergy system, it contributes between 43-62%.

- In the remaining four categories – Human Toxicity Potential (HTP), Abiotic Depletion Potential (ADP), Ozone Layer Depletion Potential (ODP) and Photochemical Oxidation Potential (POP) – the production and use of diesel for agricultural tractors and transport vehicles has the highest environmental impact in both bioenergy systems. For the *Brassica carinata* bioenergy system, it contributes between 54-86%, and for *Populus spp*., it is between 63-91%.

Life cycle stages with high global environmental impact in the *Brassica napus* bioenergy system

- Production and application of fertilizers has the highest impact in the *Brassica napus* energy crop system in four – Global Warming Potential (GWP), Terrestrial Ecotoxicity Potential (TEP), Acidifcation Potential (AP) and Eutrofication Potential (EP) – of the ten environmental categories analyzed, with an impact of between 36-54%.

- The oil extraction and transesterification stages have the highest impact in four – Abiotic Depletion Potential (ADP), Ozone Layer Depletion Potential (ODP) Marine Aquatic Ecotoxicity Potential (MAEP) and Photochemical Oxidation Potential (POP) – of the ten environmental categories analyzed, with an impact of between 27-55%.

- Production of pesticides has the highest environmental impact in two – Human Toxicity Potential (HTP) and Fresh Water Aquatic Ecotoxicity Potential (FWAEP) – of the ten environmental categories analyzed, representing 53-83% of the environmental impact.

## IX.4 Economic feasibility

Economic feasibility of the *Brassica carinata* and *Populus spp*. bioenergy systems taking into account the Royal Decree 661/2007

- Royal Decree 661/2007 promotes decentralized electricity generation and local biomass production.

- *Populus spp*. as a renewable fuel is feasible from an economic point of view with current agricultural production higher than 9.00 Mg d.b · $ha^{-1}$ irrespective of the power plant size (10 MW, 25 MW and 50 MW).

- The current *Brassica carinata* agricultural production (4.72 – 6.00 Mg d.b · $ha^{-1}$) makes this crop unfeasible as a renewable energy source from an economic point of view, as demonstrated by the Net Present Value results that present negative or very low profits in high power plants.

- The sensitivity assessment of the *Brassica carinata* system shows that increments in crop productivity can provide economic reliability in 25 MW and 50 MW power plants when production yields in the field increase. Then, NPV results increase from 7 and 26 in the base case scenario (4.72 Mg d.b .$ha^{-1}$) to 153 and 147 for scenarios with 10 Mg d.b.·$ha^{-1}$.

Key factors for the economic feasibility of bioenergy systems

- The cost of biomass production is the key factor determining the feasibility of biomass projects in a local scenario (ie, transportation distance less than 25 km). The crop stage contributes 83-89% of total costs in the case of *Brassica carinata* and 70-72% in the case of *Populus spp*.

- If local biomass fuel production can be guaranteed at a reasonable cost (15-25 € · Mg d.b.), this study demonstrates that large power plants (50 MW or 25 MW) are more economically feasible than small power plants.

- The benefits of selling $CO_2$ credits have proved an important tool to promote the economic reliability of all biomass plants in comparison to non-renewable power-generation systems.

# IX.5 Territorial planning

- The farming of crops as a renewable energy source could create an annual production of 141,614 ha of *Brassica spp*. in a rotation system with cereal and 12,186 ha of *Populus spp.* in the case study area.

- *Populus spp.* would be cultivated in the same areas as currently. Of the areas proposed for *Brassica spp.* production, 65.5% (88.508 ha) would be on land with nonexistent or scarce vegetation; the remaining 34.5% (53.106 ha) would compete for unirrigated crop land with the possible use of 11.08% of land presently allocated to cereal production.

- The proposed energy crop production for the case study area of Catalonia (southern Europe, Spain) involves designing a local biomass energy system. In all the counties analyzed, industrial areas and facilities exist capable of consuming the biomass energy produced in a local transportation distance scenario.

- A decentralized power system based on biomass would be possible with power plants lower than 10 MW in the case study area. Furthermore, a marginal quantity of biodiesel would be produced in conjunction with power production.

- In terms of Global Warming prevention, a biomass local energy system could help meet up to 36.66% of the aims outlined in the target Catalan climate change plan (5,330,000 Mg of $CO_2$ eq.) in just one year. Annual emissions could decrease by 1,997,718 Mg of $CO_2$ eq. with a local bioenergy scenario.

- The energy conversion efficiency of high power plants allows the biomass transportation distance to rise from 25 km to 100 km without increasing the environmental impact.

- Implementing local biomass energy presents more social and economic advantages (job creation, maintenance of rural areas, decentralized renewable energy generation) than importing biomass from other regions.

## IX.6 Suggestions for improvement and future research

Methodology

- Systematize a national protocol to compile an agronomic, environmental, economic, energetic and social database of bioenergy systems in Spain.

- Organize and increase knowledge of national soil characteristics to improve the environmental assessment of agricultural systems and precisely monitor soil ecosystem dynamics. For example, $CO_2$ fixation in agricultural soil due to rhizodeposits and the denitrification/nitrification process.

- Develop LCA impact indicators according to the environmental characteristics of the case study area, such as erosion and water consumption, that will be included in the global impact categories.

- Analyze the environmental, economic and social consequences of substituting farmland allocated to cereals for biomass production in Catalonia.

- Integrate LCA and GIS methodologies in a single software tool to facilitate the global impact assessment of territorial plans.

Energy and environmental balance of bioenergy systems

- Cultivate energy crops using low input agricultural methods to minimize operations taking into account that biomass is not as demanding as food production.

- Apply organic fertilizers to reduce mineral fertilizer doses and calibrate the latter to each production area according to its soil properties.

- Use biodiesel instead of diesel in tractors and transport vehicles.

- Plan energy crop production areas alongside energy consumption and input supply areas (organic fertilizers, operators, etc.) in order to reduce transportation distances.

- Analyze the economic and environmental viability of using ash from combustion plants as fertilizer.

- Study the best energy crop subspecies in order to increase biomass production.

Economic feasibility

- Develop a protocol for the cultivation of energy crops, eg., density of plantations, to allow agricultural standards to be implemented.

- Create incentives for the production of biomass energy by laws addressed directly to the agricultural sector, not the energy generators.

- Promote local biomass production through agreements between energy generators and local biomass producers which increase the feasibility of biomass crop production when compared to imported crops.

- Certify biomass power plants as enterprises authorized to sell their extra $CO_2$ credits on the $CO_2$ market and promote the beneficial effects of this on biomass producers (farmers).