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Energy Supply Chain – Sourced by bio-power and bioethanol

Maria Inês Bravo Quintiliano Lynce

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Supervisors: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Prof. Fabrizio Bezzo

Examination Committee

Chairperson: Prof. José Madeira Lopes

Supervisor: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Member of the Committee: Prof. Henrique Anibal Santos de Matos

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Abstract

The present work deals with the development of a model that optimizes a supply chain of bioethanol and bio-power.

The growing concern about environmental issues has led the society to seek for solutions in order to replace fossil fuels. Part of this research is focused in the transport sector since it is a major contributor to the high emission levels of greenhouse gases. To reverse the situation two hypotheses are proposed: integrate a new the type of fuel consumed in the existent vehicles or introduce new type of vehicles in the market. Regarding the first hypothesis, bioethanol is currently the most exploited proposal and it has the greatest potential for expansion. The other solution involves the development of the market for electric cars.

Considering the two presented solutions, a linear programming model was implemented, based on the works of Zamboni et al. [2] and Giarola et al. [3].

The referred model is built to understand what the best economical solution to produce energy from bio-products is: production of bioethanol or bio-power generation. Bioethanol production is performed by the *Dry Grain Process* (DGP) technology and bio-power is generated using the gasification and combustion.

Taking into account the different technologies, results are promising regarding the implementation of a biomass combustion system. In a situation to encourage clean energy production, the production of electricity using combustion is the most profitable situation, followed by the production of bioethanol by DGP and finally by gasification. Analyzing a situation of selling the electricity produced without tax benefits, indications favor the production of bioethanol.

Key words: Energy supply chain, bio-power, bioethanol, optimization, price

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Resumo

O presente trabalho consiste na elaboração de um modelo que otimize uma cadeia de abastecimento de eletricidade e bioetanol.

A crescente preocupação em torno de questões ambientais tem conduzido a sociedade a uma procura de soluções para a substituição dos combustíveis fosseis. Parte dessa investigação é dirigida ao sector dos transportes, um dos principais responsáveis pelos elevados níveis de emissão de gases de estufa. Para reverter a situação duas hipóteses são propostas: introduzir um novo tipo de combustível consumido nos veículos existentes ou introduzir um novo tipo de veículo no mercado. Relativamente à primeira hipótese, o bioetanol é, atualmente, a solução mais explorada e a que apresenta um maior potencial de expansão. A outra solução passa pelo desenvolvimento do mercado dos carros elétricos.

Considerando as duas soluções apresentadas, um modelo de programação linear foi implementado, sendo este baseado nos modelos anteriormente desenvolvidos por Zamboni et al. [2] e Giarola et al. [3].

O modelo construído permite estabelecer a melhor solução, de um ponto de vista económico, a partir de bio-produtos: se produzir bioetanol ou bio-eletricidade. A produção de bioetanol é realizada pela tecnologia de *Dry Grain Process (DGP)*, já a eletricidade é gerada recorrendo à gasificação e combustão.

Tendo em conta as diferentes tecnologias os resultados apresentam-se promissores relativamente à implementação de um sistema de combustão de biomassa. Numa situação de incentivo à produção de energia limpa, a produção de eletricidade recorrendo à combustão é a situação mais lucrativa, seguida pela produção de bioetanol por DGP e, finalmente, pela gasificação. Analisando uma situação de venda da eletricidade produzida sem qualquer benefício fiscal, as indicações favorecem a produção de bioetanol.

Palavras-chave: Cadeia de abastecimento, energia, bio-eletricidade, bioetanol, otimização, preço.

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BEV – Battery Electric Vehicle
BRICS – Brazil, Russia, India, China and South Africa
DGP – Dry Grain Process
DDGS - Distillers Dried Grains with Solubles
GHG – Greenhouse Gases
HEV – Hybrid Electric Vehicle
LCA – life cycle analysis
MO-MILP – Multi-objective Mixer Integer Linear Programming
MToe – Million tonnes of oil equivalent
PHEV – Plug-in Hybrid Electric Vehicle

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1. Introduction

1.1 Context

Every day, there is a growing in worldwide population as well as in their energetic needs. The need for replacing the fossil energies by renewable has also been growing it importance. Nowadays, about 80% of all energy consumed derives from fossil fuels and the transports sector has the highest contribution and is the largest source of greenhouse gas emissions in the industrialized world. In 2009, this sector was responsible for 25% of CO_2 emissions in the European Union [4]. Nevertheless, efforts have been made to balk this situation and today, 13% of all energy consumed comes from a renewable source [5].

In order to solve the situation in the transport sector, many scenarios have been proposed. These proposals range from biodiesel and bioethanol production, which substitute the fossil fuels, until fuel-cell or electric vehicles that replace the type of vehicle. Considering the role of this sector in the global emissions, the implementation of these alternatives can actually contribute to achieving a sustainable development [6].

Nowadays, the best alternatives are the bioethanol and the electric vehicles. Bioethanol is now under commercialization with great results in regions such as the EU, the USA but especially Brazil where almost 86% of all cars sold are, now, flex-fuel. In terms of electric cars they are already available but only hybrid-electric cars. In fact, the growth of electric cars sell is supported by this hybrid-electric cars market [6,7].

Supporting these substitutes in the transport sector, many studies have been done in order to optimize all the steps involved in the process, and therefore to transform these sustainable alternatives in competitive sustainable alternatives.

Taking this into account, Zamboni et al. [2] and Giarola et al. [3], developed a mixed integer linear programming model that optimizes the supply chain of bioethanol in an economical and environmental point of view. Different technologies were tested to manufacture this product and dry grain process (DGP) reveals to be the most profitable.

Considering these models, the challenge in this thesis is to create a new supply chain model that considers both bio-power and bioethanol as products that can satisfy an energy demand. The model developed finds the best economic solution to all the steps of the supply chain, including the choice of biomass type and location, the transport mean and route or the production technology. To produce the energy in demand, three technologies are tested: producing bioethanol, from dry grain process, and/or bio-power, through a gasification process or through a combustion process. In fact, although there are different papers that study the two supply chains the study of the both, the approach given in this work, i.e., the economic assess of an energy supply chain sourced by bioethanol and bio-power using a mixed integer linear program, has never been made. In this way, the development model helps to understand the most viable option between the two sources of energy.

1.2 Objectives

The objective of this thesis is to study the profitability of an energy supply chain that can has two sources: bio-power and bioethanol. This study assesses the best economic way to supply a “green” energy demand, imposed by the EU guidelines, considering that energy can be produced by different technologies: bioethanol, from dry grain process, and bio-power, through a gasification process or through a combustion process. This work intends to offer a new look in terms of the transports sector since the study of this supply chain, that combines these two source of energy, has never been done.

1.3 Methodology

This subchapter deals with the adopted methodology in this dissertation. The main steps are represented in figure 1:

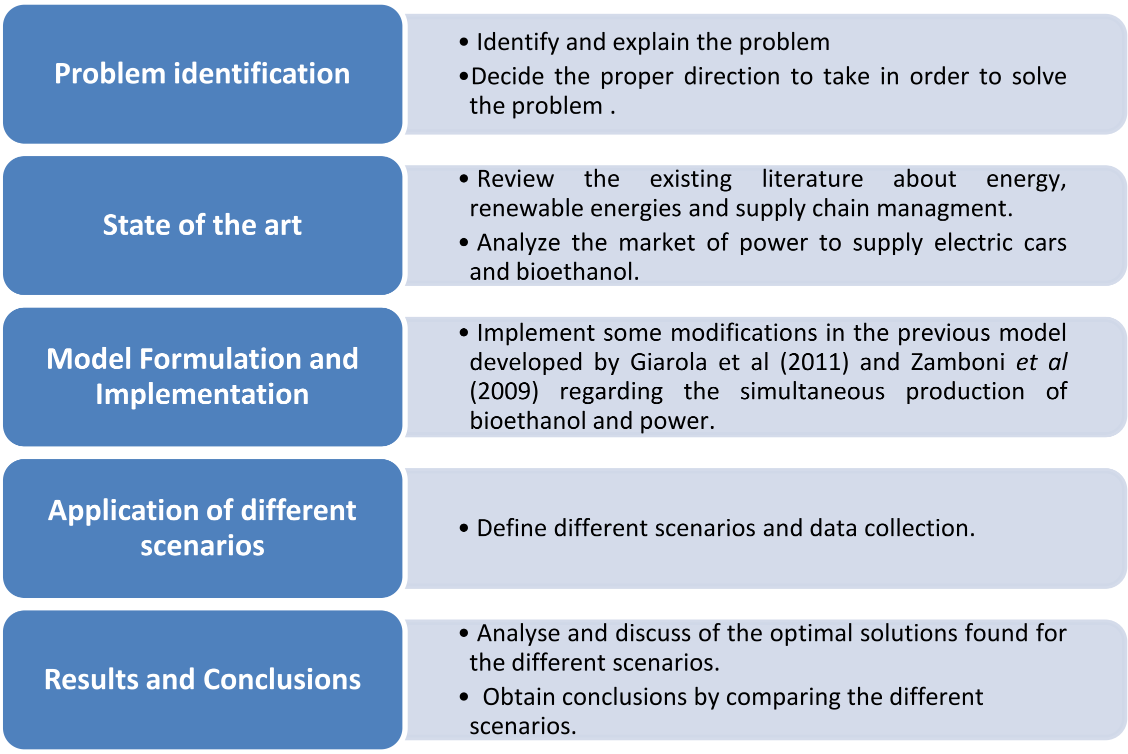

Figure 1 – Methodology followed in this thesis.

1.4 Problem

The problem addressed in this thesis is to understand the profitability of the energy supply to vehicles as a final market, being the energy produced from biomass. For this energy supply chain two sources of energy were considered, bioethanol to be integrated in the traditional fossil fuels and bio-power produced to supply electric cars.

In fact, many progresses have been made in the electric cars field and, since bioethanol is a substitute of gasoline, it is important to understand what the most profitable source of energy to supply the transports sector is. The energy supply chain will be analyzed for the Northern Italy context.

1.5 Structure of the thesis

This thesis is divided in five main chapters:

1. The first chapter explains the purpose of this work, by clarifying the problem and its objectives, and also by explaining the adopted methodology to meet them.
2. The second chapter presents the state of the art of this dissertation. It addresses issues like energy (global market), renewable energies as alternatives to the fossil fuels and the bioethanol supply chain. Inside the "green" energy sources issue, the market of bio-power and biofuels is explored as well as the forms to produce them. Regarding the energy supply chains, some nuclear concepts about supply chain are given and, more specifically, some literature about models already implemented is reviewed.
3. In the third step of this work the model is explained. All the model formulations, mathematical explanations, assumptions made and data collection are dealt within this third chapter.
4. The fourth chapter of the dissertation contains the results of the optimization process. In this chapter the outcomes of the different scenarios are assessed and discussed.
5. Chapter five draws the conclusions of this work and, also, some ideas for future projects.

2. State of the art

In this chapter is presented the contextualization of the bioethanol and bio-power as a source of energy. In section 2.1, a global analysis of the energetic market is done regarding aspects such as source of energy, principal sectors of consumption or greenhouse gases emission (GHG). An overview of the renewable energies world situation is presented in section 2.2. Section 2.3, focus in the market context of the renewable energies in study: bioethanol and bio-power. A reference about biofuels is also made. Section 2.4 presents the production processes of biofuels, bioethanol and bio-power. Section 2.5 introduces the concept of supply chain and, finally, section 2.6 sets the conclusions of this chapter.

2.1 Energy

Energy can be defined as the ability to do work and it can be found in different forms such as chemical, thermal, electricity, mechanical, gravitational, nuclear or motion [8].
Nowadays energy plays an outstanding role in our society and hence contributes to social and economic development. The growth of the world population and its economic expansion are the two main causes for the increase of energy demand. In fact, in the past decades, the global need of energy grew quickly mainly due to the remarkable economic growth of the emergent countries [8],[9]. It is estimated that, mainly to due to these countries, the world energy consumption will increase 56% in the next 30 years reaching 630 quadrillion Btu in 2020 and 820 quadrillion Btu in 2040 [10].
The evolution of the type of energy supply can be summarized as presented in figure 2:

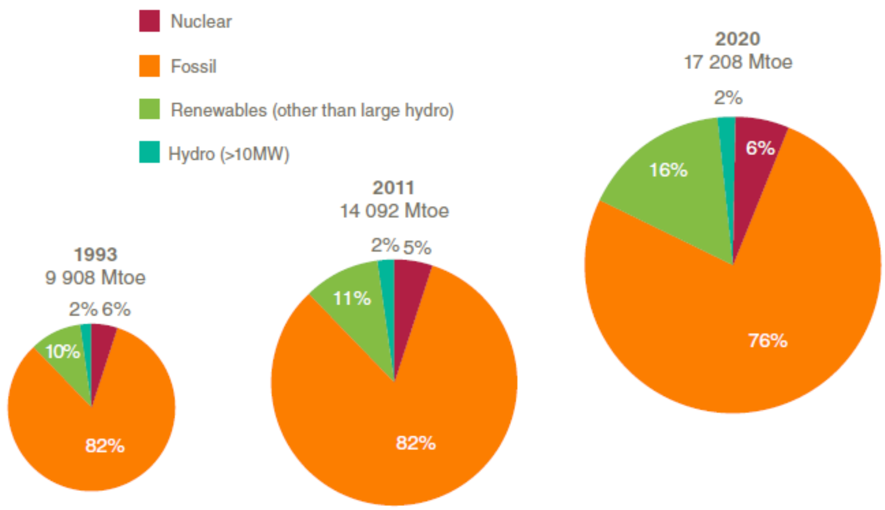

Figure 2 - Total Primary Energy Supply by resource 1993, 2011 and 2020 [11].

From figure 2 it is possible to notice that the total demand of energy has been gradually increasing throughout the years supported by a huge market of fossil fuels. The continuing growth of the energy consumption leads to an unsustainable economic and environmental situation caused, mostly, by the increase of the petroleum price and the limited lifetime of fossil fuels [8]. In an environmental perspective the dependence on this type of fuel is directly related to impacts such as acid rain or the greenhouse effect. Anticipating an extreme scenario, and looking forward to establishing a sustainable development, the dependence on fossil fuels is being fought against with an increasing “bet” in the renewable energy sources [12].

In the fossil fuels’ market, petroleum is the major application and industry (mostly petrochemical) and transports sectors concentrate the bulk of it. In fact, estimates say that in 2040 these two sectors will represent a 92% of global liquid fuels demand. Considering that petroleum and its derivatives represent 93% of the liquid fuels, these two sectors will create a tremendous impact in the fossil market as it can be seen in figure 3 [13].

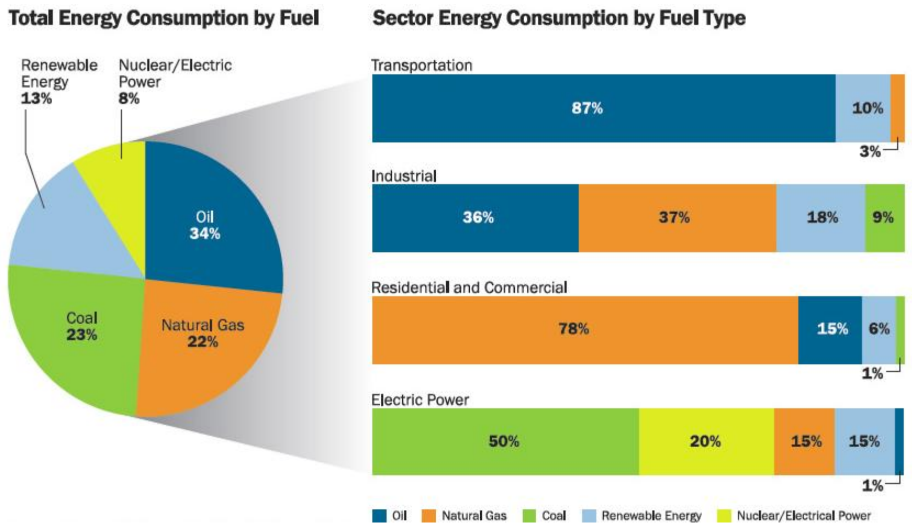

Figure 3 - Energy consumption by sector in 2030 [14].

Therefore, the transports sector is a good target to improve energy consumption which can actually contribute to achieving a sustainable development. There are two possible ways to transform the transportation market: to substitute the type of fuel or the type of vehicle. In both situations renewable energies play the main role.

The exploration of non-renewable sources of energy is producing a huge impact in the world´s climate. The main responsibility, since mid 20th century, for these changes are the greenhouse gases (GHG) resulting from human activities. These GHG are directly related to the global warming [15].

Global GHG emissions are escalating quickly and, in May 2013, the levels of carbon-dioxide in the atmosphere exceeded 400 parts per million for the first time in several hundred millennia. Globally, the situation can be described in figure 4:

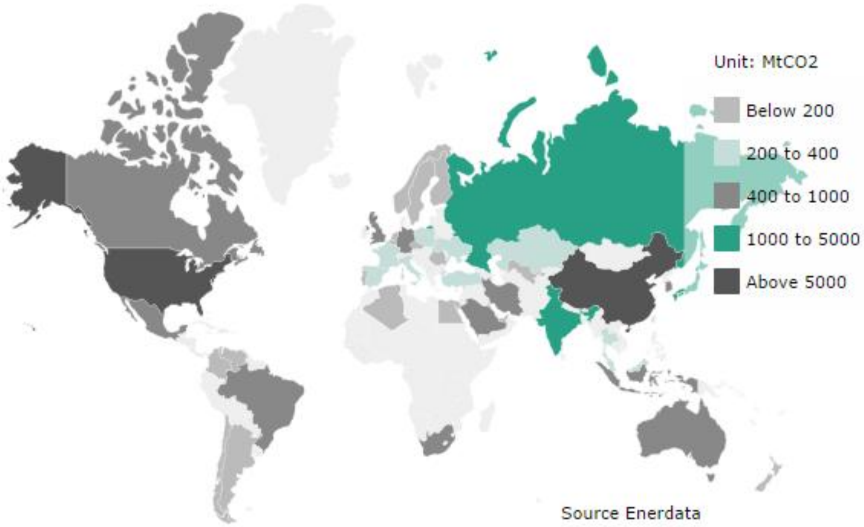

Figure 4 - CO_2 emissions from fuel combustion in 2013 [16].

Developed countries such as USA or Russia, are responsible for a large share of the all emissions representing 5 101 and 1 661 Mt_{CO2}.On the other hand, developing countries namely China with 8 502 Mt_{CO2} and India with 2 011 Mt_{CO2}, with the drastically increase of their global production, have also increased their levels of emissions. The most extreme cases of total GHG emissions are the USA and China, however, when compared with the results of GHG emissions per capita, the situation of China is diluted and Canada emerges as one of the worst cases. These results cannot be dissociated from another parameter: energy consumption. In fact, if we observe the results from the worldwide energy consumption (figure 5), the link between them is evident [16].

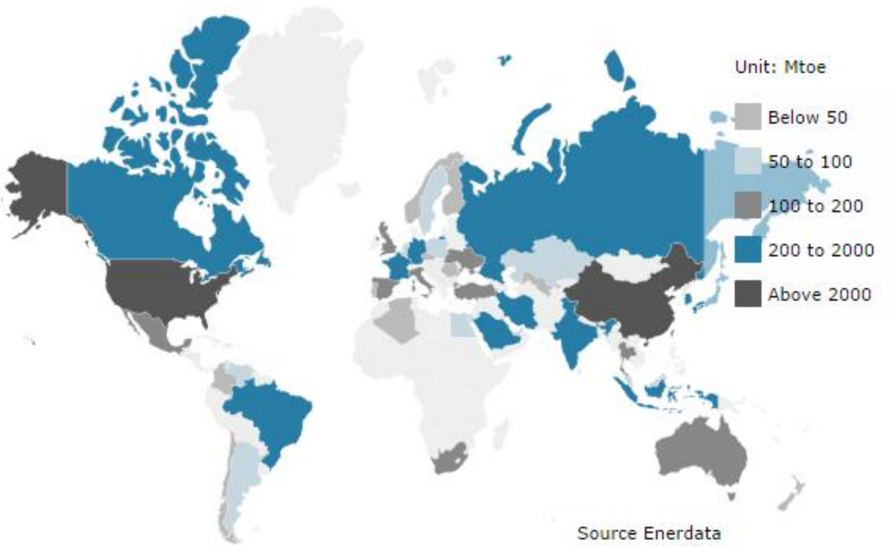

Figure 5 - Total energy consumption in 2013 [16].

Analyzing figure 4and figure 5, one notices that the GHG emissions are strictly related to the level of energy consumption. Once again, USA and China take the lead in the world situation reaching 2 187 and 3 013 MToe, respectively [16].

This situation has been fought by many countries, including USA, Russia and Canada by means of an extension of the Kyoto Protocol. Progress has been made namely with a greater engagement of the so named BRICS countries. In fact, this progress can be proven by the inclusion, for the first time, of China in an agreement about common policies to face climate changes. Though this agreement, the Copenhagen Accord, wasn't fully accepted by every government, it thrived many key issues and it was the first step to a fundamental global awareness. The objective of this deal is to promote the stabilization of the atmospheric GHG emissions so that the increase of the global temperature can come to an end. In fact, this Accord doesn't establish any emission limits for the countries but promotes instead a set of their own targets regarding a main global goal [17].

2.2 Renewable energy

A renewable energy source can be defined as a sustainable resource available over the long term at a realistic cost that can be used for any task without negative effects [18].

There is a widely variety of renewable energy sources such as hydropower, biomass, wind geothermal or solar. The use of renewable energy sources is a must to slow down the climate changes. Nowadays, renewable energy technologies are still considered to be less competitive than the ones associated to fossil fuels. This handicap of renewable energies is mainly related to three issues: the difficulty of obtaining large quantities of electricity (comparing to fossil fuels), the fact that it has not a constant production (the supply is dependent on the nature) and because it still has implementation issues (in terms of cost and infrastructures). Nevertheless, renewable energy sources have several advantages such as the decreasing dependence on fossil fuels, the reduction in GHG emissions and climate changes, the creation of export markets increasing the net employment and extension of the energy supply to other sources and thus increasing the competitiveness [9,18].

As figure 2 shows, the market of the alternative fuels has been growing over the years and today's share is about 18% and it is expected to grow significantly until 30-80% in 2100 [18]. In fact, the need to slow down the GHG emissions led the principal responsible countries, China and USA, to invest in the installation of renewable energy capacities.

In 2012 the situation was as illustrated in figure 6:

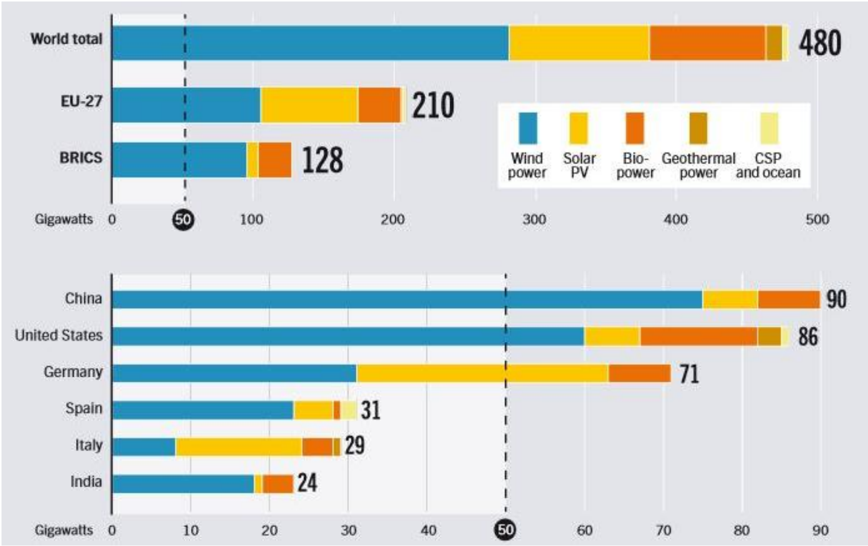

Figure 6 - Renewable power capacities in 2012 [19].

Figure 6 shows that the commitment made by the BRICS, the USA and the EU regarding climate changes policies guided them to a huge contribution in the renewable energy market. As mentioned before, the transport sector is a major contributor to the climate changes and, because of that, a good target to apply these policies regarding the growth on the renewable energies market.

In terms of renewable energies sources, biomass is the oldest known source of energy. The possible use of the biomass energy content gained a great new interest during the last decade, because of its potential to displace a large part of conventional fossil fuel. In fact, biomass is widely considered to be a major potential fuel and renewable resource for the future. In terms of size of resource, there is a potential to produce at least 50% of Europe's total energy demands [20]. Today, biomass is the one in the best position in the market contributing with 10-14% of 13-18% that the alternative market represents. As a matter of fact, some authors defend that, in short term, energy produced from biomass is the only sustainable substitute of gasoline or diesel. The derivatives of biomass are called biofuels and have been the subject of investment by some governments. Nevertheless, the transport sector can also be "environmentally improved" by means of the introduction of hybrid cars that use both gasoline and electricity as fuel. These two paths are going to be presented in the next subchapters in which issues such as policies adopted, technologies applied and the global market will be emphasized.

2.3 Global market

In order to understand properly the world situation of the selected renewable energies, is necessary to analyze their global market.

2.3.1 Biofuels

Several governments around the globe have, in the past decades, supported the growth of the biofuels production as substitute of fossil fuels in the transport sector. This support is characterized by numerous policies that influence different steps of the biofuel supply chain. Generically, the measures consist in:

1. Promoting production - using production mandates; giving investment support and feedstock support and tax incentives.
2. Encouraging consumption – via consumption mandates and incentives.
3. Trade related measures – adopting protective measures to shield local production and preventing exports by installing export taxes.

These incentives have led to a growth in the production of bioethanol from around 17 to 86 billion liters since the beginning of the century while the biodiesel increased from 0.8 to around 21 billion liters [21]. The two referred biofuels control the market bearing in mind that bioethanol represented about 80% of the market in 2010 and biodiesel about 19% [19].
Globally the situation is described as shown in figure 7:

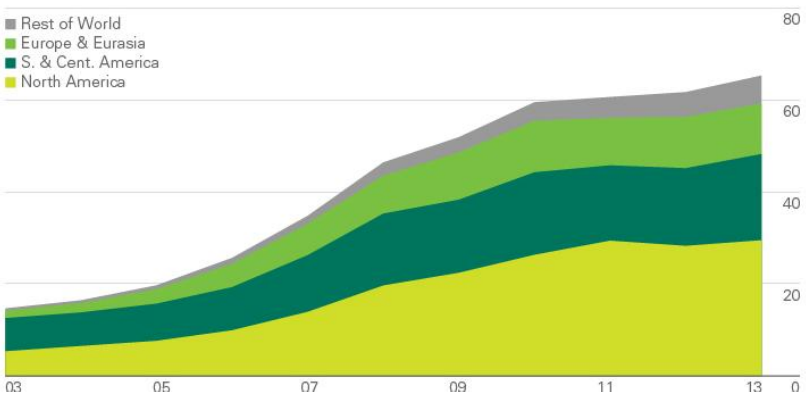

Figure 7 - World biofuels production in Mtoe by region [22].

The strong investment in biofuels led to a continued growth on this fuel production reaching 70 MToe in 2013. After that, although it was registered some growth in Central and South America and Pacific Asia, it wasn't enough to fight the decrease in North America (the main producer), leading to a situation of stagnation.

Despite this stagnation of production, the international energy agency (IEA) predicts that the demand of biofuels should rise exponentially as showed in figure 8:

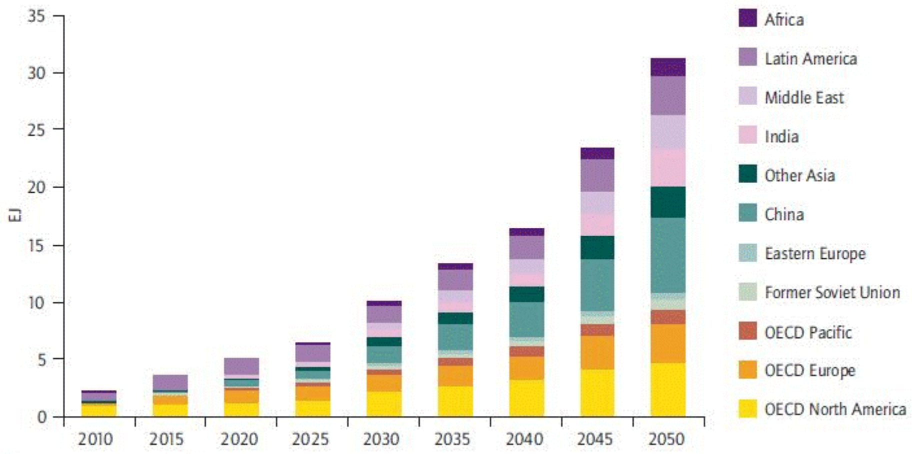

Figure 8 - Global biofuels demand from 2010 to 2050 by region [10].

Estimates show that demand for biofuels will continue to grow all over the globe and that North America will continue to have the majority of consumers. In 2050, China is expected to be the largest consumer but the continuous incentive policies and the need to change will lead OECD Europe, Middle East and Latin America countries to take a step forward in biofuels consumption.

2.3.2 Bioethanol

As referred before, bioethanol is by far the most widely used biofuel for transports worldwide. In fact, bioethanol production is one way to reduce both consumption of crude oil and environmental pollution [23].

Bioethanol (CH_3CH_2OH) is a product derived from the fermentation of biomass and it is the largest produced biofuel with about 80% of the market share. Bioethanol can be used directly in cars or blended with gasoline. Being bioethanol the major type of biofuel it is interesting to understand how its market is distributed. This distribution is shown in figure 9.

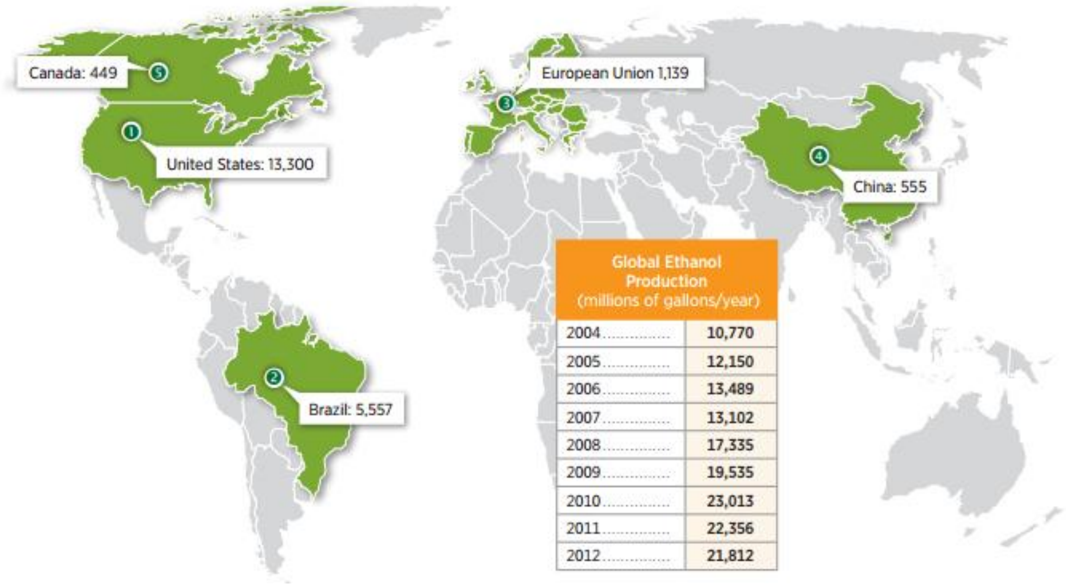

Figure 9 - Global bioethanol production and top five producers in 2012.

As figure 9 shows, bioethanol production grew from 40.9 millions of liters in 2004 to 87 million liters in 2010 representing an average annual growth of 17%. However, since 2010 the global production has slightly decreased but, the USA, Brazil and the EU, are still responsible for a huge amount of quantities produced. These three regions represent 54%, 35% and 5%, respectively, of the world production [24,25].
This market domination by these three regions is a consequence of the policies implemented by their governments.

In the USA, for instance, there is a law that ensures a minimum volume of biofuels usage in the transport sector. This law imposes that at least 136 billion liters of fuel have to be consumed per year by this sector until 2022. From this volume, about 41% has to be produced by conventional biofuels and the other 59% from advanced biofuels (use advanced technologies which have better GHG emission reduction efficiency). Besides this law there are many incentives implemented by this country such as tax credits, import tariffs or use mandates [24, 26].

In the case of Brazil, the investment in this alternative market is the most developed and is the only profitable, influenced by its ideal natural resource. In fact, in 2006, 86% of the automobiles sold were flex-fuel vehicles which proved that the commercialization can be a success. This situation was helped by the implementation of a regulation that imposes a minimum 25% of bioethanol blended in gasoline by 2003. Nowadays, there are no direct subsidies for bioethanol production but instead a policy of preferential treatment such as taxes reduction [7].

In EU, several policies have been applied such as the establishment of a goal of 5.75% using of biofuels in the transports sector by 2010 and 10% by 2020 in all member states. Other measures were implemented regarding the limitation of the first generation production technologies and creating a new accountability technique. Both measures are based in bet to benefit the advanced production technologies [24].

Consumers

As previously discussed, bioethanol is produced to provide a growing alternative market. In practice, this is made by blending the bioethanol with petrol. This mixture could have various levels, for instant, in the EU, the amount of bioethanol blended is typically 5% but can actually go up to 10% if the car does not suffer any modification or 85% (E85) if the engine is modified to a flex-fuel type. This situation also occurs in the USA where 10% (E10) is usually the level of mix between bioethanol and gasoline. Brazil is the country that presents more developments in this area since about 86% of all cars sold are flex-fuel [7,27, 28].

2.3.3 Bio-power

Bio-power is the use of biomass to generate electricity. Electricity can be generated from many sources, which can be renewable or not. In terms of non-renewable (fossil fuels and nuclear) sources they represent about 77.9% of the market. On the other hand, the renewable sources are described by figure 10 [19, 29]:

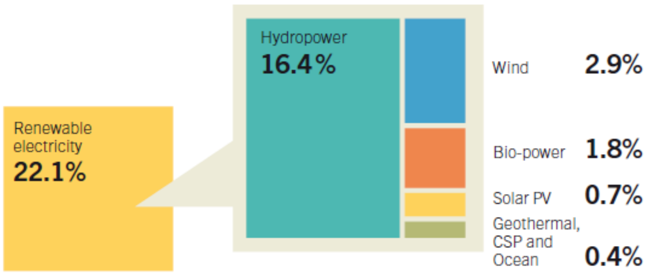

Figure 10 - Renewable energy share of global electricity production, in 2013. [19]

In terms of renewable energies, the power generation sector was the one that presented the most significant growth reaching a global capacity of 1560 GW in 2013, which represents an increase of about 8% when compared to 2012 [19].

As figure 10 shows, 1.8% is the share of all electricity produced is related to biomass. In fact, the data collected point out that the bio-power capacity reached 88 GW in operation by the end of 2013 and it is a growing source of energy. Bio-power was responsible for generating around 405 TWh of the word's electricity in 2013. This situation has evolved as table 1 shows:

Table 1 – Bio-power indicators evolution. [19]

	2004	2012	2013
Bio-power capacity (GW)	<36	83	88
Bio-power generation (TWh)	227	350	405

The growth showed in table 1 can be associated with the role of the USA, Germany, China, Brazil and India that are the top five countries, respectively, in terms of capacity and production of bio-power.

	World	EU-28	BRICS	China	United States	Germany	Spain	Italy	India
TECHNOLOGY	GW			GW					
Bio-power	88	35	24	6.2	15.8	8.1	1	4	4.4

Figure 11 - Renewable electric power global capacity, top regions and countries in 2013 [19].

As shown in figure 11, the USA represents a total of 15.8 GW in 2013, which confirms an increasing of 0.8 GW in their capacity when comparing to 2012 [19].

Germany's bio-power capacity is at the present of 8.1 GW and bio-power production improved about 7% to 48 TWh, accounting for nearly 8% of Germany's total electricity generation in 2013 as is described by figure 11 [19].

Brazil increased its bio-power capacity in about 10%, up to 11.4 GW. Sugarcane bagasse from bioethanol production accounted for nearly 7% of national electricity production. Policies in Brazil in terms of bio-power establish a target of 19.3 GW by 2021 [19].

In China, bio-power the situation is similar to the countries referred before since a growth is verified. However, the limited availability of suitable biomass slowed down this growth in the past years. By the end of 2013, bio-power capacity reached 6.2 GW and direct combustion represented the main generation process. The target to 2015 was fixed by China government in 13 GW [19].

In 2013, India reached a bio-power capacity of over 4.4 GW. However, India's capacity additions could not make the national target by 10% and was around 40% below those in 2012 [19].

Regarding the figure 11, it can be seen that about 67% of all installed capacity of bio-power plants is shared by the EU and the BRICS countries with 40% and 27% respectively. The USA by itself represents an installed capacity of about 17%.

Consumers

The bio-power produced by gasification and combustion can be applied in several areas. Considering the purpose of this work, the bio-power produced is supposed to supply an increasing demand in electric cars market. There are three main types of electric cars: hybrid electric vehicles (HEV), plug-in hybrid electric vehicles and all-electric vehicles (that can be fuel cell electric vehicle, FCEV, or battery electric vehicle, BEV).
Hybrid electric vehicles are already in use and work adding an electric traction motor and battery bank to a smaller version of the existing internal combustion engine to provide two sources of motive power. Plug-in hybrid electric vehicles have batteries that can be charged from the grid, so some gasoline use is replaced by electricity. The vehicles that only use electricity eliminate the internal combustion engine and depend exclusively on the electrical grid [6,30].
It is expected in the near future that the market share of hybrid vehicles will raise and that, in the long term, the market share of plug-in hybrid vehicles will be significant as figure 12 shows [30]:

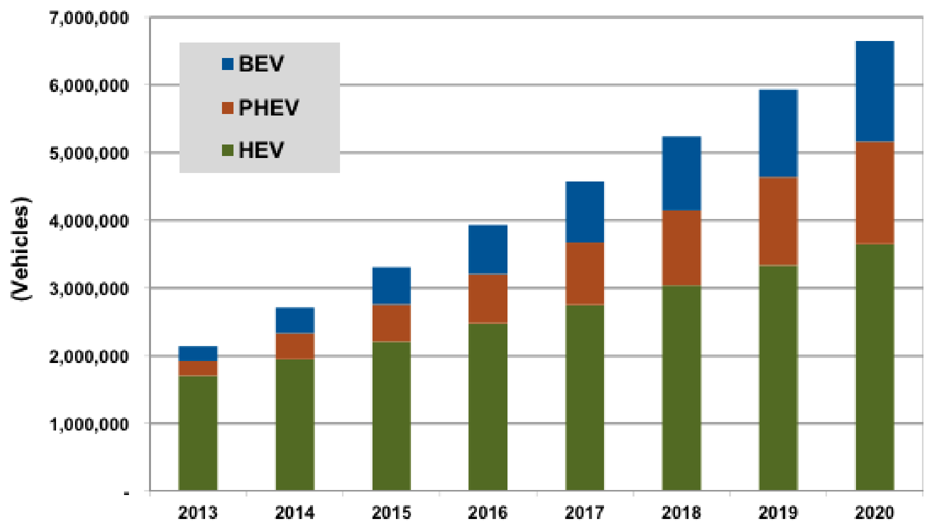

Figure 12 - World annual light duty electric vehicle sale [31].

Figure 12 shows that in the next few years, HEVs will dominate in terms of electric vehicles. However, the development of the technologies will allow an increasing importance of the BEV and PHEV in the market.
The growth showed in figure 12 reflects the continued stimulation made by the governments in order to increase the adoption of these electric cars. This stimulation occurs through the use of incentives that include income tax credits and deductions, sales tax waivers, single-passenger access to carpool lanes, and waivers of emissions testing, registration and parking fees [32].

2.4 Production processes

Considering bioethanol and bio-power as the sources of energy selected, is important to comprehend their production process since they can, significantly, influence different parameters of the model. To properly understand the bioethanol process is necessary to have a first look in biofuels production

2.4.1 Biofuels

Biofuels are combustible materials directly and indirectly derived from biomass, commonly produced from plants, animals and micro-organisms but also from organic waste. Regarding the renewable energies sources, biofuels are being drawn more and more attention that echoes in an increasing production and consumption around the globe. The interest in biofuels is not new, in fact, it is almost as old as cars are. In 1897, Rudolf Diesel, inventor of the diesel engine, originally designed an engine to run on vegetable oil. In the beginning of the 20th century, Henry Ford designed a car to run on ethanol. However, because of the costs, this type of fuel suffered a setback allowing the fossil fuels to gain market. Years later, during the World War II, the needs of fossil fuel increased so much that they became scarce leading to an increasing demand of biofuels. The popularity of this fuel went up during the crisis of the 70s and finally established its position in the market in the 90s due to the increasing environmental concerns [33].

Biofuels can be produced in many different ways depending on their source or the technology adopted. Globally, they can be divided in two main groups: primary and secondary. Primary biofuels concern a raw utilization, i.e., they are used in an unprocessed form. Secondary biofuels require the transformation of the biomass into bioethanol, biodiesel or others. Secondary biofuels can be classified in first, second and third generation as figure 13 shows [33,34,35]:

1st generation

- Derive from starch, sugars, animal fat or vegetable oil and the most common feedstock are corn, wheat and sugar can.
- Produce mainly bioethanol or butanol (fermentation of starch or sugar) and biodiesel (transesterification of plant oils).

2nd generation

- Made from lignocellulosic biomass. Forest and agricultural production wastes, as well as dedicated biofuel crops can, also, be used.
- Produce mainly bioethanol or butanol (enzymatic hydrolysis), biomethane (anaerobic digestion), methanol and green diesel (thermochemical processes).

3rd generation

- Derive from algae and sea weeds.
- Produce biodiesel (algae), bioethanol (algae and sea weeds) and hydrogen (green algae and microbes)

Figure 13 – Secondary biofuels type of production technologies.

First generation biofuels are considered to have the most economical competitive technologies. However, they are not, yet, the answer to a sustainable energy supply. In fact, recent concerns on environmental degradation and economic sustainability are bringing these practices to a debate. On the one hand, there is the problem of competition for the land and water with the food sector. On the other hand, first generation technologies depend on feedstock supply costs, on the incomes coming from by-products as well as governmental incentives. Another problem is that the effective environmental impact is strongly associated to the technological and geographical contexts [3, 36].

Second generation biofuels may be, partially, the answer to concerns raised about first generation. Actually, one of the advantages of this way of producing biofuel is that it limits the direct competition with the food sector since it achieves a better land use efficiency. Also in terms of costs, second generation biofuels have the potential to reduce them. However, these practices have, also, some problems: the high conversion costs and complex logistics, the soil quality exhaustion and the competition with other agricultural uses or industries such as electricity generation [3,34].

Third generation biofuels are the most potential to produce fuel in terms of quantity and diversity. This diversity is explained by the fact that the oil produced by algae can be refined into diesel and by the fact that it can be genetically manipulated to produce any gasoline substitute. As in the other cases, this method has a downside too. The ideal conditions to the algae growth implicates a quantity of fertilizer so high that it would produce more GHG emissions than the ones saved by using this third generation fuel. In economical terms this method is not viable due to its high implementation costs. In fact, studies show that, economically speaking, this option won't be feasible for at least the next 25 years [33].

2.4.2 Bioethanol

Bioethanol is a liquid biofuel that can be produced from several different feedstock and conversion technologies. The production processes are going to be described in the following points.

First-generation

There are two main first-generation feedstock types used: 1) sugarcane, the market leader, used in tropical areas such as India, Colombia but above all in Brazil; 2) corn that can be found in regions such as the USA, EU or China. Ethanol produced from sugar crops accounts for about 40% of the total produced and approximately 60% corresponding to starch crops. In the case of corn, its availability and feasibility as a feedstock can be in risk due to the increasing demand as a food source and due to its rising price. This situation can influence a further expansion of bioethanol production limiting the use of first generation feedstock [37].

In terms of process, bioethanol production can be summed into three major steps:

1. Obtain the solution containing fermentable sugars
2. Fermentation of sugar converting them into bioethanol
3. Bioethanol separation and purification

The referred steps are described in figure 14:

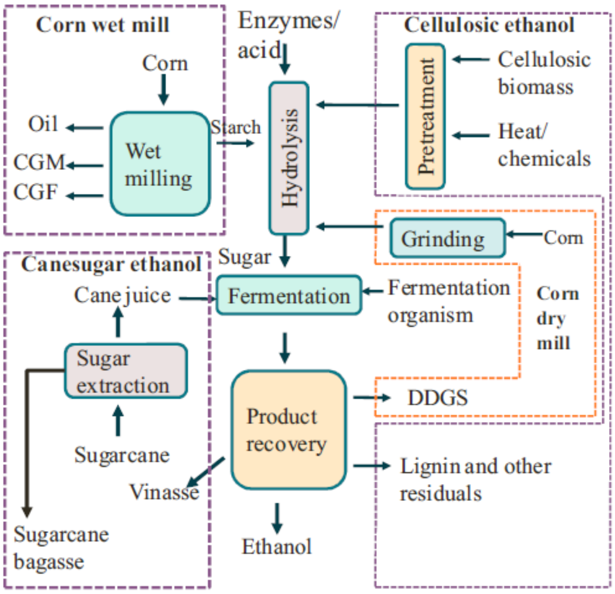

Figure 14 - Schematic representation of bioethanol production from sugarcane, corn and cellulosic biomass [37].

Once the biomass arrives at the ethanol plant, it is stored in a warehouse where it is conditioned to prevent early fermentation and contamination. Firstly, a pretreatment during which carbohydrates are extracted or transformed to be more accessible to a further extraction is performed. Next, a large portion of fibers that may remain are converted into simple sugars through hydrolysis reaction or other techniques. The next step is the fermentation where hydrolysate, yeasts nutrients and other ingredients are added. The fermentation is followed by a distillation step where bioethanol is dehydrated to obtain bioethanol containing up to 99.6% purity. The remaining flow from the distillation can lead to numerous co-products such as Distillers Dried Grains with Soluble (DDGS) [37].

The most common bioethanol production process used with conventional corn-based is known as dry grind (DGP) and wet mill.
The process initializes by milling down the corn into a proper particle size in order to facilitate the subsequent water's penetration. The mixture is then processed in a slurry tank where sterilization is achieved. During the sterilization process starch hydrogen bonds are broken so that water can be absorbed. The next step is liquefaction whereby the viscosity of the mixture is reduced by the action of enzymes. This mixture is conducted to a fermentation reactor where, simultaneous, saccharification and fermentation occur following the main reaction R1:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad \text{R1}$$

At this point, starch oligosaccharides are almost completely hydrolyzed into glucose but some carbon dioxide is also produced being, the most part of it, immediately purged. The next step is a distillation section where three columns work: the fermentation broth is split into two stripping columns at different pressure and the distillate products of these columns are sent to a final rectifying column where bioethanol is produced with high purity (99.99%). The non-fermentable products of the feedstock like grain solids or water are sent to a centrifuge to get a wet cake and a *thin stillage*. This *thin stillage* is sent to an evaporator where it is concentrated into final solid, *syrup*. The wet cake and the *syrup* are mixed and dried up in order to produce DDGS [38].

Second-generation

Second-generation fuels use, frequently, non-edible lignocellulosic biomass, i.e., residues of forest management or food crop production or whole plant biomass as feedstock. These kinds of feedstock do not compete with food and feed and are considered to be renewable feedstocks for bioethanol production [37].
The process initializes with the pre-treatment where, usually, diluted acid is added to the lignocellulosic biomass in opening up its structure to make it accessible for enzymes to hydrolyze the cellulose components. In this way, most of the hemicelluloses is hydrolyzed to form xylose and other sugars leaving a porous structure of primary cellulose and lignin. The next operation is characterized by an enzymatic hydrolysis and glucose fermentation. Enzymes are added to the pretreated mixture taking place a cellulose enzymatic hydrolysis where cellulose is transformed into glucose. Once the glucose is formed, it undergoes a combined process of fermentation and saccharification. The final treatment is performed in a distillation section [39,40].

2.4.3 Bio-power

In terms of bio-power generation, there are three primary technology categories used to convert biomass into electricity:

1. Pyrolysis – consists of a thermo-chemical decomposition of biomass in an anaerobic environment to produce gases and condensable vapors. These gases suffer later combustion in a gas turbine.
2. Gasification – process where biomass is partly oxidized to produce combustible gases, which have a high calorific value. Produced gases are driven into a combined cycle gas turbine power plant.
3. Direct combustion - is the complete oxidation of biomass in excess air, to produce carbon dioxide and water. The gases produced are used to heat water to steam, which feed a turbine.

From the categories referred above, direct combustion is the oldest, the most used and the simplest process. However, it is the least efficient [41]. Biomass gasification is a mature technology and the generation of heat and power using this process is already commercialized. On the hand, pyrolysis technologies are more recent and not that commonly used as gasification or combustion [42].

Considering the facts expose above, namely the maturity of the technologies, the technologies applied in this dissertation were direct combustion and gasification considering

Combustion

Nowadays, most of the biomass power plants are direct-fired system but this technology has been used since the 19th century. Nevertheless, this process still plays a major role in industrial process heating, commercial and institutional heating and electricity generation. In fact, biomass combustion plants are expected to grow with a rate of 180% and 140% from 2008 to 2020, in small-scale and medium-large scale plants, respectively [43].
The combustion process starts by feeding a pretreated biomass into a furnace and then to a boiler. The pretreatment depends on the type of boiler but usually consists of physical processing methods such as drying and grinding, chemical methods that can, for example, remove metal constituents in biomass or physicochemical treatments such as steam explosion. Once in the boiler, the remaining water is evaporated into steam and superheated, with excess of air. The steam is then expanded to a low temperature and pressure through to a steam turbine where electric power is generated [43].

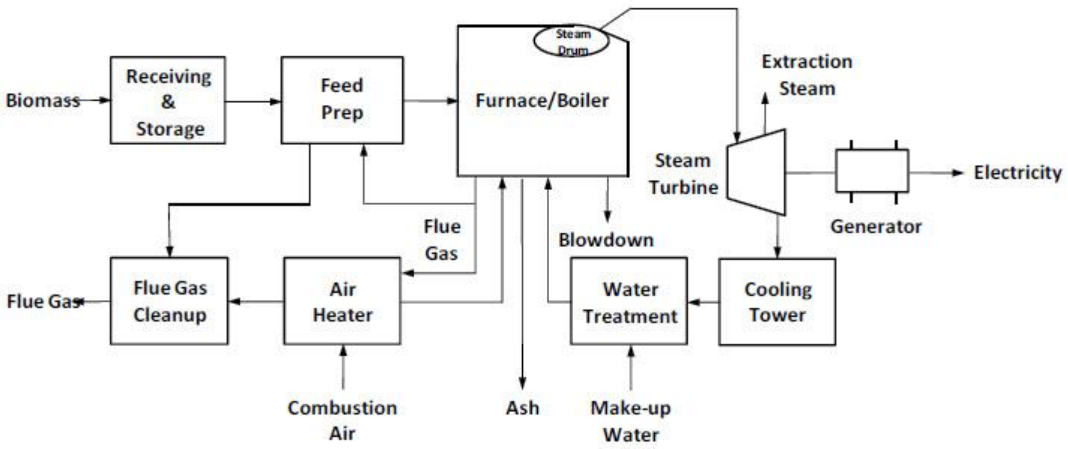

Figure 15 – Block diagram of a combustion process.

In the referred process, high-pressure steam is produced in a boiler, the core of the system. The most commonly types of boilers used for biomass firing are fluidized bed and stoker boilers. Both methods have their advantages and disadvantages and some of them are summed in table 2:

Table 2 – Comparison of stoker and fluidized bed boilers [44].

	Boiler type	
Feature	**Stoker**	**Fluidized bed**
Combustion Mechanism		
Combustion zone	On the stoker	Entire area of the combustion furnace
Mass transfer	Slow	Active vertical movement-mass and heat transfer
Combustion control		
Responsiveness	Slow response	Quick response
Excess air control	Difficult	Possible
Fuel issues		
Applicability to various fuels	Fair	High
Fuel pretreatment	Generally not necessary	Lumps must be crushed
Environmental factors		
Low SO_x combustion	In-furnace desulfurization not possible	High rate of in-furnace desulfurization
Low NO_x combustion	Difficult	Inherently low NO_x
Appropriate facility size	Small	Medium to large
Efficiency		
	Medium	High
Cost		
Small sizes	-	3 times higher than stoker
Large sizes	-	35-40% more expensive than stoker

Considering the factors presented in table 2 and bearing in mind the great advantage in economic terms, the selected method to produce power from combustion was the stoker boiler combustion [44].

Gasification

Gasification technology has a long history starting in the middle of the 19th century when produced gas from coal was used for home heating. However, the major developments in the gasification process took place more recently and in two main periods. The first one is characterized by coal gasification and it was caused by the 1973 oil embargo. The second one started in the mid-1990s and was driven by the increasing awareness of climate changes.[43] Gasification technology has been developed to effectively and economically convert low-value biomass (in this case, corn-stover) into a gaseous mixture, called *syngas*, containing mainly CO, H_2, CO_2 and traces of CH_4 [45].

The gasification process starts by drying the biomass feedstock. The dried biomass is fed to a gasifier, operating at high temperatures (>800°C), where endothermic, heterogeneous, reversible and reduction reactions take place, using steam as an oxidant agent. The *syngas* produced is driven to a hot *syngas* conditioner where it is treated, coming out as a clean, hot and hydrogen-rich *syngas* composed mostly of CO and H_2. This gas is used to generate electricity through gas engines or turbines [43,45].

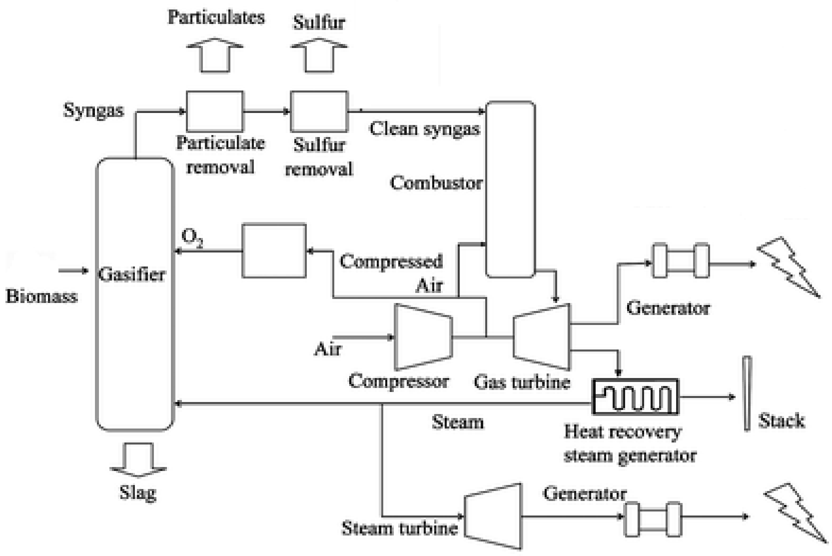

Figure 16 – Flowsheet of bio-power production through a gasification technology.

The gasifier is the most important step of the gasification process and has to be analyzed more carefully. There are two types of gasifiers: fluidized and fixed bed. The significant differences between both are presented in table 3.

Table 3 – Differences between fixed and fluidized bed gasifier [46].

Gasifier type	
Fixed bed	**Fluidized bed**
10% higher investment	Lower investment
Feedstock fines must be agglomerated	No problems with feedstock fines
Particle size as uniform as possible	Broad particle size distribution
Very great particle size possible	Limited particle size
Nearly tar free gas	High tar content in the gas
High carbon conversion rate	Low carbon conversion rate

Comparing the data collected and presented in table 3, fixed bed gasifiers represent a more expensive solution and are more likely to have feedstock problems. However this type of gasifier has advantages in terms of the size of particles used, carbon conversion and tar content since it allows a more wide range of particle size, has a high rate of carbon conversion and almost any tar is produced. Considering these factors the fixed bed gasifier was the selected one.

2.5 Supply chain

A supply chain consists of all steps involved, directly or indirectly, in satisfying a customer request. The supply chain not only includes the manufacturer and the supplier, but also transporters, warehouses, retailers and customers [47].

In the past years, the awareness of academic, consultants and business management on supply chain management has been increasing since it is believed to be a tool to improve competitiveness. The key objective of supply chain management is to: improve the organization performance and customer satisfaction by improving product or service delivery to consumer. Actually, supply chain allows the visualization of the product's lifecycle, i.e., it is possible to plan, control and, eventually, optimize different steps of a process [48,49]:

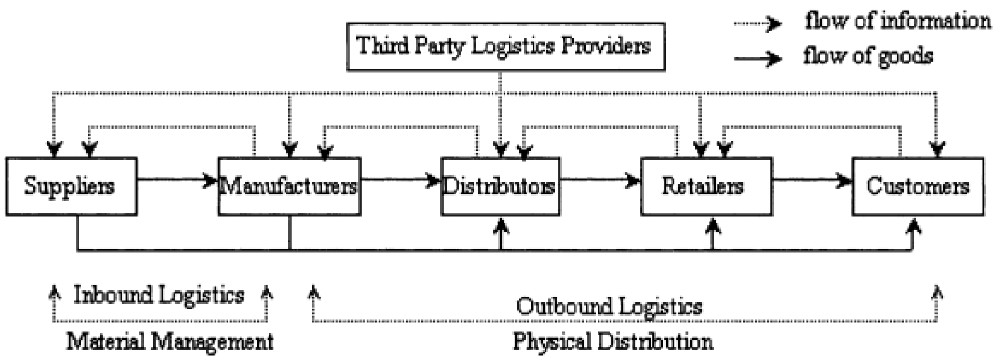

Figure 17 - The supply chain generic structure [50].

As it can be seen by figure 17, a supply chain includes two main strands: Material management and physical distribution. Material management is related to the purchase and storage of raw materials, parts and supplies. Physical distribution concerns all outbound logistic activities related to providing customer service [50].

Supply chains can be classified, concerning the modeled flows, in three main types [51]:

1. Forward supply chain – combination of processes to accomplish customers' needs and comprises all entities such as suppliers, transporters, warehouses or customers. Forward supply chain has the objective to improve efficiency, profitability and competitiveness of all parties involved. This improvement can be accomplished in different stages that go from the source of materials (suppliers) to the final product (customers) [50,52].

2. Reverse supply chain – series of activities needed to retrieve a used product from its typical final destination with the intension of capturing value or proper disposal. A reverse flow supply chain includes the recovery of products and materials and it has gained more and more relevance as the concerns with the environment grow. This type of supply chain has been influenced by the environmental regulations, consumers' pressure and by the opportunities to reduce cost by reusing products [53,54].

3. Closed loop supply chain – supply chain that combines both reverse and forward flow representing a dynamic situation over the entire life cycle. This supply chain has to be well planned and designed in order to achieve competitiveness. This type of supply chain is considered to have a huge potential in economic, social and environmental terms [53].

2.5.1 Bioethanol supply chain

Considered as a promising substitute of gasoline, bioethanol has been the focus of several studies and numerous papers that have been published.

Dunnett, A. J. et al. [55] first proposed a steady-state spatially explicit MILP model to optimize the cost of a lignocellulosic bioethanol supply chain taking into account a wide range of technological, system scale, biomass supply and ethanol demand distribution scenarios.

Fernando et al. [56] introduced a work about the design of supply chains (SC) for sugar/ethanol production with economic and environmental concerns. This work shows a bi-criterion mixed-integer linear program (MILP) that at the same time minimizes the total costs and the environmental performance of the life cycle of the product.

In the same year, Zamboni et al. [1,2] presented two papers that considered a spatially explicit mixed integer linear program (MILP) that accounts for the simultaneous minimization of the supply chain operating costs (part a) and the environmental impact in terms of greenhouse gas

(GHG) emissions (part b). With this work Zamboni developed a tool to optimize the emerging Italian corn-based ethanol system by an economical and environmental point of view.

Akgul, O., et al [57] developed, also, a spatially explicit MILP model for the integrated management of the key issues affecting corn-based ethanol supply chains.

Dal-Mas et al. [58] presented a dynamic, spatially explicit and multi-echelon Mixed Integer Linear Program (MILP) modeling framework with the aim to help decision-makers and potential investors assessing economic performances and risk on investment by identifying the best network topology. This work is a branching of the one made by Zamboni et al. because presents a strategic design and planning of the ethanol supply chain under price uncertainty.

Zamboni et al. [59] proposed a multi-objective optimization model combining LCA and supply chain optimization in order to show how a crop management strategy can contribute to mitigate global warming in s first generation ethanol.

Giarola et al. [3] published a paper addressing a spatially explicit multi-objective optimization for design and planning of hybrid first and second generation biorefineries. This approach was based in an optimization regarding the NPV and, in the other hand, the GHG emissions.

Akgul et al. [36] presented a MILP cost optimization framework for the strategic design of hybrid first/second generation ethanol supply chain that concerns the land use requirements.

Giarola et al. [60] developed a MILP modeling framework to assess the design and planning of a multi-period and multi-echelon bioethanol supply chain accounting the carbon trading effects and under market uncertainty.

More recently, Ortiz-Gutiérrez et al. [61] also developed a model similar to the one made by Giarola et al. [60] considering trading effects and multiple technologies for side-product exploitation.

Also in 2013, Mazzetto et al. [62] studied the impact on the optimal design of bioethanol supply chains by a new European Commission proposal considering a model similar to the one described in Zamboni et al [1,2]..

2.5.2 Bio-power supply chain

Once again, it is interesting to analyze and understand what has been done about this bio-power subject and which are the challenges ahead in supply chain's perspective.

In 2012, Pérez-fortes et al. [63] developed a model to solve the problem of designing and planning regional sustainable bio-based networks for electricity generation supply chain taking into account three main objectives: economic, environmental and social criteria. The model decision-king model was formulated as a MO-MILP (multi- objective mixed integer linear program).

Shabani and Sowlati [64] presented a dynamic optimization to maximize the supply chain configuration of a typical forest biomass power plant. The model considers biomass procurement, storage, energy production and ash management in an integrated framework at the tactical level. This model was developed as a nonlinear mixed integer programming.

Aldana and Lozano [65] developed an analysis, through a comprehensive MILP model, that takes into account all aspects of the supply chain with real data to evaluate the potential for producing energy from agricultural residues in Mexico.

Pantaleo et al. [66] presented a mixed integer linear programming (MILP) approach to optimize multi-biomass and natural gas supply chain strategic design for heat and power generation in urban areas. The work was focused on spatial and temporal allocation of biomass supply, storage, processing, transport and energy conversion (heat and CHP) to match the heat demand of residential end users.

Akgul et al. [67] presented a work that uses a mixed integer nonlinear programming (MINLP) model of carbon negative energy generation in the UK to study the potential for existing power generation assets to act as a carbon sink as opposed to a carbon source. The problem addressed in this work was related with variables such as geographical locations and capacities of current and potential future electricity generation plants or the total electricity demand. For the optimal design of a bio-power supply chain was formulated as a spatially-explicit, static, multi-objective, mixed integer nonlinear programming (MINLP) model.

2.6 Chapter conclusion

Since the last decades, efforts have been made to supply the energy demand using alternative sources. This search is a consequence of the growing concerns about the effects of global warming cause, mainly, by the emission of GHG. Governments are promoting these alternatives by applying some policies and the transport sector is one of the principal targets.

There two main ways to modify the transport sector: changing the vehicles or their type of fuel. If changing the type of vehicles is the choice, electric cars that use clean power appear as one of the solutions. If modifying the type of fuel is the selected alternative, bioethanol is the largest produced biofuel around the world and, for that, a viable solution. The two options are tested in this dissertation, considering that bio-power is produced using biomass by gasification or combustion and bioethanol is produced by DGP.

Considered as a promising substitute of gasoline, bioethanol has been the focus of several studies and numerous papers that analyze the all supply chain of this product. On the other hand, the studies about bio-power's supply chain are limited. However, a new look on these supply chains is given in this thesis where the two referred approaches are combine in one energy supply chain. In fact, the work develop creates a new tool to analyze the most profitable solution between bioethanol and bio-power. The study of this energy supply chain is a new approach in terms of the transport sector green solutions and a good instrument to find the most profitable way to supply the energy demand.

3. Energy supply chain model

Aiming at solving the problem addressed in this thesis, i.e., to understand the profitability of a bio-power and bioethanol supply chain in Northern Italy, a Mixed Integer Linear Programming (MILP) was developed and implemented on GAMS®. It was used the version 24.1.3 (released on July 26, 2013) of the software, and the results were obtained in an Asus X54C-SX289V computer, with an Intel® Core™ i3-2350M Dual Core processor.

The model developed is based on the work started by Franceschin et al. [38], Zamboni et al. [2] and Giarola et al. [3]. In order to achieve the objective of integrate a bio-power and a bioethanol supply chain in the same model, some changes were made in the existing model. All the modifications applied to the main model, are going to be describe in this chapter.

This chapter is divided in four sections. Section 3.1 presents an overview of the problem defining several characteristics such as, objective functions, supply chain structure, and the main variables considered. In section 3.2 are presented the assumptions and the data collected essential to the model. In section 3.3 the mathematical formulation of the implemented model is described. Finally, section 3.4 has the conclusion of the chapter.

3.1 Model overview

The developed model, based on Giarola et al. [3] establishes a strategic design and planning of a general energy supply chain over a 15-year horizon. The problem is formulated as a spatially explicit multi-period where an optimization is realized with the objective of maximization of the financial performance of the business (Net Present Value, NPV) in operating the system.

The structure of the supply chain network elaborated in this thesis is presented in figure 18:

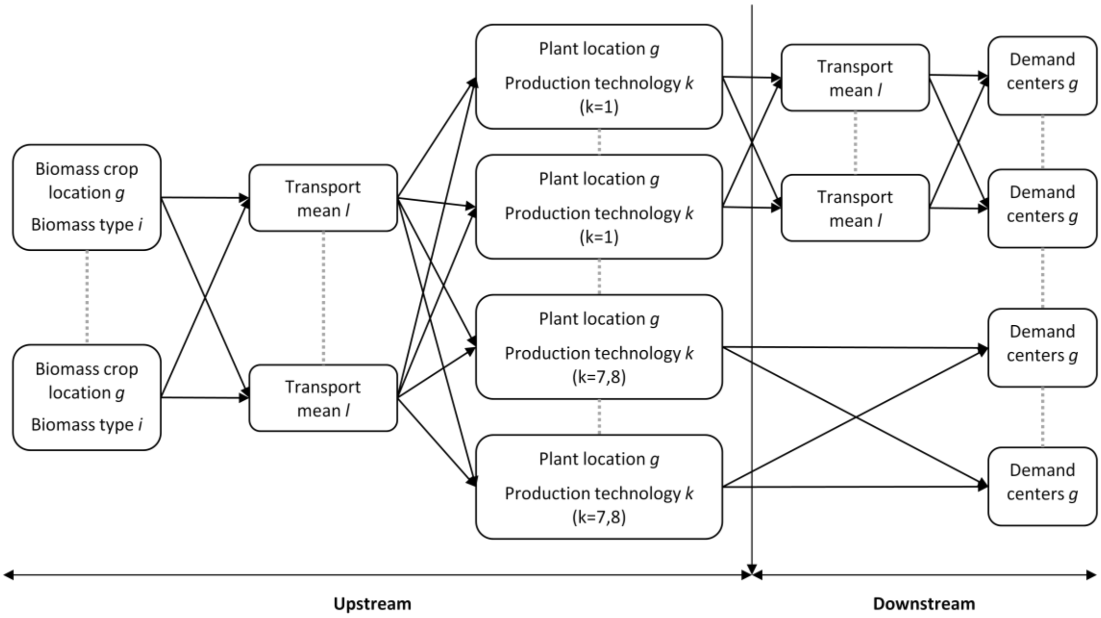

Figure 18 – Bio-power and bioethanol network supply chain.

The structure is divided in two substructures: upstream and downstream. The upstream fuel production involves biomass cultivations, biomass delivery and bio-power (k=7,8) and bioethanol (k=1) production sites and the downstream is concerned with product distribution to the demand centers.
In order to solve the problem it is necessary to take into account all the above mentioned factors and the following inputs:

1. bio-power and biofuel market characteristics;
2. biomass geographical availability, production potential and production costs as a function of geographical region;
3. energy market prices and existing subsidies;
4. energy demand over the entire time horizon;
5. geographical distribution of demand centers and location of biomass production sites;
6. technical (yields) and economic (capital and operating costs) parameters such as biomass type, production technology and plant scale;
7. transport logistics (modes, capacities, distances, availability, environmental burdens and costs).

The model developed is used to economically optimize the following key variables [3]:

1. bioethanol facilities technology selection, location and capacity;
2. bio-power facilities technology selection, location and capacity;
3. biomass production rate and geographical location for each site;
4. characterization of transport logistic in terms of biomass and bioethanol;
5. economic performance of the supply chain over the time horizon.

3.2 Model assumptions and data collection

Once known the key inputs and outputs of the model, it is necessary to define some parameters that support the model.

3.2.1 Spatially explicit feature

In order to implement the spatially explicit part of the model it is necessary to map the entire available networks configuration within the North Italy area and also set a geographical target for the model parameters. In this sense, the region is divided considering that the whole region is approximated through a grid of 59 homogeneous squares of 50 km of length. Another fictional square (g=60) is added to represent the possibility of biomass import.
In terms of biomass production capacity, the cell 60 is considered to have unlimited production and the value of the other cells is estimated considering the specific geographical configuration of each square. All the values are taken from Zamboni, et al. [3].

3.2.2 Production technologies

In the model there are two main types of technology: one to produce bioethanol, GDP, and two to produce bio-power, gasification and combustion.

1. k=1 – Dry Grind Process with DDGS sale - first generation;
2. k=7 – Corn-stover Gasification - second generation;
3. k=8 – Corn-stover Combustion - second generation.

Each technology is linked to some technical and economic data.
The data related with DGP is taken from Giarola et al. [3]. This technology to produce bioethanol and DDGS was proved to be the most profitable so, it is the chosen to integrate in the new model.
The data related with the technical parameters of each technology of bio-power is presented in table 4.

Table 4 – Conversion of biomass to bio-power by technology *k* ($MWh/t_{biomass}$) [44,45].

Biomass	Technology	
	Gasification	Combustion
Corn	0	0
Stover	0.615	0.621

In table 4 is explicit the quantity of bio-power produced by ton and the type of biomass needed using gasification and combustion process, respectively.
The economic data related with bio-power technologies is presented in tables 5 and 6.

Table 5 – Capital investment for each plant size *p* and for each technology *k,* (M€) [44,45].

Plant sizes	Technology	
	Gasification	Combustion
1	2.7	1.3
2	27.2	12.7
3	136.1	63.5
4	272.2	126.9
5	408.3	190.4
6	544.4	253.8

In table 5 is presented the value of the investment needed to build the bio-power plants. The different plant sizes considered, take into account minimum size feasibility in economic terms and are presented in table 7.

Table 6 – Coefficient for linear regression of production costs [44,45].

Coefficient	Technology	
	Gasification	Combustion
Slope (€/MWh)	9.827	1.179
Intercept (€/month)	59244	84097

In table 6 is exposed the data related with the production costs of bio-power technologies that will be used as parameters in the new model developed.

3.2.3 Biomass

Concerning the technologies selected above, there are two types of biomass: corn and corn-stover.

In this sense, some assumptions are made:

1. Stover yields are equal to corn yield according to the common assumption of fixed grain to stover ratio 1:1;
2. Stover costs are derived by assuming a fixed allocation factor of nearly 24%.

3.2.4 Demand

The definition of the demand is the step that allows the model to initialize its optimization. According to Zamboni, et al [2], the bioethanol is assumed to be sent to blending terminals existing at given location. This blending is imposed by the EU guidelines that set a minimum blending factor of bioethanol within gasoline of 5.75% by 2010 and 10% by 2020. To adapt these guidelines to the model it is considered a varying blending quota for the 5 time periods starting from 2010 to 2024.

In the context of this thesis, it is considered that the bio-power produced is also supposed to feed these terminals. In fact, in order to have a base to compare the supply chains of bio-power and bioethanol, it is assumed that the biofuels demand is now an energy demand that can be satisfied either by bio-power or by bioethanol. To redefine the demand a conversion factor of 0.128 t_{EtOH}/MWh was established. In the sense, the location and the volume of the demand squares can be consulted in reference [3].

3.2.5 Transport

The transport between infrastructures can be provided by: trucks, rail, barges or ships. In the specific case of biomass trans-shipping is also an option. All the transport related data can be found in Zamboni, Shah, et al. [2]. This assumption is valid for all technologies. However, regarding bio-power production it is assumed that the final product is not transported but, instead, directly sent to the grid. In this way, there is no cost associated to the transport of electricity.

3.2.6 Price

There are three products contributing to the incomes of the process: bioethanol, DDGS and bio-power. In a first approach, market prices for these products are taken from Zamboni, Shah, et al (2009) [2] and consider equal to 710 €/t_{EtOH}, 300 €/t_{DDGS} and 180 €/MWh. However, these prices represent a higher value comparatively to the ones used in industries nowadays. This happens because incentives to a green energy production are taken into account [3].

For a more realistic approach, it is considered a second scenario in which the power price is fixed in 66.5 €/ MWh, corresponding to the price, taxes and levies excluded, for a consumption greater than 150 000 MWh defined by Eurostat [68]. This approach is taken into account once power, and not bioethanol, can be obtained by non-renewable energy sources.

3.2.7 Plant sizes

In terms of plant sizes the problem is divided in two: bioethanol plants and bio-power plants. In both cases six plant sizes are considered and they were defined based on the typical size plants installed.
For bioethanol plants, a maximum capacity of 23 000 tons per month is established. The different values for the limits and the plant sizes are taken from S. Giarola et al. [3].
In bio-power plants the maximum capacity established is 140 000 MWh per month and the different plant sizes can be seen in table 7:

Table 7 – Bio-power production capacity for each plant size *p* [20,41,69,70].

Bio-power plant, p	Production capacity (MWh/month)
1	679
2	6792
3	33958
4	67917
5	101875
6	135833

In table 7 are exposed different capacities of bio-power production that are valid to gasification and combustion technologies.

3.3 Model Formulation

All the sets, parameters and variables necessary to the model developed are described is this chapter. The data needed to run the model is presented above and, the remaining data, can be consulted in Franceschin et al., Zamboni et al., and Giarola et al. [2,3,38].

Sets

$c \in C$	Coefficients for costs linearization, C = {slope, intercept}
$g \in G$	Grid squares, G = {1,…,60}
$i \in I$	Biomass types, I = {corn, stover}
$j \in J$	Products from biomass conversion, J = {bioethanol, DDGS, bio-power}
$k \in K$	Production technologies, K = {1, 7, 8}
$l \in L$	Transport means, L = {truck, rail, barge, ship, tship}
$p \in P$	Capacity index for conversion facilities, P = {1,…,6}
$t \in T$	Time periods, T = {1,…,5}

Subsets

$elec(k) \subset K$	Technologies which involve bio-power production elec (k) = {7,8}
$tech\ (k) \subset K$	Technologies which involve DDGS sale, tech (k) = {1}
$sub\ (p) \subset P$	Discretization intervals, sub (p) = {1,…,5}

Scalars

DY	DDGS yield - 0.954 t_{DDGS}/t_{EtOH} corn
ffc	Fixed costs over total incomes - 0.15
$Trate$	Taxation rate - 0.36
$Pcap_{Max}$	Maximum bioethanol production capacity – 23100 t_{EtOH}/month
$Pcap_{Min}$	Minimum bioethanol production capacity – 7900 t_{EtOH}/month
$Pcap_{max}^{power}$	Maximum bio-power production capacity – 140000 MWh/month

$Pcap_{min}^{power}$	Minimum bio-power production capacity – 600 MWh/month
θ	Conversion factor – 0.128 t_{EtOH}/MWh [71]
M	Maximum profit value - 2000000000 €
y	Zero representative - $1x10^{-6}$

Parameters

BCD^{max}_{g}	Maximum biomass cultivation density in region *g* ($km^2_{cultivation}$ / $km^2_{arable\ land}$)
ER_p	Bioethanol production rate for each plant size *p* (t_{EtOH}/month)
ER_power_p	Bio-power production rate for each plant size *p* (MWh/month)
$dfTCI_t$	Discount factor for investment at time *t*
$dfCF_t$	Discount factor for cash flow at time *t*
dk_t	Depreciation charge at time *t*
IBF_g	Internal biomass production grids (binary parameter)
MP_j	Market price of the product *j* at time *t* (€/t or €/MWh)
$quota_i$	Maximum percentage of corn and stover suitable for energy production
$BA_{g,i}$	Biomass *i* availability for energy production in region *g* ($t_{biomass}$/time period)
$\xi_{i,k}$	Conversion of biomass *i* into bio-power for each technology *k* (MWh/$t_{biomass}$)
$\gamma_{i,k}$	Conversion of biomass *i* into bioethanol for each technology *k* (t_{EtOH}/$t_{biomass}$)
$\beta e_{i,k}$	Fraction of energy rate from biomass type *i* for each technology *k*
$CI_{p,k}$	Capital investment at each linearization interval *p* and for technology *k* (M€)
$c_{k,c}$	Slope (€/t_{EtOH} or €/MWh) and intercept (€) coefficients for the linear regression of production costs for each technology *k*.
$LD_{g,g'}$	Delivery distance between grids *g* and *g'* (km)

$UPCb_{i,l}$	Unitary purchase cost for biomass (€/t $_{biomass}$)
$\tau_{g,l,g'}$	Tortuosity factor of transport mode *l* between *g* and *g'*
$UPCi_{i,g}$	Unitary transport cost via mode l and biomass i (€/(ton.km))
$UTCj_{l}$	Unitary transport cost via mode l and product j (€/(ton.km))
AD_g	Arable land density in region *g* (km^2 $_{arable\ land}$ / km^2 $_{grid\ surface}$)
$Dterm_g$	Energy demand at terminals g (thousand kg per month)
etperct	Bioethanol blending percentage at time *t*
GS_g	Grid surface (km^2)
$TCapi_{l,i}$	Capacity of transport mode *l* for biomass *i* (t/trip)
$TCapj_{l}$	Capacity of transport mode *l* for product *j* (t/trip)
$QMaxi_{l,i}$	Maximum flow rate of biomass *i* via mode *l* (t/month)
$BY_{g,i}$	Biomass *i* yield for each region *g* ($t_{biomass}$/time period km^2)

Variables

BPC_t	Biomass production costs at time t (€/time period)
$Cap_{i,k,g,t}$	Supply of biomass i to plant of tech (k) in region g at time t (t/month)
$dCCF$	Discounted cumulative cash flow (€)
$dFCC$	Facilities capital costs (€)
CF_t	Cash flow at time *t* (€/time period)
D_t	Depreciation at time *t* (€/time period)
$Dtot_{g,t}$	Energy demand in region *g* at time *t* (ton/time period)
$Dtoti_{i,g,t}$	Biomass *i* demand in region *g* at time *t* (ton/month)
EPC_t	Bioethanol production costs at time *t* (€/time period)
$Etot_{g,t}$	Bioethanol demand in region *g* at time *t* (t/time period)
$FixC_t$	Fixed cost at time *t* (€/time period)
$Incomes_t$	Gross earnings at time *t* (€/time period)
$\lambda_{p,k,g,t}$	Linearization variable for TCI_t at interval *p* and for technology *k*, in region *g* at time *t*

$\lambda_{p,k,g,t}^{plan}$ Linearization variable for TCI_t at interval *p* and for technology *k*, in region *g* at time *t*

NPV Net Present Value (€)

Obj_{eco} *O*bjective function expressed as negative NPV (€)

PBT_t Profit before taxes at time *t* (€/time period)

$Pb_{i,g,t}$ Production rate from biomass *i* in region *g* at time *t* (t/time period)

$Pf_{i,k,g,t}$ Bioethanol production rate from biomass *i* through technology *k* in region *g* at time *t* (t_{EtOH}/time period)

$Potot_{g,t}$ Bio-power demand in region *g* at time *t* (t/time period)

$Pp_{i,k,g,t}$ Bio-power production rate from biomass *i* through technology *k* in region *g* at time *t* (MWh/time period)

PPC_t Bio-power production cost at time *t* (€/time period)

$Pppower_{k,g,t}$ Production of pure bio-power through technology *k* in region *g* at time *t* (MWh/time period)

$Ptot_{j,k,g,t}$ Total production rate for product *j* through technology *k* in region *g* at time *t* (t/time period or MWh/time period)

$Qi_{i,g,l,g',t}$ Biomass *i* flow rate from technology *k* in region *g* at time *t* (t/time period)

$Qj_{g,l,g',t}$ Total energy flow rate between *g* and g' via transport mode *l* at time *t* (t/time period)

$Qje_{g,l,g',t}$ Total bioethanol flow rate between *g* and g' via transport mode *l* at time *t* (t/time period)

$TAR_{j,k,t}$ Gross profit from product *j* related to technology *k* at time *t* (€/time period)

TAX_t Tax amount at time *t* (€/time period)

TCb_t Biomass transport costs at time *t* (€/time period)

TCp_t Product transport costs at time *t* (€/time period)

TCI_t Total capital investment at time *t* (€/time period)

$TCIl_{k,g,t}$ Total capital investment for plant of technology *k* in region *g* at time *t* (€/time period)

TD_t	Total energy demand at time *t* (t/time period)
TP_t	Total energy production at time *t* (t/time period)
TPe_t	Total bioethanol production at time *t* (t/time period)
$TPot_{i,t}$	Total potential production of biomass *i* at time *t* (t/time period)
TPp_t	Total power production at time *t* (t/time period)
$VarC_t$	Variable costs at time *t* (€/time period)

Binary variables

$Y_{k,g,t}$	1 if a production facility *k* is already established in region *g* at time *t* or 0 otherwise
$Y_{k,g,t}^{plan}$	1 if the establishment of a new conversion facilities *k* is to be planned in region *g* during time period *t* or 0 otherwise
$Y_{k,g}^{start}$	1 if the establishment of a new conversion facilities *k* is to be planned in region *g* at the beginning or 0 otherwise.
$\Delta_{p,k,g,t}$	1 if a production facility k of size p is to be established in region g at time t or 0 otherwise

After establishing all the model's premises, the mathematical formulation is given by:

Objective function

$$Obj_{eco} = NPV \tag{1}$$

Equation (1) represents the objective function that maximizes the Net Present Value (NPV)

Economic functions

$$NPV = dCCF - dFCC \tag{2}$$

The *NPV* is given by the difference between the discounted cumulative cash flows *dCCF* , and the discounted facilities capital costs *dFCC*, as equation (2) shows.

$$dFCC = \sum_t (TCI_t \cdot dfTCI_t) \quad (3)$$

The *dFCC* represents the capital investment required to build the set of conversion facilities, multiplied by the respective discount factor and is given by equation (3).

$$dCCF = \sum_t (CF_t \cdot dfCF_t), \quad (4)$$

In equation (4) is defined the *dCCF* as the sum of the cash flows for each time period t multiplied by a discount factor.

$$TCI_t = \sum_{g,k} \left(TCIl_{k,g,t}\right), \qquad \forall\, t \quad (5)$$

Equation (5) defines the linearization of TCI_t per technology k.

$$TCIl_{k,g,t} = \sum_p \left(\lambda_{p,k,g,t}^{plan} \cdot CI_{p,k}\right), \qquad \forall\, k, g, t \quad (6)$$

In equation (6) is calculated the $TCIl_{k,g,t}$ multiplying a linearization variable with the capital investment for each plant size of each technology k.

$$CF_t = PBT_t - TAX_t + D_t, \qquad \forall\, t \quad (7)$$

The definition of cash flows are showed in equation (7) and they are obtained by summing the profit before taxes PBT_t and the depreciation charge D_t and, finally, subtracting the tax amount TAX_t.

$$D_t = \sum_{p,k,g} \left(\lambda_{p,k,g,t} \cdot CI_{p,k} \cdot dk_t\right), \qquad \forall\, t \quad (8)$$

D_t represents depreciation at time t and it is presented in equation (8). D_t is evaluated adopting the straight line depreciation method and therefore depreciating the total capital investment TCI_t through a fixed quota of 20%. However, since this model is developed with a multi-period strategy, where investment decisions may occur at different time periods, capital depreciations should have been evaluated since the time period in which the investment decision actually took place [3].

$$TAX_t \geq Trate \cdot PBT_t, \qquad \forall\, t \tag{9}$$

Equation (9) presents TAX_t that is defined as the total tax amount. A taxation charge is applied only when a positive annual gross profit is obtained. *TAXt,* is a function of PBT_t, would make this a non-linear problem. This dilemma is overcome by fixing a taxation rate of 36% which represents a conservative approximation with respect to the current Italian taxation [3].

$$PBT_t = Incomes_t - VarC_t - FixC_t - D_t, \qquad \forall\, t \tag{10}$$

PBT_t, appears in equation (10) and is represented by deduct both variable and fixed costs and depreciation to the incomes.

$$Incomes_t = \sum_{j,k} \left(TAR_{j,k,t}\right), \qquad \forall\, t \tag{11}$$

$$TAR_{j,k,t} = \sum_{g} \left(Ptot_{j,k,g,t} \cdot MP_j\right), \qquad \forall\; t, k \tag{12}$$

The *Incomes* (equation 11 and 12) come from the sum of the total annual revenues earned through the selling of product j.

$$FixC_t = Incomes_t \cdot ffc, \qquad \forall\, t \tag{13}$$

The fixed costs are reflected in equation (13) and account the facility general expenses. These costs are calculated by applying a fixed quota *ffc*, set equal to 15% to the global incomes [3].

$$VarC_t = EPC_t + BPC_t + TCb_t + TCp_t + PPC_t \quad , \quad \forall\; t \tag{14}$$

The variable costs are reflected in equation (14) and result from the sum of the main costs involved in the steps of the supply chain in study: bioethanol production cost, EPC_t, biomass production costs, BPC_t, biomass transport costs, TCb_t, bioethanol transport costs, TCp_t, and bio-power production costs, PPC_t. **This is a new equation added to the model.**

$$EPC_t = \sum_{k,g} \left(Ptot_{j,k,g,t} \cdot c_{k,'slope'} + Y_{k,g,t} \cdot c_{k,'intercept'} \right), \qquad \forall \ t \tag{15}$$

Bioethanol production cost, *EPC_t*, is represented by the sum of two main contributions, a linear function of the total production rate of the product and a fixed quota depending on the production technology, k, adopted (equation 15).

$$BPC_t = \sum_{i,g} \left(Pb_{i,g,t} \cdot UPC_{i,g} \right), \qquad \forall \ t \tag{16}$$

BPC_t is estimate by multiplying the total biomass i rate produced in region g at time period t, by the corresponding unit production costs, *$UPC_{i,g}$*.

$$TCb_t = \sum_{i,l} \left(UPCb_{i,l} \cdot \sum_{g,g'} \left(Qi_{i,g,l,g',t} \cdot LD_{g,g'} \cdot \tau_{g,l,g'} \right) \right) + \sum_{i,g} \left(Pb_{i,g,t} \cdot UPCb_{i,l} \cdot LD_{g,g'} \right), \qquad \forall \ t \tag{17}$$

$$TCp_t = \sum_{l} \left(UTCj_l \cdot \sum_{g,g'} Qje_{g,l,g',t} \cdot LD_{g,g'} \cdot \tau_{g,l,g'} \right), \qquad \forall \ t \tag{18}$$

In terms of costs associated with biomass (*TCb_t*) and products transport (*TCp_t*), they are considered as an additional service provided by existing companies already operating within the market. These costs are presented in equations (17) and (18), respectively.

$$PPC_t = \sum_{k,g} \left(Pppower_{k,g,t} \cdot c_{k,'slope'} + Y_{k,g,t} \cdot c_{k,'intercept'} \right), \qquad \forall \ t \tag{19}$$

Bio-power production cost, *PPC_t*, is represented by the sum of two main contributions, a linear function of the total production rate of the product and a fixed quota depending on the production technology, k, adopted. **This is a new equation added to the model.**

Constraints: Linearization and logical

$$\sum_{p} (\lambda_{p,k,g,t}^{plan}) = Y_{k,g,t}^{plan}, \qquad \forall\, k, g, t \tag{20}$$

$$\sum_{p} (\lambda_{p,k,g,t}) = Y_{k,g,t}, \qquad \forall\, k, g, t \tag{21}$$

Equations (20) and (21) present two continuous variables (λ and λ^{plan}) that are constrained by planning decision variables (Y and Y^{plan}). $Y^{plan}{}_{k,g,t}$ is the binary variable planning the establishment of a new production facility and $Y_{k,g,t}$ is the recursive variable keeping memory of the plant establishment. These two equations are related with the technology selection.

$$Y_{k,g,'1'}^{plan} = Y_{k,g}^{start}, \qquad \forall\, k, g \tag{22}$$

Equation (22) sets the first year configuration.

$$Y_{k,g,t} - Y_{k,g,t-1} = Y_{k,g,t}^{plan}, \qquad \forall\, k, g, t \tag{23}$$

A rational supply chain planning over the time is based upon the assumption that once a production facility is constructed, it will be operating for the remaining time frame. This is ensured using the recursive definition given in equation (23).

$$\lambda_{p,k,g,t} - \lambda_{p,k,g,t-1} = \lambda_{p,k,g,t}^{plan}, \qquad \forall\, p, k, g, t \tag{24}$$

Equation (24) is responsible to bind the continuous variables λ and λ^{plan}.

$$\lambda_{p,k,g,t}^{plan} \leq \Delta_{p,k,g,t} + \Delta_{p-1,k,g,t}, \qquad \forall\, p, k, g, t \tag{25}$$

$$\lambda_{p,k,g,t} \leq \Delta_{p,k,g,t} + \Delta_{p-1,k,g,t} \quad \forall p, k, g, t \tag{26}$$

The equations (25) and (26) are constraints on the key linearization variables and bind the selection of the continuous values within a suitable range.

$$\sum_{k}(Y_{k,g,t}) \leq 1, \qquad \forall\, g,t \tag{27}$$

From equation (27) it is imposed that only one conversion plant can operate within one territorial element *g*.

$$\sum_{p}(\Delta_{p,k,g,t}) = Y_{k,g,t} \quad \forall\, k,g,t \tag{28}$$

Finally, in equation (28), a link between the investment decisions $Y_{k,g,t}$, and the linearization procedure is imposed by imposing the $\Delta_{p,k,g,t}$ variables to the planning decision variable value.

Constraints: Capacity and production

$$Ptot_{'ethanol',k,g,t} \leq Pcap_{Max} \cdot Y_{k,g,t} \qquad \forall\, k,g,t \tag{29}$$

Equation (29) imposes that the production rate cannot exceed a certain limits, even if it allows for a capacity adjustment according to market demand.

$$Ptot_{'ethanol',k,g,t} \geq Pcap_{Min} \cdot Y_{k,g,t} \quad \forall\, k,g,t \tag{30}$$

Equations (30) impose minimum capacity of a plant regarding to economic feasibility heuristics.

$$Ptot_{'ethanol',k,g,t} \leq \sum_{p}(ER_p \cdot \lambda_{p,k,g,t}) \quad \forall\, k,g,t \tag{31}$$

Equation (31) sets the amount of bioethanol produced in each region by multiplying a continuous recursive variable, which has assumed a non-zero value since the moment an investment decision was taken, with the nominal production rate of bioethanol for each plant size.

$$Pf_{i,k,g,t} = Cap_{i,k,g,t} \times \gamma_{i,k} \qquad \forall\, i,k,g,t \tag{32}$$

Equation (32) defines bioethanol production from biomass i through technology k in region g at the time t.

$$Pf_{i,k,g,t} = Ptot_{'ethanol',k,g,t} \times \beta e_{i,k} \quad \forall\, i,k,g,t \tag{33}$$

Equation (33) defines what kind of feedstock is selected for each technology.

$$Ptot_{'DDGS',k,g,t} = Pf_{'corn',k,g,t} \times DY \quad \forall\, k,g,t \tag{34}$$

In equation (34) is explicit the relation between the bioethanol produced and the DDGS form as a by-product.

$$Ptot_{'power',k,g,t} = Pppower_{k,g,t} \quad \forall\, k,g,t \tag{35}$$

Equation (35) reveals that all the bio-power produced and sell is only coming from pure bio-power production facilities. **This is a new equation added to the model.**

$$Pppower_{k,g,t} \leq Pcap_{max}^{power} \cdot Y_{k,g,t} \quad \forall\, k,g,t \tag{36}$$

Equation (36) imposes that the production rate cannot exceed a certain limits, even if it allows for a capacity adjustment according to market demand. **This is a new equation added to the model.**

$$Pppower_{k,g,t} \geq Pcap_{min}^{power} \cdot Y_{k,g,t} \quad \forall\, k,g,t \tag{37}$$

Equation (37) imposes minimum capacity of a plant regarding to economic feasibility heuristics. **This is a new equation added to the model.**

$$Pppower_{k,g,t} \leq \sum_{p} \left(ER\_power_{p} \cdot \lambda_{p,k,g,t} \right) \quad \forall\, k,g,t \tag{38}$$

Equation (38) sets the amount of bio-power produced in each region by multiplying a continuous recursive variable, which has assumed a non-zero value since the moment an investment decision was taken, with the nominal production rate of bioethanol or bio-power for each plant size. **This is a new equation added to the model.**

$$Pp_{i,k,g,t} = Cap_{i,k,g,t} \times \xi_{i,k} \qquad \forall\, i,k,g,t \tag{39}$$

Equation (39) defines the bio-power production from biomass i through technology k in region g at the time t. **This is a new equation added to the model.**

$$Pp_{i,k,g,t} = Pppower_{k,g,t} \times \beta e_{i,k}\ , \qquad \forall\, i,k,g,t \tag{40}$$

Equation (40) defines what kind of feedstock is selected for each technology. **This is a new equation added to the model.**

$$\sum_{k}\left(Ptot_{'ethanol',k,g,t} + Ptot_{'power',k,g,t} \times \theta\right) = \sum_{l,g'}\left(Qj_{g,l,g',t} - Qj_{g',l,g,t}\right) + Dtot_{g,t},\ \ \forall\ g,t \tag{41}$$

In equation (41) is presented the global balance of products for each region *g,* represented by a square. **This is a new equation added to the model.**

$$\sum_{k}(Ptot_{'ethanol',k,g,t}) = Etot_{g,t}\ + \sum_{l,gp}(Qje_{g,l,g',t} - Qje_{g',l,gp,t})\ \ , \quad \forall\ \ i,g,t \tag{42}$$

In equation (42) is presented the mass balance of bioethanol for each region *g,* represented by a square. **This is a new equation added to the model.**

$$Pb_{i,g,t} = Dtoti_{i,g,t} + \sum_{l,g'}\left(Qi_{i,g,l,g',t} - Qi_{i,g',l,g,t}\right) \qquad , \quad \forall\ \ i,g,t \tag{43}$$

In equation (43) is presented the balance of biomass for each region *g,* represented by a square.

$$Pb_{i,g,t} - BA_{g,i} \leq 0 \quad , \quad \forall i,g,t \tag{44}$$

Equation (44) consists in an upper-bound that is imposed to the biomass mass balance and is related with the effective regional production capability.

$$TPot_{i,t} = \sum_{g} (BA_{g,i} \cdot IBF_g) \quad , \quad \forall \ i,t \tag{45}$$

$$quota_i \cdot TPot_{i,t} - \sum_{g} \left(Pb_{i,g,t} \cdot IBF_g\right) \geq 0 \quad , \quad \forall \ i,t \tag{46}$$

To ensure a sustainable biomass to biofuel purposes, it was fixed the maximum amount of domestic biomass available for bioethanol production applying a factor $quota_i$ (set equal to 14% for corn and 33% for stover) [3]. These values were also assumed to be applied in bio-power production case and influence equations (45) and (46).

$$TP_t = TD_t \quad , \quad \forall \ t \tag{47}$$

Equation (47) sets that total production should be equal to total demand. Total demand is equal to the sum of bioethanol and bio-power demand as equation (55) shows.

$$TD_t = \sum_{g} (Dtot_{g,t}) \quad , \quad \forall t \tag{48}$$

$$Dtoti_{i,g,t} = \sum_{k} \left(Cap_{i,k,g,t}\right) , \qquad \forall \ i,k,g,t \tag{49}$$

Equations (48) and (49) define the demand, i.e., energy and biomass demand are established in these equations respectively.

$$TPe_t = \sum_{k,g} \left(Ptot_{'ethanol',k,g,t}\right) , \qquad \forall \ t \tag{50}$$

$$TPe_t = \sum_{g} \left(Etot_{g,t}\right) , \qquad \forall \ t \tag{51}$$

Equations (50) and (51) define the bioethanol production. **These are new equations added to the model.**

$$TPp_t = \sum_{k,g} \left(Ptot_{'power',k,g,t} \cdot \theta \right) \ , \qquad \forall \ t \tag{52}$$

$$TPp_t = \sum_{g} \left(Potot_{g,t} \right) , \qquad \forall \ t \tag{53}$$

Equations (52) and (53) define the bio-power production. **These are new equations added to the model.**

$$TP_t = TPe_t + TPp_t \ , \qquad \forall \ t \tag{54}$$

In equation (54) the contribution from bio-power and bioethanol are summed to have the total production. **This is a new equation added to the model.**

$$Dtot_{g,t} = Etot_{g,t} + Potot_{g,t} \ , \qquad \forall \ g,t \tag{55}$$

In equation (55) the total demand is presented by the sum of bio-power and bioethanol demands. **This is a new equation added to the model.**

Constrains: Non-negative

All equations presented below, from (56) to (68), impose a physical meaning in some of the variables by not allowing the model to present negative values.

$$Cap_{i,k,g,t} \geq 0 \quad , \qquad \forall \ i,k,g,t \tag{56}$$

$$\lambda^{plan}_{p,k,g,t} \geq 0 \quad , \qquad \forall \ p,k,g,t \tag{57}$$

$$\lambda_{p,k,g,t} \geq 0 \quad , \qquad \forall \ p,k,g,t \tag{58}$$

$$Pb_{i,g,t} \geq 0 \quad , \qquad \forall \ i,g,t \tag{59}$$

$$Ptot_{'ethanol',k,g,t} \geq 0 \, , \quad \forall \ k,g,t \tag{60}$$

$$Dtot_{g,t} \geq 0 \,, \quad \forall\, g,t \tag{61}$$

$$Qb_{i,g,l,g',t} \geq 0 \quad , \quad \forall \;\; i,g,l,g',t \tag{62}$$

$$Qj_{g,l,g',t} \geq 0 \quad , \quad \forall \;\; g,l,g',t \tag{63}$$

$$Qje_{i,g,l,g',t} \geq 0 \quad , \quad \forall \;\; g,l,g',t \tag{64}$$

$$Pppower_{k,g,t} \geq 0 \quad , \quad \forall \;\; k,g,t \tag{65}$$

$$Etot_{g,t} \geq 0 \,, \quad \forall \;\; g,t \tag{66}$$

$$Potot_{g,t} \geq 0 \,, \quad \forall \;\; g,t \tag{67}$$

$$TAX_t \geq 0, \quad \forall\, t \tag{68}$$

3.4 Chapter conclusions

The model presented in this chapter assesses the economic performance of a bio-power and bioethanol supply chain design in Northern Italy. This work is based on several models developed in CAPE-Lab at University of Padova and contains a level of information that is not provided in this dissertation but can be consulted in the following works: Franceschin et al., [38], Giarola et al. [3], Giarola et al. [72], Mazzetto [62], Ortiz et al. [61] and Zamboni et al. [1,2]. The information provided by these articles includes technical and economical parameters that are necessary to implement the model.

4. Application of different scenarios

This chapter is divided in nine subchapters. Section 4.1 presents the results from the base case which considers only bioethanol production from DGP. In sections 4.2 and 4.5 is built up a scenario in which is considered the production of bio-power from gasification and bioethanol from DGP. In sections 4.3 and 4.6 bio-power is produced by a combustion process and bioethanol is produced by DGP. Sections 4.4 and 4.7 present scenario III and VI, where are consider the technologies of combustion and gasification to produce bio-power and DGP to bioethanol. In sections 4.2, 4.3 and 4.4 is considered that both prices of bioethanol and bio-power have fiscal benefits. In section 4.5, 4.6 and 4.7 only bioethanol is consider to have a price with incentives. A sensitivity analysis is performed to power's price in section 4.8. This analysis is tested for the different technologies. Finally, in section 4.9 the conclusions of the chapter are presented.

4.1 Scenarios description

The different scenarios presented in this chapter are summarized in figure 19.

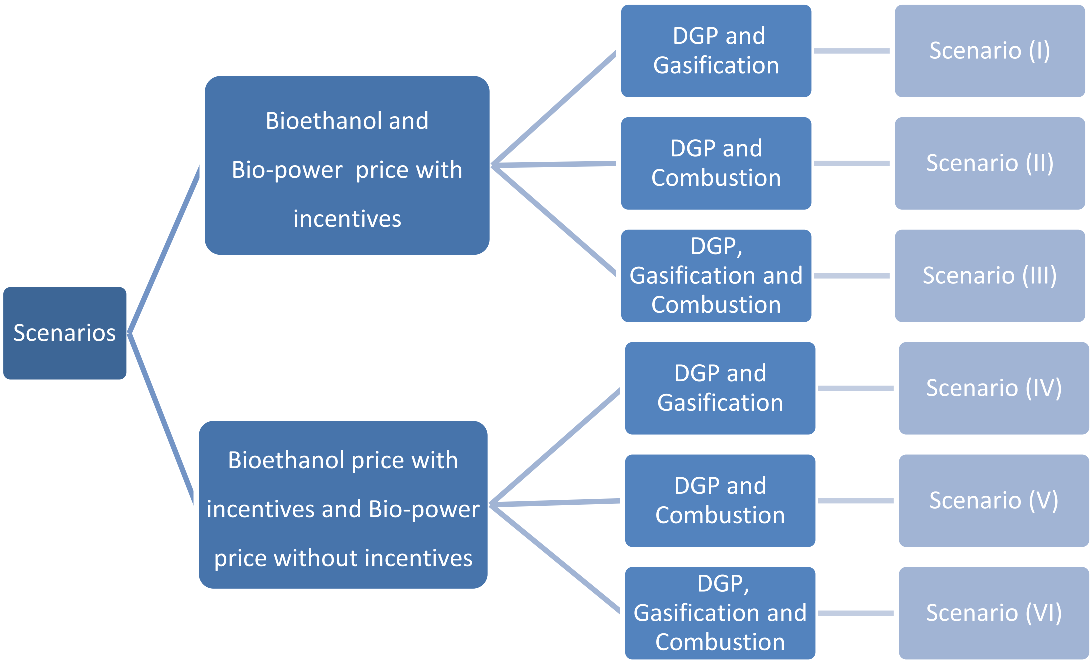

Figure 19 – Scenarios created to assess the profitability of a bio-power and bioethanol supply chain.

The different scenarios were created considering two factors: price and technology.

In terms of price, two approaches are considered: 1) bioethanol and bio-power price with incentives; 2) bioethanol price with incentives and bio-power price without incentives. These two scenarios are presented to simulate a situation where power is sold as a renewable and non-renewable sourced product, respectively.

Regarding the different technologies, DGP is chosen since it was proved to be the most profitable technology for bioethanol production by Giarola et al. [3]. In terms of bio-power production, the selection regards the most mature technologies.

4.2 Base case: DGP

The base case of this model is the production of bioethanol by DGP only. In this way it is possible to replicate the results from S.Giarola et al. [3] in order to confirm the new model.

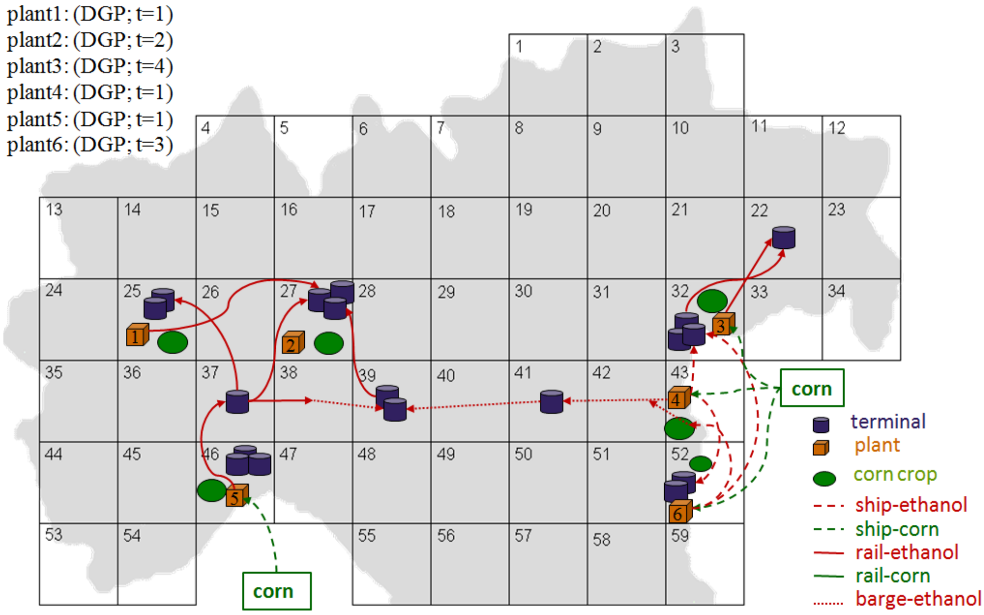

Figure 20 - Economical optimization of the supply chain considering only DGP technology.

As figure 20 shows, the model suggests the construction of six plants of DGP (k=1) technology that use corn as feedstock. Part of this biomass is imported (76.5%) and transported by ship into regions 46, 32, 43 and 52 and the other part is produced locally (23.5%), in the same cell as the production facility. These production facilities produce only bioethanol that is driven to the demand center by rail, barge and/or ship. This technology is also responsible for producing DDGS that is sold and increases the profit of the facility as figure 21 shows.

Table 8 – Results from economical optimization using technology k=1.

Incomes (M€)	11400
Var. Costs (M€)	6410
Fix. costs (M€)	1710
NPV (M€)	363
NPV (€/GJ)	1,18

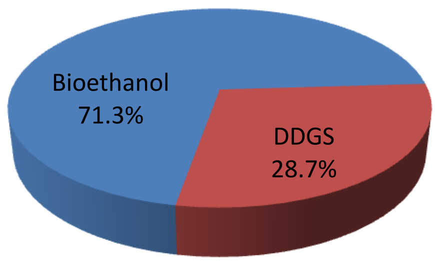

Figure 21 - Share of profit by product sold.

The results from table 8 show that this is a profitable method to produce bioethanol and, consequently, to supply the energy in demand. As figure 21 shows, about 71% of the profit comes from the selling of bioethanol and 29% from the by-product DDGS.

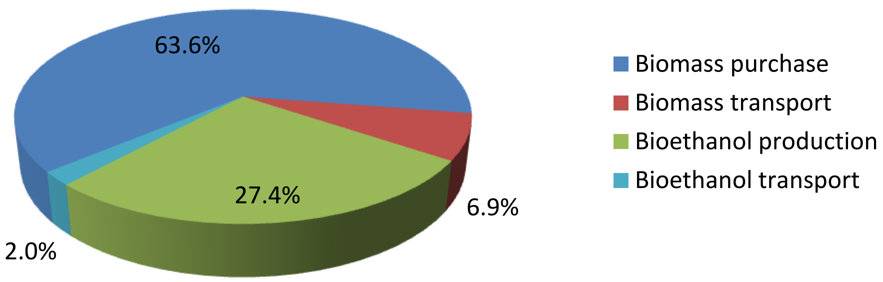

Figure 22 – Costs per supply chain stage for the base case.

According to figure 22, the costs associated with this energy supply chain are, mainly, related with biomass purchase and growth representing about 63.6% of all costs. In this case, only bioethanol is produced and, for that reason, only corn is needed as raw material and transported.

4.3 Scenario I: DGP and Gasification

The first tested scenario includes the production of bioethanol and bio-power. In this case, the bioethanol is produced by DGP technology and the bio-power is generated by gasification.

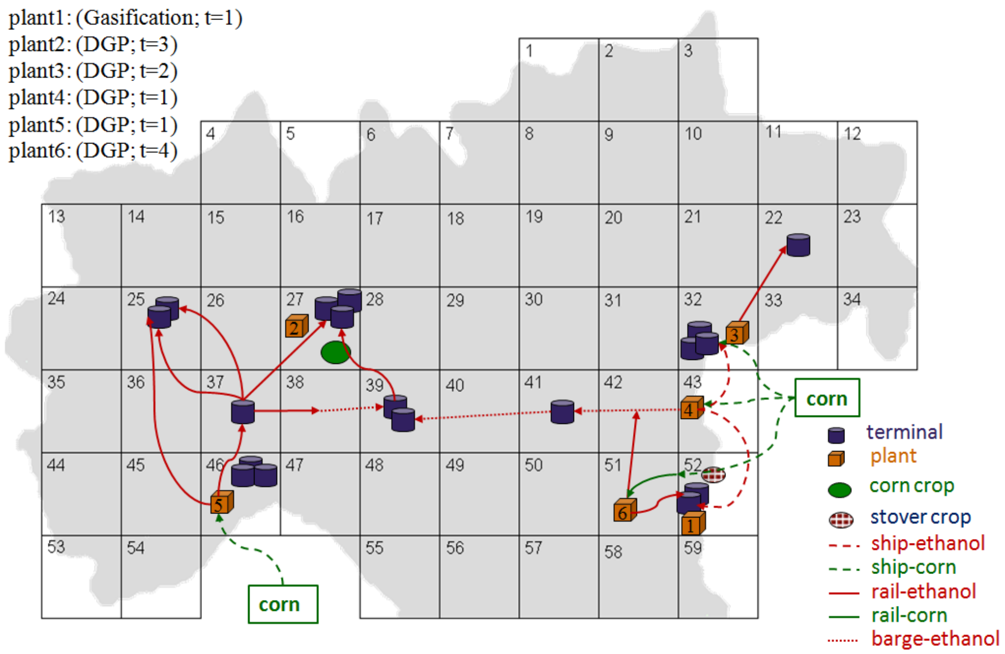

Figure 23 - Economical optimization of the supply chain considering DGP and gasification technologies.

As presented in figure 23 the optimal solution that combines these two technologies includes the implementation of five plants of DGP (k=1) technology that use corn as feedstock and one facility where corn-stover is transformed into bio-power by a gasification process.

The facility that generates bio-power is located in region 52 and has access to corn-stover by producing it. The bio-power produced in this plant is then sent to the grid, to supply the demand center located in region 25, without any transportation cost associated.

Regarding the facilities producing bioethanol, their biomass is, once again, partially imported (92%) and transported by ship and rail into regions 32, 43, 46 and 52 and the other part in produced locally (8%) or transported by rail into the production centers with biomass demand. These production facilities produce only bioethanol that is driven to the demand center by rail, barge and/or ship. This technology is also responsible for producing DDGS that is sold and, as in bio-power's case, it has no transport cost associated.

In terms of profitability the results are exposed in table 9 and figure 24.

Table 9 – Results from economical optimization using technology k=1 and k=7.

Incomes (M€)	11440
Var. Costs (M€)	6430
Fix. costs (M€)	1720
NPV (M€)	370
NPV (€/GJ)	1,20

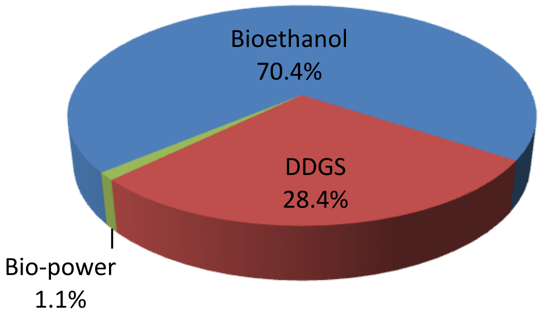

Figure 24 - Share of gross profit by product sold.

Table 9 reflects an improvement on the NPV results of 1.9% regarding the base case and confirms the profitability of the supply chain. Comparing to the base case, the results show a small increase in terms of incomes and both fixed and variable costs but confirm that the introduction of one gasification facility improves the economic performance of the supply chain. In terms of profit bioethanol is still the main contributor and the share of bio-power is almost inexistent (1.1%).

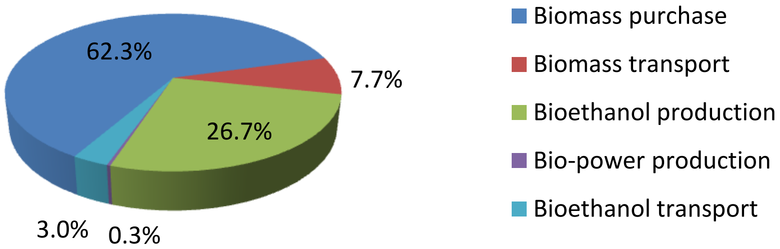

Figure 25 - Costs per supply chain stage for scenario I.

In figure 25 is showed the impact of each stage in terms of the overall costs. Analyzing the figure, is important to notice that biomass purchase and growth accounts 62.3% of these costs and that the cost associated with bio-power production is insignificant. This may be explained by the fact that only one gasification plant is constructed comparing to the five of DGP .

4.4 Scenario II: DGP and Combustion

The second scenario of optimization tests the best economical solution between producing bioethanol by DGP with DDG sale and producing bio-power from a combustion process.

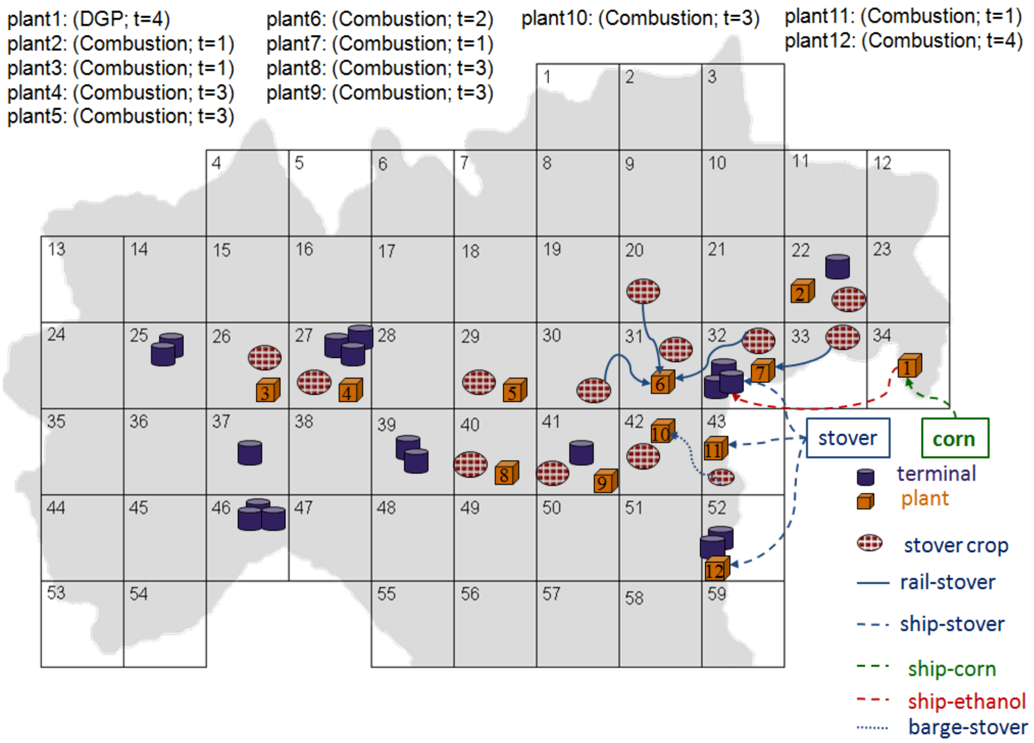

Figure 26 - Economical optimization of the supply chain considering DGP and combustion technologies.

As figure 26 shows, the optimal solution is to construct eleven bio-power plants and only one bioethanol plant. This scenario includes the creation of eleven combustion plants (k=8) technology that use corn-stover as feedstock and that produce bio-power. The feedstock reaches the production facilities by importation (58%), using ship or by cultivation (42%) using rail. The bio-power produced is sent to the grid to supply the demand center without any transportation cost.

There is also a bioethanol plant to be constructed in region 34 that is supplied by imported corn that gets there by ship. This facility is built to partially supply the demand in region 32.

Table 10 – Results from economical optimization using technology k=1 and k=8.

Incomes (M€)	15730
Var. Costs (M€)	6000
Fix. costs (M€)	2360
NPV (M€)	953
NPV (€/GJ)	3.09

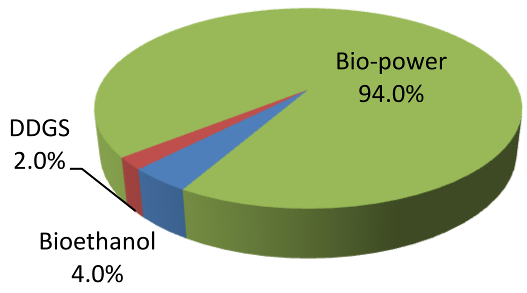

Figure 27 - Share of gross profit by product sold.

Table 10 shows the results of the economic optimization performed and reveals a 62% increase in the NPV comparing to the base case. This situation results from the increasing incomes and the decrease on variable costs. This reduction in terms of variable costs is associated with the inexistence of transport costs to bio-power distribution. In terms of fixed costs the table 10 shows a slight increase when compared to the base case possibly due to the large number of new facilities.

Figure 27 shows that, as expected, the major contributor to gross profit in this scenario is the bio-power sold.

Another interesting aspect is the large number of plants suggested by the model. This result maybe related with the fact that the capital investment needed to small plants is significantly lower than DGP plants and significantly higher otherwise.

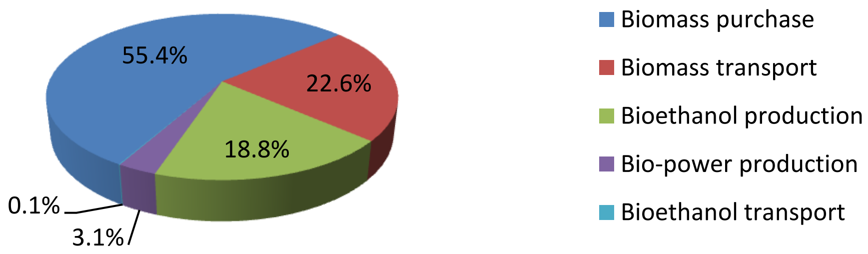

Figure 28 - Costs per supply chain stage for scenario II.

Regarding figure 28, once again, the main contributor to the supply chain costs is the biomass purchase stage. However, with the large number of facilities constructed, the biomass transport cost grows representing 22.6% of all costs. Considering the low quantity of bioethanol produced, the costs associated to its transport are, as expected, low. The low costs associated with bio-power production comparing to bioethanol production may be explained the higher conversions and lower capital investment (for small plant scales) associated to the gasification process comparing to DGP.

4.5 Scenario III: DGP, Gasification and Combustion

The third scenario assesses, from an economical point of view, the three referred technologies.

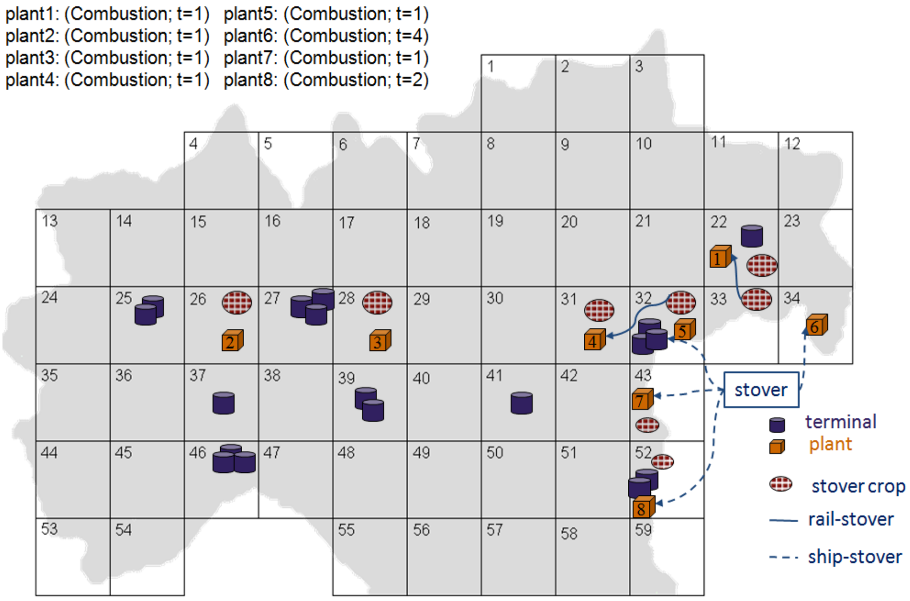

Figure 29 - Economical optimization of the supply chain considering DGP, gasification and combustion technologies.

Due to the great economical benefits pointed in the previous optimization (scenario II), regarding the deployment of combustion as a source of bio-power, the choice of this technology as preferable is expected. The result showed in figure 29 reflects that expectation since the model suggests the construction of only eight combustion facilities.

In this case, the introduction of the gasification technology creates different boundaries, leading to a different optimal solution. Nevertheless, these results reveal that the optimal solution is to construct only bio-power plants (k=8) that use corn-stover as feedstock and combustion as technology. Once again, feedstock reaches the production facilities by importation (53.1%), using ship or by cultivation (46.9%) and further transport using rail.

Table 11 – Results from economical optimization using technology k=1, k=7 and k=8.

Incomes (M€)	16090
Var. Costs (M€)	5860
Fix. costs (M€)	2410
NPV (M€)	958
NPV (€/GJ)	3.11

Results from table 11 prove that, considering the three technologies, the most profitable way of supplying the demand of energy, in the terminals, is by investing in combustion bio-power plants. This can be linked to two reasons: the production costs in combustion facilities are relatively low and with the, above mentioned, fact that in this thesis the transport costs of bio-power are not considered. In this structure all profit comes from the selling of bio-power. On the other hand the costs associated with the supply chain are distributed as figure 30 shows.

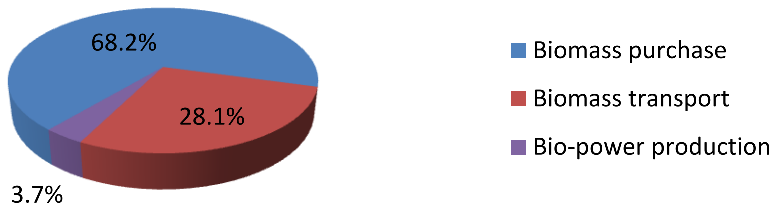

Figure 30 - Costs per supply chain stage for scenario III.

Figure 30 reveals that 68.2% of the costs this energy supply chain are related with the biomass plantation or purchase. The second major contributor to the costs of the supply chain is the biomass transport to the facilities that is carried out by rail, by ship or barge. All production process that accounts capital investment and operational costs, represent 4% of the overall costs. As referred, the bio-power transport has no cost associated.

4.6 Scenario IV: DGP and Gasification without incentives

Regarding the possibility of the governments to slow down their policies in terms of incentives on green energy production, a new scenario is tested. In this sense, an optimization is carried out considering the same premises of the scenario I but reducing the price of bio-power from 180 to 66.5 €/MWh. As assumed in subchapter 3.2.6, this is the price for industrial purpose without taxes in the first semester of 2014. These results, presented in figure 31, reveal that the structure of the supply chain is similar to the one given by the base case (figure 20).

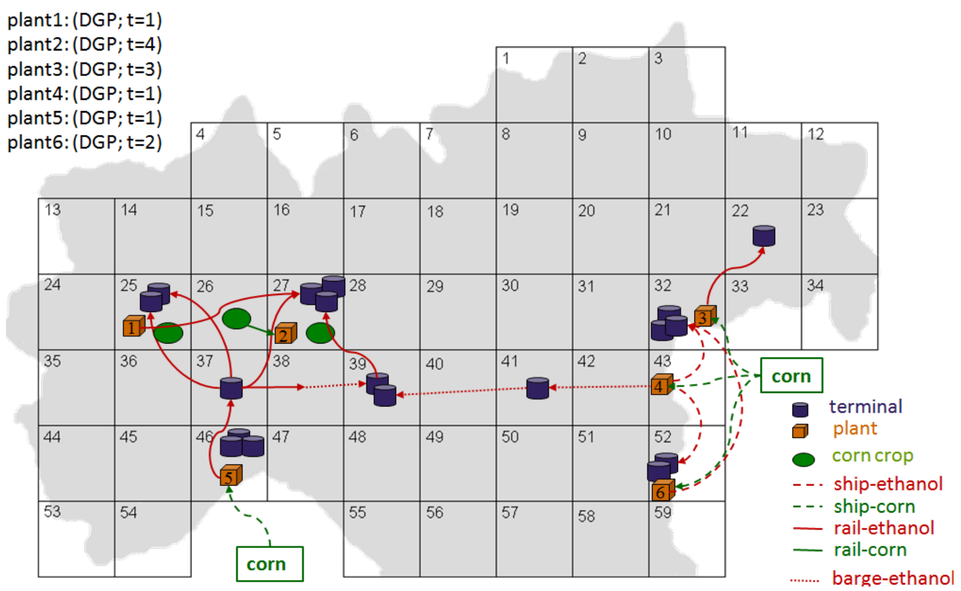

Figure 31 - Economical optimization of the supply chain considering DGP and gasification technologies and power's price without incentive.

Figure 31 shows an optimal solution that suggests the implementation of six plants of DGP (k=1) technology to produce bioethanol, using corn as feedstock. Regarding the facilities producing bioethanol, their biomass is mostly imported (77%) and transported by ship into regions 32, 43, 46 and 52 and the other part in produced locally (23%) or transported by rail into the production centers with biomass demand. These production facilities produce only bioethanol that is driven to the demand center by rail, barge and/or ship as presented in figure 31. This technology is also responsible for producing DDGS that is sold and, as in bio-power's case, it has no transport cost associated.

Table 12 – Results from economical optimization using technology k=1 and k=7.

Incomes (M€)	11400
Var. Costs (M€)	6410
Fix. costs (M€)	1710
NPV (M€)	364
NPV (€/GJ)	1.18

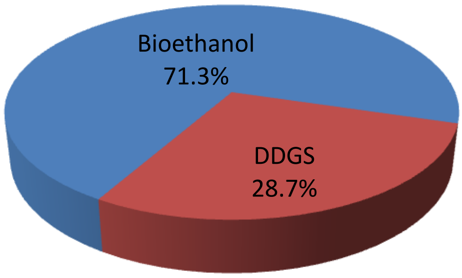

Figure 32 - Share of gross profit by product sold.

Considering the results presented in table 12, it is possible to confirm the profitability of the supply chain. In this scenario, the addition of gasification as a possible technology choice does not affect the results of the supply chain since the optimization results only suggests the implementation of bioethanol by DGP plants. In this sense, the profit of the supply chain is given by the selling of bioethanol and DDGS as figure 32 shows.
In terms of costs they can be analyzed considering the different stages of the supply chain as figure 33 shows.

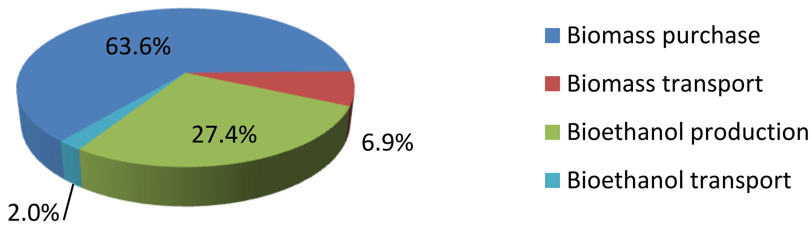

Figure 33 – Costs per supply chain stage for scenario IV.

Figure 33 shows that the main contributor to the supply chain costs is the biomass purchase stage. The impact of bioethanol production and transport in the overall costs is about 30%.

4.7 Scenario V: DGP and Combustion without incentives

In this case, the same premises of the scenario II are considered but with the reduction of the price of bio-power from 180 to 66.5 €/MWh. As assumed in subchapter 3.2.6, this is the price for industrial ends applied without taxes in the first semester of 2014.

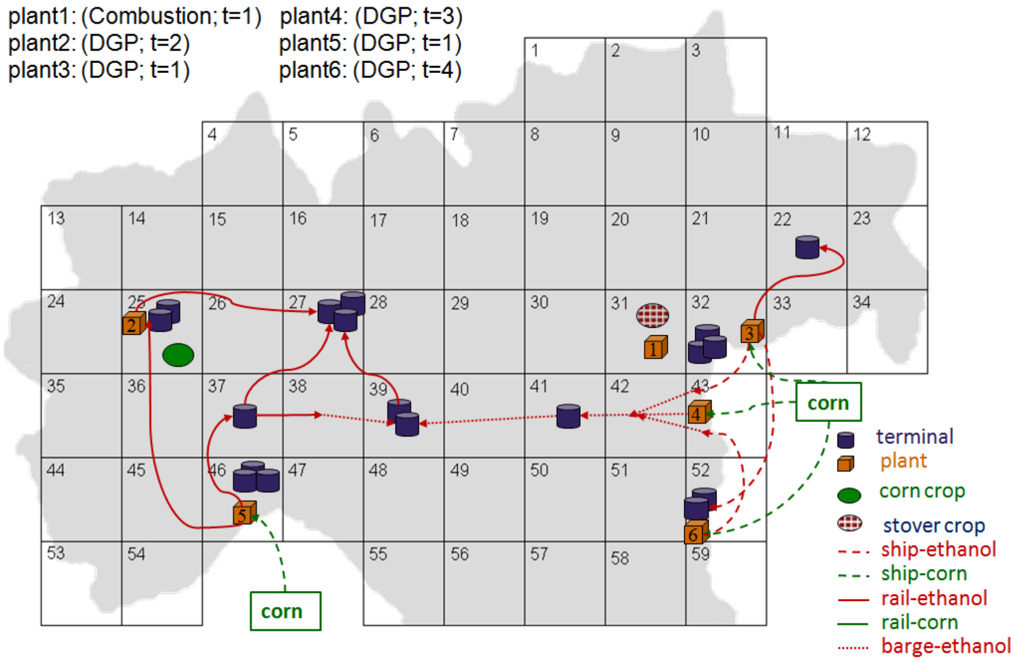

Figure 34 - Economical optimization of the supply chain considering DGP and combustion technologies and power's price without incentive.

The reduction of bio-power price drives the model to suggest a completely new optimized structure. In this structure five DGP facilities are built and only one plant uses combustion to produce bio-power as the selected technology.

The combustion facility is allocated in region g = 31 and is supplied with feedstock from local cultivation. The bio-power produce by this plant intends to supply part of the demand center located in region 25, 27 and 39.

The five DGP plants get biomass in two ways: importing, 88.5%, or producing it, 11.5%. In the first way, the corn is transported by ship and in terms of corn produced it can be directly used in the region or transported by rail to the centers with biomass demand.

In terms of profits the results are presented in figure 35 and table 13.

Table 13 – Results from economical optimization using technology k=1 and k=8.

Incomes (M€)	11380
Var. Costs (M€)	6400
Fix. costs (M€)	1710
NPV (M€)	369
NPV (€/GJ)	1.20

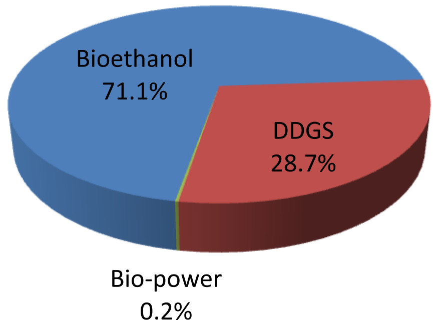

Figure 35 - Share of gross profit by product sold.

The results from table 13 and figure 35 show that, the structure proposed by the model, is a profitable solution and that bioethanol is the principal responsible for that. The results from this case are very similar to the base case. This fact, associated with the scenario IV, support the idea that without incentives to produce clean power, this product is not an effective alternative to bioethanol.

In terms of costs, theirs distribution is presented in figure 36.

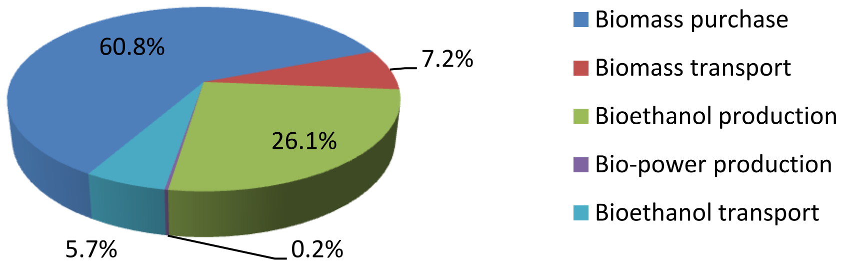

Figure 36 - Costs per supply chain stage for scenario V.

From figure 36, it is revealed that biomass purchase, growth and transport account 68% of the overall costs. The costs related with bioethanol represent 31.8% of all costs and considered the production and the transport to the blending centers. Bio-power's slice of the costs is very small since it does not have transport cost and the production costs are low.

4.8 Scenario VI: DGP, Gasification and Combustion without incentives

For this scenario, the conditions of scenario III are replicated but the power price that is considered a lower value (66.5€). In this sense, the results obtained demonstrate, once again, that the price of power influence the supply chain in a significant way.

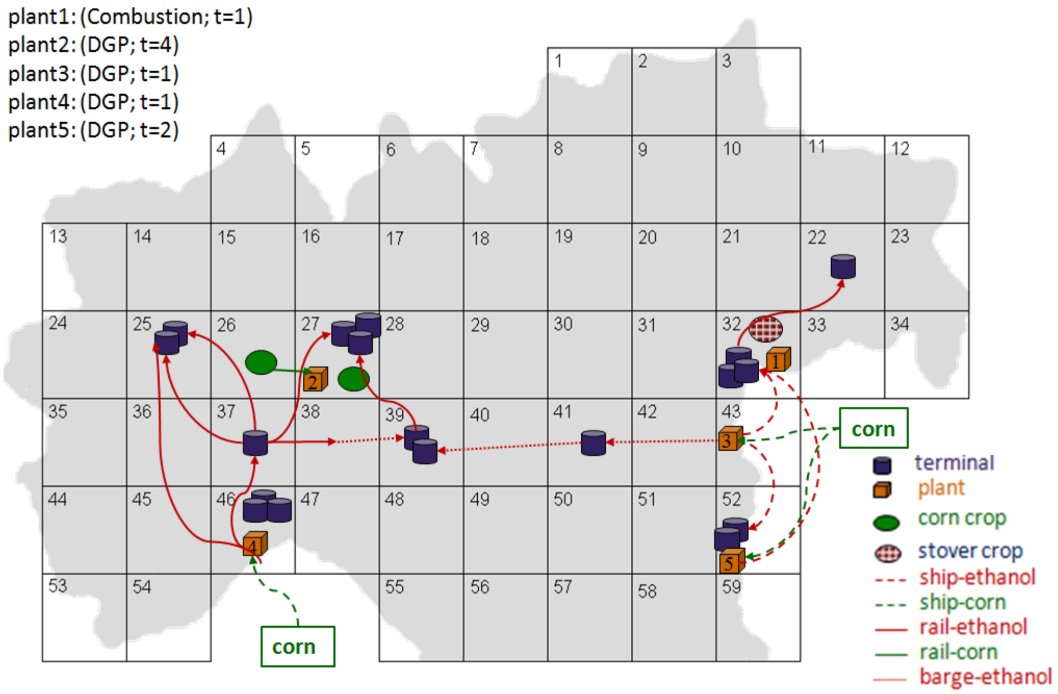

Figure 37 – Economical optimization of the supply chain considering DGP, gasification and combustion technologies and power's price without incentive.

The reduction of power price drives the model to suggest a completely new optimized structure comparing to scenario III. In this new structure four DGP facilities are built and only one plant uses combustion to produce bio-power as the selected technology.

The combustion facility is allocated in region *g* = 32 and is supplied with feedstock from local cultivation. The bio-power produce by this plant intends to supply part of the demand center located in region 25. This distance between the production facility and the demand center can be explain by the fact that bio-power does not have any transport associated leading the model to optimizes the structure without any distance constraints.

The four DGP plants get biomass mostly by importing it, 90%, and producing it, 10%. In the first way, the corn is transported by trans-ship. In the cases where biomass is locally produced, it can be directly used in the region or transported by rail to the centers with biomass demand. The bioethanol produced is transported in to the blending centers by rail, barge or ship.

In terms of profits the results are presented in figure 38 and table 14.

Table 14 – Results from economical optimization using technology k=1, k=7 and k=8.

Incomes (M€)	11374
Var. Costs (M€)	6384
Fix. costs (M€)	1706
NPV (M€)	368
NPV (€/GJ)	1.20

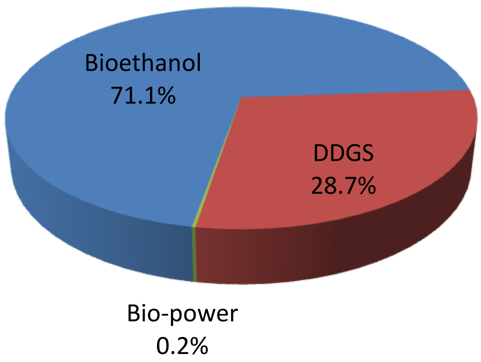

Figure 38 - Share of gross profit by product sold.

From table 14 and figure 38 it is possible to see that the structure proposed by the model is a profitable solution with an NPV of 368 M€. This profit is accomplished, principally, by selling bioethanol and DDGS. The selling of bioethanol represents 71% of the gross profit as in scenario V. The complete supply chain is demonstrated to be profitable with a slight improvement regarding the base case. Nevertheless, the model indicates a preference to bioethanol.

Regarding the costs of the supply chain they can be divided considering the different stages of the supply chain, as figure 39 shows.

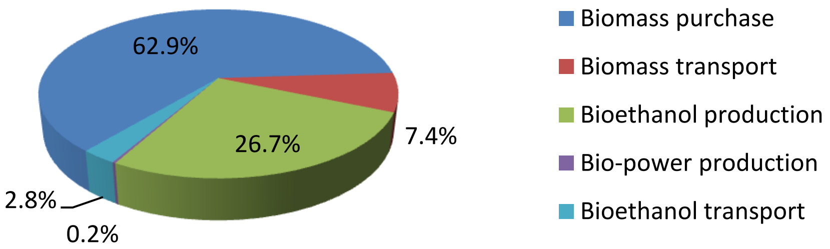

Figure 39 - Costs per supply chain stage for scenario VI.

Figure 39 presents the impact of each supply chain stage in its costs. Biomass purchase, growth and transport account 70.3% of the overall costs. The costs related with bioethanol represent 29.5% of all costs and considered the production and the transport to the blending centers. Bio-power's slice of the costs is very small since it does not have transport cost and the production costs are low.

4.9 Price sensitivity analysis

In this subchapter a sensitivity analysis is made in order to show the influence of the bio-power price in the number of facilities constructed by each technology. This analysis is performed due to the uncertainty associated to this parameter.

4.9.1 Scenario I

The first analysis considers a situation where only DGP and gasification technologies are available for selection by the model.

Table 15 – Number of plants built of each technology *k*, regarding different power prices.

Price (€/MWh)	Technologies	
	DGP	Gasification
200	4	6
190	5	1
180	5	1
160	5	1
100	4	1
80	5	1
66.5	6	-

The results of the sensitivity analysis are exposed in table 15. This results reveal that, unless the gasification process suffers a great improvement or the incentives in order to produce clean energy raise the power price above 200€/MWh, producing bio-power by a gasification process is not the best option. Nowadays, with the governments incentives, the bio-power can be sold at 180€/MWh. At this price, the model suggests the construction of five DGP plants and only one gasification plant. In fact, this optimization is suggested if the price is fixed between 66.5 and 200 €/MWh. However, below 66.5 €/MWh, the introduction of gasification plants is no longer an improvement in the supply chain profitability. Above 200 €/MWh is driven to a situation where gasification is the most selected technology.

4.9.2 Scenario II

The second analysis considers a situation where DGP and combustion technologies are available for selection by the model.

Table 16 - Number of plants built of each technology *k*, regarding different power prices.

Price (€/MWh)	Technologies	
	DGP	Combustion
180	1	5
160	1	7
150	2	7
147	2	6
146	3	5
145	4	4
140	4	4
130	5	1
120	5	1
70	5	1
66,5	5	1

From table 16 it is possible to identify three different regions of interest. The first region is located in the range between 66.5 and 130 €/MWh in which the construction of DGP plants are preferable although the construction of one combustion plant is also suggested. The second region is establishes between 140 and 145 €/MWh and, in this conditions, any technology is privileged. Above that upper price of the last region the model suggests the construction of mainly combustion plants. In this sense, it can be assumed that even if the incentives decrease the power price, until 146 €/MWh, the production of bio-power by a combustion process can compete with the construction of bioethanol plants (by a DGP process).

4.9.3 Scenario III

The third analysis considers a situation where DGP, gasification and combustion technologies are available for selection by the model.

Table 17 - Number of plants built of each technology *k*, regarding different power prices,

Price (€/MWh)	Technologies		
	DGP	Gasification	Combustion
180	-	-	8
160	1	-	7
150	2	-	6
140	3	-	4
138	5	-	1
135	5	-	1
120	4	-	1
66,5	4	-	1

From table 17 two main conclusions can be made. First conclusion is that technology 7, gasification, is not a profitable way to get energy when compared with DGP or combustion. On the other hand, only above 140€/MWh combustion technology starts to emerge as the preferable technology with the implementation of a greater number of facilities. Otherwise, production of bioethanol by DGP is the best option.

4.10 Chapter conclusions

To accomplish the objective of this work, assess the economical performance of a bio-power and bioethanol supply chain, two groups of scenarios were tested. In the first group, three different production scenarios were analyzed and a value of power's price with incentives was considered. The NPV in €/GJ from these three scenarios are presented in figure 40.

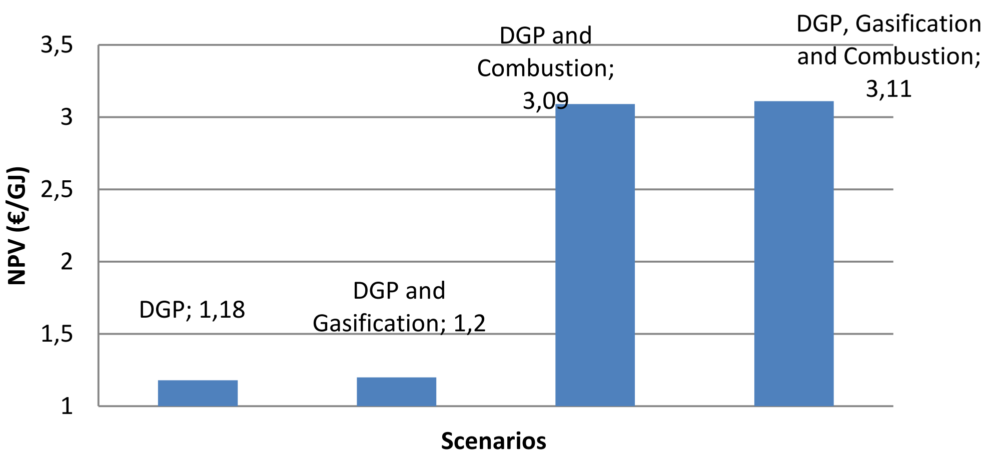

Figure 40 - Economic performance of all supply chain studied with price incentive.

The base case presents the lower value of NPV with 1.18 €/GJ. The test performed using DGP and gasification as technologies revealed a NPV of 1.2 €/GJ that constituted an increase of 1.9%. In fact, the optimization scenario reveal that only 1.1% of all the profit is coming from bio-power sale so this small increase is justified by that.

In scenario II only DGP and combustion could be selected as technology. In this case, the new technology implemented made a great impact in terms of the profitability of the supply chain raising the NPV to 3.09 €/GJ revealing a growth of 62%. This results reveal that, when considered combustion, the NPV more than doubles showing a positive influence in the supply chain. Bio-power is, in this case, the preferable source of profit with 94% of share. This can be linked to two reasons: the production costs in combustion facilities are relatively low and with the fact that the transport costs of bio-power are not considered. Considering the low impact of transport costs in the overall costs, the first reason can be considered to have a greater contribution.

The last optimization scenario of this group accounts DGP, gasification and combustion as technologies that the model can select to produce energy. This scenario shows the best results with a NPV of 3.11 €/GJ. In this case only combustion bio-power plants are built which make this technology the best solution to supply the energy demand in these conditions.

A second approach on the previous scenarios was taken. This new approach optimizes the model using the same technologies and parameters but change the power price to a lower value regarding the possibility of selling the power without fiscal benefits.

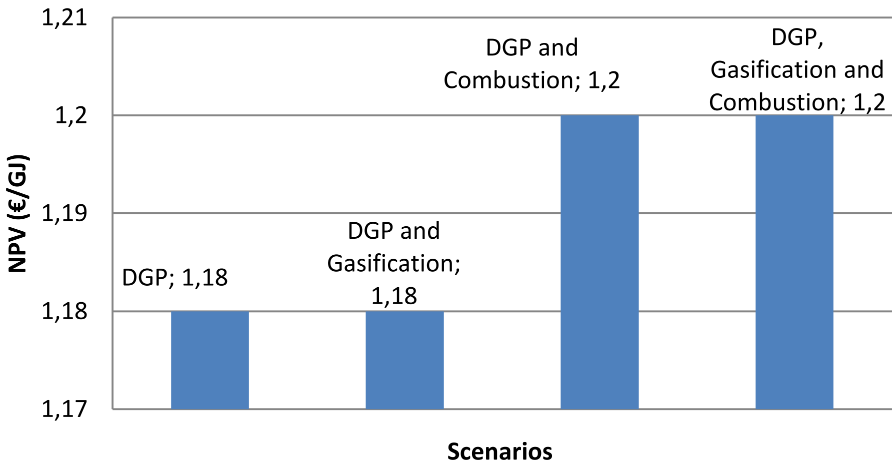

Figure 41 - Economic performance of all supply chain studied without price incentive.

From figure 41 is possible to identify that all optimization scenarios drive the supply chain to approximately the same results. In fact, if the power price is fixed in 66.5 €/MWh the advantage of producing energy by gasification or combustion is not great enough to influence the supply chain significantly. In fact, in this case, all three scenarios of optimization lead the model to suggest the investment in majority bioethanol plants (four to six) and only one (or none) combustion facility. From these results it can be deducted that, at these conditions, bioethanol obtained by a DGP process is the technology that provides a more profitable supply chain and that the production of bio-power does not significantly influence this situation.

By comparing figure 40 and 41 it can be verified that the decrease in bio-power's price implicates a decrease of 1.6%, 61.2% and 61.4% in terms of NPV for each scenario tested.

For all scenarios the computational results are presented in table 18.

Table 18 – Computational results.

	Scenario I	Scenario II	Scenario III	Scenario IV	Scenario V	Scenario VI
Nº variables	467 616	467 616	467 712	467 616	467 616	467 712
Nº binary variables	2 784	2 784	2.880	2 784	2 784	2.880
Gap	0.048932	0.046	0.009094	0.0459	0.0341	0.03658
Time (s)	2.761	2.652	2.668	2.652	3.151	2.636

5. Conclusion and future work

The problem addressed in this thesis was to maximize the economic performance of an energy supply chain, considering bio-power and bioethanol production in Northern Italy. To assess this problem, a mixed integer programming model based on the work of Giarola et al. [3] was applied and implemented in GAMS®.

This problem appears in response to a growing concern of the society to substitute the fossil fuels, principal responsible by the global warming. The model developed assesses the best economic way to supply a clean energy demand, imposed by the EU guidelines, considering that energy can be produced by different technologies: bioethanol, from dry grain process, and bio-power, through a gasification process or through a combustion process.

These technologies are selected taking into account the maturity of the technologies, in bio-power case, and the most profitable solution, considering the work of Giarola et al. [3], in bioethanol case.

A new look on the bioethanol supply chains is given in this thesis where the bio-power supply chain is combine with the first one in order to create energy supply chain. In fact, the work developed focused on the data collection and model implementation of the bio-power part of the energy supply chain. This new perspective creates a tool to analyze the most profitable solution between bioethanol and bio-power. The study of this energy supply chain is a new approach in terms of the transport sector green solutions and a good instrument to find the most profitable way to supply the energy demand.

A set of scenarios were analyzed through the application of the mathematical model. From the first group of scenarios, where bio-power and bioethanol prices are both considered to have tax benefits, it is possible to conclude that producing bio-power from combustion is the best solution followed by bioethanol by DGP and bio-power by gasification. The two first solutions are both economic viable by itself, contrasting with gasification that is not profitable. However, since it is an energy supply chain, certain scenarios of optimization chose a technology as preferable over the others but not exclusively. In those cases the combustion is the dominant process.

In the second group of scenarios, where only bio-power price is considered without tax benefits, the conclusions taken are significantly different. In fact, without the incentives in power price, all scenarios suggest the construction of mainly bioethanol plants.

Regarding these results it is possible to assume that, without the incentives on power price, this solution to supply energy is not preferable to bioethanol. In fact, if the price gets down to 66.5 €/MWh, the production of bio-power is no longer a viable solution by itself, independently if is considered a combustion or a gasification process. Although the scenario in which bioethanol price is considered without incentives was not performed, taking into account the situation of bioethanol production in Brazil, a viable solution without incentives can be possible. In fact, nowadays, bioethanol produced in Brazil does not get direct subsidies to promote bioethanol production [7].

Nowadays, no single alternative such as biofuels or bio-power will, alone, reach environmental goals due to innumerous factors. However, if the governments keep supporting alternative energies, producing bio-power by a combustion process seems to be the best way to reach those targets. Nevertheless, governments cannot continue to support these alternatives forever and, considering that the incentives will slow down, bioethanol produced by DGP emerge as the most promising solution [6].

In order to take this energy supply chain to the next level some adjustments have to be made.

For instance, assuming that bio-power does not have a transport cost associated because it is send directly to the grid is causing an underestimation on variable costs. In a future work it could be interesting to take a deeper look into this step of the supply chain or even include electric cars in the fleet. Another aspect that could be improved is the environmental optimization. In fact, the environmental benefits of the technologies presented are unquestionable but it could be interesting to analyze the reaction of the supply chain when optimized by an environmental point of view.

The model developed is an innovative and useful tool that can, actually, determinate if the energy supply chain sourced by bio-power or bioethanol is or is not a viable solution and, if yes, what is the most profitable structure.

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