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**TESI DI LAUREA SPECIALISTICA IN INGEGNERIA CHIMICA PER LO SVILUPPO SOSTENIBILE**

# Ethanol from corn: analysis of using corn stover to supply heat and power to ethanol plant

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# Abstract

Bioethanol is currently the most important biofuel for automotive transportation and the European Community has set common objectives about the utilization of biofuels for all member states. The current Italian production of bioethanol is not sufficient to achieve these goals. In this work the existing processes for ethanol production from corn and for energy generation from corn stover are analyzed with an exhaustive simulation approach. They are supplemented by local (internal) energy generation used to supply heat and/or electrical power to minimize the energy consumption from fossil sources. Different scenarios are analyzed to determine better, if not the best, way of production of bioethanol from corn while minimizing the energy consumption from fossil sources. An economic and profitability analysis for every scenario is also provided.

# Riassunto esteso

Il bioetanolo da mais è uno dei più importanti combustibili rinnovabili e il suo sviluppo può contribuire alla riduzione degli impatti ambientali derivanti dall'impiego di combustibili di origine fossile. Nel 2009 ne sono stati prodotti in tutto il mondo circa 73.9 miliardi di litri. Il primo produttore, con circa 40 miliardi di litri (e una produzione programmata per il 2022 di circa 56.8 miliardi di litri) sono gli Stati Uniti seguiti dal Brasile. La produzione della Comunità Europea, nel 2009, è stata di circa 3.9 miliardi di litri ed è probabilmente destinata ad aumentare sensibilmente nei prossimi anni.

Data l'importanza dell'etanolo come combustibile rinnovabile, la Comunità Europea ha recentemente fissato degli obiettivi comuni riguardo al suo utilizzo nel settore degli autotrasporti. Una prima direttiva, 2003/30/EC, già recepita dalla normativa italiana, richiedeva a ciascuno stato membro di raggiungere un impiego del 2% di etanolo entro il 2005 e del 5.75% entro la fine del 2010. Tale direttiva è stata seguita dalla 2009/28/EC, che ha fissato nuovi obiettivi: 10% entro la fine del 2020. La scadenza per il recepimento di questa direttiva era fissato per il 5 dicembre 2010.

Nonostante gli obiettivi posti dalla Comunità Europea, la produzione italiana di etanolo è modesta (72 milioni di litri nel 2009) e assolutamente non sufficiente. Risulta quindi chiara la necessità di incrementare tale produzione al fine di raggiungere gli obiettivi comunitari nel più breve tempo possibile. A tale scopo è importante, da un lato, continuare la ricerca per lo sviluppo e la messa a punto di nuovi processi di produzione, sia dall'amido che dalla cellulosa, ma contemporaneamente si deve avviare una filiera produttiva basata sui processi attualmente consolidati e disponibili in commercio, ovvero quelli di prima generazione. Tali processi potranno, in futuro, essere affiancati da quelli di nuova generazione al fine di ridurre progressivamente il consumo di combustibili fossili nel settore degli autotrasporti.

Le principali materie prime utilizzate a livello europeo sono grano e mais. In Italia il mais è la scelta vincente, date le elevate rese ottenibili (da 10 a 14 tonnellate annue per ettaro).

Lo scopo di questa tesi è di dimostrare che, mediante l'utilizzo di *corn stover* (insilato di mais) quale fonte rinnovabile di energia, è possibile ridurre significativamente la richiesta di energia da fonti fossili dei processi per la produzione di etanolo.

Il lavoro è stato quindi suddiviso in tre parti.

La prima parte ha riguardato lo studio dei tre principali processi per la produzione di etanolo da mais: dry milling tradizionale, dry milling con riciclo dei distillers' grains e quick germ – quick fiber. Sono stati considerati solo processi di macinazione a secco in quanto è stato dimostrato che tali processi, rispetto a quelli con macinazione bagnata, presentano rese più elevate e sono contemporaneamente più semplici e meno costosi.

Allo stesso modo sono stati considerati i tre principali processi per la produzione di energia dall'insilato di mais: combustione per la produzione di solo vapore, cogenerazione di energia elettrica e termica e gassificazione per la produzione di energia elettrica.
Per i processi di produzione di etanolo sono stati studiati i seguenti aspetti:

- resa in etanolo [l/kg];
- produzione di DDGS [kg/kg];
- fabbisogno di energia termica [kWh/l];
- fabbisogno di energia elettrica [kWh/l];
- emissioni di $CO_2$ [kg/l];
- scala dell'impianto [Ml/anno];
- investimento [M$].

In modo analogo, per i processi di produzione di energia da insilato sono stati analizzati:

- produzione di energia termica [kWh/ton];
- produzione di energia elettrica [kWh/ton];
- fabbisogno di energia termica [kWh/ton];
- fabbisogno di energia elettrica [kWh/ton];
- emissioni di $CO_2$ [ton/ton di insilato];
- produzione di ceneri [ton/ton di insilato];
- scala dell'impianto [Ml/anno];
- investimento [M$].

L'obiettivo dello studio è stato di reperire tutti i dati necessari per la costruzione di un set di sei modelli, in cui ciascun processo è rappresentato da semplici correlazioni che legano la quantità di materiale trattato (mais o insilato) agli altri parametri (produzione di etanolo, produzione di sottoprodotti, richiesta di energia, etc.). Graficamente, i modelli sono rappresentati come gli elementi di un diagramma di flusso.
Nella seconda parte del lavoro, i sei modelli sono stati combinati per definire nove diversi diagrammi di flusso che rappresentano le nove possibili combinazioni. Ogni configurazione è composta da un processo per la produzione di etanolo accoppiato ad un processo per la produzione di energia da insilato al fine di minimizzare l'apporto esterno di energia da fonti fossili.
Nella terza ed ultima parte della tesi si sono poste a confronto le diverse configurazioni ottenute. A tal fine, è stata fissata, per tutte le configurazioni, una produzione di 75 Ml/y di etanolo e sono stati calcolati a ritroso i seguenti parametri:

- quantità di mais necessaria;
- estensione del terreno richiesta;
- quantità di insilato disponibile;
- quantità di energia elettrica e termica richieste dal processo per l'etanolo;

- quantità di energia elettrica e termica richieste dal processo per l'insilato;
- quantità di energia elettrica e/o termica prodotte dal trattamento dell'insilato;
- produzione di sottoprodotti;
- emissioni di $CO_2$.

Sulla base di tali dati sono stati calcolati i costi e i ricavi operativi per ciascuna configurazione, al fine di determinarne il profitto. Sono stati presi in considerazione i costi relativi a mais, insilato, energia elettrica, gas naturale, ed il costo di smaltimento delle ceneri. I ricavi includono etanolo, DDGS, proteina, crusca, olio di mais ed energia elettrica. Successivamente, sono stati calcolati anche i costi di impianto per ciascuna configurazione sulla base dei valori reperiti in letteratura. Tali costi, riferiti a diverse scale di impianto e a diversi anni, sono stati tutti aggiornati al primo quadrimestre del 2010 utilizzando l'indice di Marshal and Swift. Una volta aggiornati, i costi dei diversi processi sono stati riscalati considerando le dimensioni di impianto calcolate per ciascuna configurazione.

È stata inoltre condotta un'analisi di redditività considerando una vita utile dell'impianto di 20 anni ed un periodo di realizzazione di 2 anni. Per l'ammortamento è stato utilizzato un approccio a quote costanti distribuite su 10 anni considerando un tasso di interesse del 5%. Sulla base di questi dati sono stati calcolati tre indici di redditività: periodo di rimborso, valore attuale netto (NPV) e tasso interno di rendimento (IRR). Per poter considerare il processo redditizio, sono stati quindi definiti dei limiti per ogni parametro: periodo di rimborso inferiore a 20 anni, valore attuale netto maggiore di zero e tasso interno di rendimento maggiore del 10%.

Infine, è stata condotta un'analisi di sensitività al variare dei costi di materie prime, energia e del valore di mercato dei prodotti. In questo modo è stato possibile verificare quali configurazioni, considerate redditizie con i dati relativi all'anno 2010, rimangono tali anche in seguito ad ampie variazioni dei prezzi.

Analizzando le configurazioni ottenute, la migliore è sembrata essere quella costituita da un processo di quick germ – quick fiber per la produzione di etanolo e da un processo di cogenerazione di energia termica ed elettrica dall'insilato. Con una simile configurazione è infatti possibile produrre 75 milioni di litri di etanolo all'anno senza l'apporto di energia termica o elettrica dall'esterno. Infatti tutta l'energia richiesta è prodotta dall'insilato di mais disponibile. Inoltre viene prodotta energia elettrica in eccesso che può essere venduta. Va inoltre sottolineato che questi risultati sono ottenuti processando il 79% dell'intero quantitativo di insilato disponibile, contribuendo quindi a contenere le dimensioni e i relativi costi di impianto.

L'analisi economica ha confermato che la migliore configurazione è quella appena descritta (quick germ – quick fiber e cogenerazione): essa presenta infatti i più elevati IRR e NPV fra quelli calcolati, 13.4% e 83.4 M$ rispettivamente. Allo stesso tempo garantisce il più breve periodo di rimborso, 6.5 anni, ed è la configurazione che meglio sopporta le variazioni dei prezzi studiate nell’analisi di sensitività. Questo è legato al fatto che non richiede l’apporto di energia dall’esterno ed è in grado di produrre un elevato numero di prodotti (proteina, olio di mais e crusca), non solo etanolo e DDGS come la maggior parte delle altre configurazioni, garantendo quindi una maggiore flessibilità.

Purtroppo, questa configurazione presenta una elevata richiesta di suolo per le coltivazioni (poco meno di 16000 ettari) a causa della ridotta resa in etanolo del processo quick germ – quick fiber. Allo stesso tempo è l’opzione con il più elevato costo di impianto. È quindi necessario sottolineare che sono state individuate altre due configurazioni con redditività di poco inferiori ma con costi di impianto significativamente più contenuti. Entrambe queste alternative utilizzano un processo quick germ – quick fiber per la produzione di etanolo e si differenziano solo per il processo di generazione di energia. La prima utilizza un processo di combustione mentre la seconda uno di gassificazione.

Si può quindi concludere che la redditività è principalmente legata al tipo di processo utilizzato per la produzione dell’etanolo e solo secondariamente a quello per la produzione di energia. Va però tenuto in considerazione che, in tutte le configurazioni con un processo di gassificazione, sono state utilizzate solo piccole percentuali dell’intero quantitativo di insilato disponibile (15÷22% circa) al fine di contenere i costi di impianto. Tale tecnologia ha infatti costi di impianto decisamente superiori rispetto alla combustione e alla cogenerazione. Si suggerisce quindi, di studiare la possibilità di aumentare i quantitativi di insilato processati per incrementare la produzione di energia elettrica.

# Index

# Introduction

Ethanol is one of the most important renewable fuels contributing to the reduction of negative environmental impacts generated by the utilization of fossil fuels. In 2009 about 19.5 billion gallons (73.9 billion litres) was produced worldwide. It is evident that the United States are the biggest world producer with 10.6 billion gallons (40.1 billion litres) produced in 2009 and a projected production of 15 billion gallons (56.8 billion litres) in 2022, while Brazil is a close second. At the same time, the European Community produced about 1.04 billion gallons in 2009 (3.9 billion litres) with likely increase in years to come (RFA – 2010 Ethanol Industry Outlook). Given the importance of bioethanol as a renewable fuel, the European Community has recently set common objectives for all member states regarding the utilization of bioethanol in the automotive sector. The first directive, the 2003/30/EC, that is already implemented in the Italian law, was followed by the 2009/28/EC, for which the deadline for the transposition in the member state's law was December 5$^{th}$ 2010. The first directive required the members states to reach the utilization of 2% of bioethanol in 2005 and 5.75% in 2010 while the second one raises the percentage of bioethanol that have to be used. The new objective is to reach 10% by the end of 2020 (http://europa.eu/).

In Europe, ethanol is mainly obtained by the fermentation of both wheat and corn, depending on the country. In Italy, the favourite feedstock is corn because of very high yields that can be obtained, especially in northern Italy (10÷14 tonnes/ha per year). However, the Italian production of ethanol as a biofuel has just started (72 million litres in 2009). It is therefore clear the need of new plants for ethanol production. From this point of view it is important to continue the research for the conversion of starch and for new renewable fuels. It is also important to reach as soon as possible the objectives set by the European Community, and the technology definitely matures and already commercial, that can be used for this purpose, are relative to the first generation of biofuels. Therefore this thesis work will focus on this type of processes.

The aim is to study the most important processes for ethanol production from corn and for energy generation from corn stover with an exhaustive simulation approach. These processes are supplemented by local (internal) energy generation used to supply heat and/or electrical power to minimize the energy consumption from fossil sources. In this way different configurations of ethanol from corn processes will be defined and compared on a technical, economic and profitability base. The main objectives of this work are then to demonstrate that by using corn stover it is possible to reduce significantly the energy intake from fossil sources. It is also hoped that it will possible to define a configuration that ensures the largest profitability.

The work is divided in three main parts.

The first part is a review of existing processes for ethanol production and for energy generation from corn stover. The processes that have been taken into account for ethanol production are traditional dry milling, dry milling with recycle of distillers' grains and quick germ – quick fiber. This is because the dry milling process is proven to have higher yield compared to the wet milling one and it is also less complex and less capital-intensive (Drapcho et. al. – 2008). The processes for treatment of corn stover are combustion for heat generation, combustion for combined heat and electricity generation and gasification. For each ethanol process, data about the ethanol yield, by-products' yields and energy required have been researched and reported. At the same time, for every process for the treatment of corn stover, data regarding the amount of thermal and/or electrical energy that can be produced, internal energy consumption, ash production and environmental emissions has been studied.

In the second part, all the data described in the literature review have been summarized representing each process with a simplified model that is a flow diagram with input, output and side effects. Once built the sets of model for ethanol and corn stover processes, they have been combined to define nine different configurations. In each one of them the energy produced by the treatment of corn stover is supplied to the ethanol plant to minimize the use of energy from fossil fuels.

In the third and last part of the work, the different configuration have been compared considering economic and profitability criteria by setting the ethanol production to 75 Ml/y for all the configurations. First of all the operating costs, incomes and profit for every configuration have been calculated. Then the plant costs have been determined. On the base of these economic data, a profitability analysis calculating discounted payback period, discounted cumulative cash position (NPV) and discounted cash flow rate of return (IRR) for every configuration have been carried out. Then the profitability's trend over time has been studied considering the last four years as a time range. As a result, it has been possible to determine which is the best configuration, among those taken into account, considering prices and economic parameters for the first four-months period of 2010. Moreover it has been possible to check if the best configuration remains the same changing the prices and economic parameters by a sensitivity analysis.

# Chapter 1

# Literature review

In this chapter all the processes taken into account for ethanol production and for the treatment of corn stover are described. Then, for each ethanol process, data regarding the ethanol yield, by-products yields, energy required and environmental emissions are reported. In the same way, for the corn stover processes, are reported data about the amount of thermal and/or electrical energy that can be generated, ash production, energy required and environmental emissions. Moreover the plant's costs as found in literature were summarized.

## 1.1 Ethanol processes

The processes for ethanol production taken into account are traditional dry milling, dry milling with recycle of distillers' grains and quick germ – quick fiber. Only processes of dry milling have been taken into account because dry milling is less complex and capital intensive compared to wet milling and it has also a higher ethanol yield (Drapcho et. al. – 2008; Bothast and Schlicher - 2004). However, in the wet milling process, corn is fractionated and only the starch fraction is then fermented. In this way wet milling can produce valuable by-products such as corn gluten feed and corn gluten meal.

### *1.1.1 Traditional dry milling*

In the dry milling process, the entire corn kernel is ground into a coarse flour and then slurred with water to form a mash. The mash is then cooked because the corn endosperm starch cannot be used directly by yeast but it must be first broken down into simple sugars. To accomplish this process, enzymes are added to the mash during cooking. To break down the starch molecule an alpha-amylase enzyme and steam are utilized and usually the temperature is above 100°C. This part is called gelatinization and liquefaction. The next step involves adding gluco-amylase enzyme at a lower temperature (80÷90°C) to produce smaller fermentable sugars (the major part is glucose) and it is called saccharification. The following step is the fermentation that is carried out at about 32°C and adding yeast. This is a long operation that requires 48÷72 hours and the final ethanol concentration in the beer is 10÷12%. Both saccharification and fermentation can be carried out simultaneously to improve the energy efficiency and also the ethanol yield of up to 8%. At this point the ethanol is separated by distillation from the solids and water in the mash. The resulting component is alcohol with a concentration of 95%: to reach a concentration of 100%, the modern dry grind ethanol plants use a molecular sieve system. The anhydrous ethanol is then mixed with a 5% of denaturant. The solid and liquid fraction remaining after the ethanol separation, is called whole stillage. Usually, this product is centrifuged and the 15÷30% of the liquid fraction is recycled as backset. The other part of the liquid fraction is concentrated by evaporation and then mixed with the solid residue from the fermentation. This product is known as wet distillers' grains with solubles (WDGS). WDGS normally has a moisture content of 65% and so they have a short life, 1 or 2 weeks. To increase shelf-life and reduce transportation cost, the moisture content can be reduce to 10÷12%. The new product obtained is DDGS and it can be sold as animal feed (Bothast and Schlicher 2004; Drapcho et. al. 2008).

A reasonable ethanol yield value for the dry milling process is 2.8 gallons per bushel of corn (0.42 l/kg) while the amount of DDGS produced is 8.6 kg/bu (0.34 kg/kg). Considering the energetic facet, the dry milling process requires 3.1 and 28.5 kWh/bu of electricity and heat (steam at about 0.4 MPa and 110°C), respectively. These two values reported for litre of ethanol produced are 0.29 and 2.69 kWh/l, respectively. The last facet is the environmental effect. The amount of $CO_2$ emitted for every bushel of corn treated is 8.4 kg/bu (0.79 kg/l of ethanol).

The capital cost found in literature and used as a base for investment calculation, which is referred to a 100 million gallons per year plant (379 Ml/y), amounts to 148.26 M$ (Perkis et. al. 2007).

### *1.1.2 Dry milling with recycle of distillers' grains*

In the traditional dry milling, distillers' grains are recovered and used as animal feed. However, because of their high content of polymeric sugar that have not been used during the dry grind process, distillers' grains have potential useful not only as an animal feed, but also as an additional source of fermentable sugar to increase the ethanol production. In this modification of the traditional dry milling, the material from the bottom of the distillation column is pre-treated with a heating process and a subsequent hydrolysis of polymeric sugars and residual starches by an optimum mixture of enzymes including amylase, cellulases and hemicellulases. Then, the sugar-rich liquid is separated to be recycled back through the original hydrolysis and fermentation processes. The remaining distillers' grains not recycled are dried and sold as eDDGS, an animal feed with higher protein levels than conventional DDGS. Unfortunately, eDDGS does not show an increase in value compared to DDGS because of loss of lysine that is a particularly important amino acid in the animal diet (Kim et. al. 2007; Perkis et. al. 2007).

It has been shown that the modified dry milling process ethanol yield is about 21% higher than the conventional process one (3.4 gal/bu; 0.51 l/kg) while the production of DDGS is smaller than the traditional one, and it is 7.7 kg/bu (0.3 kg/kg). Regarding the energy required, there is a rise in both electrical and thermal energy demand that are respectively 4.6 and 39 kWh/bu (0.35 and 3.03 kWh per litre of ethanol produced), resulting in +23% and +12.7%. The amount of $CO_2$ generated per every bushel of corn is 9.7 kg/bu (0.75 kg/l).

The plant cost considered as a base value is 158.45 M$ for a 112.67 million gallons per year (427 Ml/y) production (Perkis et. al. 2007).

### *1.1.3 Quick germ – quick fiber*

The two processes described above are designed to ferment as much of the corn kernel as possible. Ethanol, distillers dried grains with solubles (DDGS) and $CO_2$ are the materials generated with these processes. This means that there are only two valuables products; ethanol and DDGS. As a result these kinds of processes are exposed to fluctuation in prices of corn and ethanol and have suffered in the past due to the high degree of dependence on these prices.

The quick germ – quick fiber process allows removal of germ and pericarp fiber at the beginning of the dry milling. The advantage of this process is that the recovered germ and fiber can be further processed to generate valuable by-products such as bran, protein and oil. At the same time the removal of fiber and germ can increase the protein content of DDGS making this product suitable for non-ruminant diet animals such as swine and poultry. The last facet is an improvement of fermentation efficiency.

The front end of the quick germ – quick fiber process is similar to the conventional wet milling and involves soaking whole corn with water (typically without chemicals) for 3÷12 hours at the temperature of about 60°C and then using a conventional mill for degermination. Subsequently, both fiber and germ can be separated from the remaining slurry by hydrocyclones due to the density differences. The mixture of the germ and pericarp are then dried and separated using an aspirator, whereas the rest of the corn is ground wet and then processed by normal dry milling methods (Changying Li et. al 2010; Luis F. Rodrigues et. al. 2010).

A typical ethanol yield for a quick germ – quick fiber process is 2.69 gal/bu (0.4 l/kg) while the by-products yields for DDGS, bran, protein and oil are respectively 4.5, 1.78, 1.78 and 1.27 kg/bu (0.18, 0.07, 0.07 and 0.05 kg/kg) (NREL 2009). Regarding the energy facet, this process requires 3.3 kWh/bu (0.32 kWh/l) of electricity and 21.8 kWh/bu (2.14 kWh/l) of heat. The $CO_2$ specific emission is 8 kg/bu (0.79 kg/l).

The capital cost for a quick germ – quick fiber process is about 39% higher in comparison to a traditional process. The value considered as a base is 111.14 M$ and it is for a production of 42 million gallons per year (160 Ml/y).

## 1.2 Corn stover processes

The processes to generate energy from corn stover taken into account here are combustion for process heat generation (PH), combined heat and electricity generation (CHP) and gasification. In this paragraph a brief description of each process and all the data needed for the simplified model's construction are reported.

### *1.2.1 Process heat (PH) generation*

At present, the primary fuel used to generate process heat is natural gas while the electricity comes from power grids. Fluctuations in natural gas and electricity prices may reduce the profitability of ethanol production. For this reason the utilization of biomass (corn stover) as a source of energy can be useful. At the same time, this can have positive effects on the environmental emissions during the life cycle of ethanol corn.

The proposed process consists of a biomass fired steam boiler which generates saturated steam at 0.5 MPa and 152°C used to supply process heat to the ethanol plant. The flue gas from the combustor is released to the atmosphere through multicyclone and electrostatic precipitation. The thermal efficiency is estimated to 80%.

The process burns 121270 tonnes of corn stover generating 52.3 MW of heat constantly throughout the year. It means that for every ton of stover burned, the process generates 3515 kWh of heat. The specific $CO_2$ emitted is 234.6 ton/MW while the ash yield is 0.08 ton/ton of stover. Regarding the energetic facet, the internal electricity consumption is the 2% of the thermal input of the plant.

The plant cost is 18.89 M$ on the basis of generating 52.3 MW of thermal energy, as reported by (Mani et. al. 2009).

### *1.2.2 Combined heat and electricity generation (CHP)*

This process is able to produce thermal and electrical energy with a heat to power ratio of 5.5 and an overall efficiency of 83.3%. The CHP is a biomass fired back pressure turbine system. In this process, the corn stover is combusted in the boiler to produce high pressure steam which drives a steam turbine. The turbine converts the thermal energy into mechanical energy, which is then converted into electricity by the generator. The resulting condensed steam is fed to the boiler for reheating.

The process taken into account generates 9.5 MW of electricity and 52.3 MW of thermal energy by processing 137450 tonnes of corn stover, hence securing specific thermal and

electrical productions of 380.5 and 69.1 W/ton respectively. The heat generated is steam at 0.5 MPa and temperature of 152°C. As for the PH generation system, the internal electricity demand is the 2% of the thermal input of the plant, and the ash production is 0.08 ton/ton. The specific $CO_2$ emission is 0.10 ton/ton of stover.
The total investment for this plant is 38.15 M$, as reported in Mani et. al. 2009.

### *1.2.3 Gasification*

Thermochemical gasification is a process that converts biomass feedstock into a gas containing CO, $H_2$, $CH_4$, $CO_2$ and $N_2$. Gasification operates at high temperature and requires the presence of catalysts and oxidizing agents. It is possible to use different kinds of feedstock and the gas obtained (syngas) can be used to produce energy or a wide range of chemicals. For this work, only the energy generation from the syngas has been taken into account.
The process considered here consists of two main parts; gasification reactor and CHP system. The gasification section is a combination of two reactors and a separator. In the first reactor occurs a pyrolysis process while the gasification reactions are carried out in the second one. The separator is interposed between the two reactors with the purpose to remove char. The gas produced by the optimized gasification section is supplied to the CHP generation system. The main component of the CHP process are combustor, gas and steam turbine. The combustion product gas is fed to the gas turbine that generates electricity. The exhaust gas from the gas turbine are then used in a boiler to generate steam which drives the steam turbine. The heat of the steam discharged by the steam turbine is recovered in a heat condenser to produce hot water. It is therefore clear that the CHP process is optimized for the electricity production and the heat is a kind of by-product that can be used for space heating. A detailed description of the process and operating condition is provided by Kumar et. al. 2010.
Regarding the energy facet, the reaction section is an energy intensive process. In fact it requires 0.64 kg of air at 400°C, and 1.47 kg of steam at 400°C and 1 atm, per kg of biomass. Given that the air compressor is driven by the gas turbine, the CHP process does not require additional energy. As a result the overall process only needs thermal energy for producing air and steam at the specified conditions.
The process taken into account is fed with 2000 kg/h of stover, and it is able to produce 4.63 MW of electrical power and 6.12 MW of heat by condensing and cooling the product gas. The electrical and thermal efficiencies are respectively 37% and 49%, and the plant cost is 12.4 M$.
Considering the environmental facet, this process generates 0.415 kg of $CO_2$ per kg of biomass while the ash production is 0.08 kg/kg.

## 1.3 Aim of the work

The main objective of the thesis is to demonstrate that by using corn stover it is possible to significantly reduce the energy intake form fossil sources. At the same time, it is hoped that it will possible to define a configuration, composed of an ethanol process and a corn stover one for energy generation, able to ensure a large profitability.

All the data regarding the three ethanol process taken into account, and described in the this chapter, are reported in Table 1.1.

**Table 1.1:** *Performances and costs for ethanol processes*

| | Traditional dry milling | Dry milling with recycle of distillers' grains | Quick germ – quick fiber |
|---|---|---|---|
| **Ethanol yield [l/kg]** | 0.42 | 0.51 | 0.4 |
| **DDGS yield [kg/kg]** | 0.34 | 0.3 | 0.18 |
| **Bran yield [kg/kg]** | - | - | 0.07 |
| **Protein yield [kg/kg]** | - | - | 0.07 |
| **Oil yield [kg/kg]** | - | - | 0.05 |
| **Heat request [kWh/l]** | 2.69 | 3.03 | 2.14 |
| **Electricity request [kWh/l]** | 0.29 | 0.35 | 0.32 |
| **Plant scale [Ml/y]** | 379 | 427 | 160 |
| **Capital cost [M$]** | 148 | 158 | 111 |
| **$CO_2$ emissions [kg/l]** | 0.79 | 0.75 | 0.79 |

Table 1.2 summarizes all the data for the energy generation processes from corn stover.

**Table 1.2:** *Performances and costs for energy generation processes*

| | Process heat generation | Combined heat and electricity generation | Gasification |
|---|---|---|---|
| **Heat produced [kWh/ton]** | 3515 | 3101 | 3060 |
| **Electricity produced [kWh/ton]** | - | 563 | 2315 |
| **Heat request [kWh/ton]** | - | - | 1435 |
| **Electricity request [kWh/ton]** | 90 | 90 | - |
| **Plant scale [ton/y]** | 121270 | 137450 | 16300 |
| **Capital cost [M$]** | 18.9 | 38.15 | 12.4 |
| **$CO_2$ emissions [ton/ton]** | 0.1 | 0.1 | 0.4 |
| **Ash yield [ton/ton]** | 0.08 | 0.08 | 0.08 |

# Chapter 2

# Methodology

In this chapter the methodology used to compare different processes for ethanol production and for energy generation from corn stover will be described. First, it will be discussed how the processes models have been built and then how they have been combined to define the overall configurations of ethanol plant and energy generation process. Finally, the profitability analysis developed will be explained.

## 2.1 Processes' models

One of the objectives of this work is to model different configurations for corn ethanol process and energy generation process from corn stover. The final aim is to find the best configuration, among the alternatives taken into account, to produce ethanol with a view to reducing the energy utilization from fossil fuels.

One way of screening the considered options is by building mathematical models of different process that can be combined to define the overall configurations. It has been chosen to build a model of each single process for ethanol production and for energy generation from corn stover.

The first step for the models building is the selection of the most important processes, which are traditional dry milling, dry milling with recycle of distillers' grains and quick germ – quick fiber for ethanol production and combustion, combined heat and electricity generation and gasification for energy generation from corn stover. Then, data for different facets, such as energy consumptions, main product and by-products yields, etc, has been provided. On the base of the available data, the model of each process has been built.

In the approach developed, a process is represented as a flow diagram with a several streams: input, output, and side effects. In all cases, there are a main input (corn), a main output (ethanol) and the side effects are divided in valuable by-products and environmental emissions. Only DDGS for the traditional dry milling and dry milling with recycle and four by-products (DDGS, protein, bran and oil) for quick germ – quick fiber are considered as useful by-products. The environmental effects (emissions) are represented as kilograms of carbon dioxide emitted per litre of ethanol produced. The last facet shown in the models is the energy required, in the form of electricity and/or heat. The heat required is steam at about 0.4 MPa and 110°C for all the ethanol processes.

For all the energy generation processes, the main input is corn stover, the outputs are electricity and/or heat generated, while the main by-product is ash. As for the ethanol processes, the environmental effects are shown as kilograms of carbon dioxide emitted, but this time it is per tonne of stover processed. The thermal and/or electrical energy requests, expressed per tonne of stover processed, are also reported.

The exhaustive simulation approach is proven to be suitable for screening different options. In fact, if the mathematical models are not complex, they allow for comparison of different processes and configurations taking into account most important aspects of every option. In this way it is possible to identify which process has the higher ethanol yield, for the ethanol processes, or which one shows the larger conversion efficiency, among the energy generation processes. As a result, it has been possible to identify the best configuration to produce ethanol hence reducing the energy request from fossil fuels and, at the same time, maximizing the economic performances.

## 2.2 Overall configurations models

In the first part of the work, a set of models for the considered processes has been built. Six models are available, three for ethanol production and three for energy generation. The next step involved the definition of the overall configurations that are composed of one process for ethanol production and one for energy generation. The two processes are strictly linked because the energy generated by the treatment of corn stover is supplied to the ethanol plant to reduce the use of energy from fossil sources. In this way, nine configurations have been built and compared to determine which one is the best considering different facets: soil required, energy request, environmental emissions, ethanol yield and economic performances.

For the sake of comparison, the same level of ethanol production was set for all the configurations: 75 million litres per year. This scale has been determined on the basis of the Italian gasoline consumption for 2008 and the objectives set by the European Community.

Given the scale of the ethanol plant, all other data have been calculated accordingly:

- amount of corn required;
- soil required;
- corn stover available;
- electrical and thermal energy required by the ethanol and the stover plant;
- amount of thermal and/or electrical energy generated from corn stover;
- amount of by-products;
- environmental emissions.

The amount of corn needed to produce 75 million litre of ethanol has been determined on the basis of ethanol yield characteristic of each process. Then, the required soil has been calculated considering a corn yield of 12 ton/ha. The corn stover production has been calculated on the basis of the rule of one tonne of stover above ground per tonne of corn harvested. However, the corn stover that can be sustainability collected is about 30÷35% of the global stover production (Kiran and McMillan – 2002).

The others parameter reported in the above list are all characteristic of a single processes and they have been calculated from data found in literature.

As described above, the energy generated from the treatment of corn stover has been supplied to the ethanol plant. However, the energy that can be generated from the available amount of corn stover has never been equal to the amount required by the ethanol plant. Therefore, for some cases it has been necessary to use natural gas to generate steam and buy electricity from the grid to reach the energy request of the ethanol plant. In other cases, it has been necessary to reduce the amount of stover processed or sell the excess electricity.

## 2.3 Economic and profitability analysis

After the engineering comparison between options described in the previous paragraph, an economic analysis has been carried out. It is very important to note that this is only *an order of magnitude analysis* with the aim of screening different options, not to provide absolute accurate figures.

For each configuration, costs and incomes to calculate the profit have been determined. The costs taken into account are costs associated with corn, corn stover, electricity, natural gas together with ash disposal cost. Incomes include incomes from ethanol, DDGS, protein, bran, oil and electricity. Some other costs, such as the labour, have not been taken into consideration here. From the costs and incomes, the profit for each configuration has been calculated. After the definition of the operating costs, the plant costs have been calculated and analyzed.

The prices we have referred to are those for the first quarter of 2010 and they are reported in Table 2.1 together with the respective references.

**Table 2.1:** *Prices for the first four-months period of 2010*

| | Price | Reference |
|---|---|---|
| Corn [$/bu] | 3.42 | USDA market news |
| Corn stover [$/ton] | 19.6 | Sokhansanj et. al. 2002 |
| Electricity [$/kWh] | 0.176 | Autorità per l'energia elettrica e il gas |
| Natural gas [$/m$^3$] | 0.43 | Eurostat |
| Ethanol [$/gal] | 1.63 | USDA market news |
| DDGS [$/ton] | 105.6 | USDA market news |
| Bran [$/ton] | 92.02 | USDA market news |
| Protein [$/ton] | 400 | Dickey et. al. 2010 |
| Oil [$/ton] | 893 | USDA – Oil crops outlook 2010 |
| Selling electricity [$/ton] | 0.098 | Autorità per l'energia elettrica e il gas |
| Ash disposal cost [$/ton] | 100 | Mani et. al. 2009 |

### *2.3.1 Plant costs*

The plant costs have been calculated by updating and rescaling the plant costs found in literature. In fact, the data from literature are reported for different years and different plant scale. Here, every cost has been rescaled to the first quarter of 2010 using the Marshal and Swift cost index as calculated by:

$$C_2 = C_1 \cdot \left(\frac{I_2}{I_1}\right) \tag{2.1}$$

where *I* is the Marshal and Swift cost index and *C* is the plant cost.
At this point, the costs have been rescaled according:

$$C_a = C_b \cdot \left(\frac{A_a}{A_b}\right)^{0.6} \tag{2.2}$$

where *C* is the cost and *A* is the equipment cost attribute. For the ethanol plant, the cost attribute is the ethanol production while, for the energy generation process, it is the amount of corn stover processed.
In this way, the plant cost for each process and also the overall configuration plant cost have been calculated. Then, the operating and plant costs are used for the profitability analysis described in the following Section.

### 2.3.2 Profitability analysis

The profitability analysis has been carried out considering a plant life of 20 years and a construction period of 2 years. In addition, a straight line depreciation method of 10 years with an interest rate of 5% was assumed. The working capital and the savage value were respectively calculated as the 15% and the 3% of the capital investment, as described by Douglas – 1988. The soil cost has not been taken into account. From these data, three profitability parameters, discounted payback period, discounted cumulative cash position (NPV) and discounted cash flow rate of return (IRR) were calculated. The criteria are one for each base that can be used to evaluate the profitability: time, cash and interest rate.

In addition, limits were set for every parameter: the payback period must be shorter than 20 year, the NPV must be greater than zero and the IRR should be bigger than 10% to consider the process profitable. In fact, if one of this parameter is outside the imposed limits, the process has been considered uneconomic. The limit of 10% of the IRR has been chosen because the actual “cost of money” is very low but it is expected to rise in the near future.

### 2.3.3 Profitability trend over time

The profitability analysis given in the previous Section was carried out on the basis of prices in the first four-month period of 2010. However, some prices have seen wide variations in the last few years and they could have the same behaviour in the future. Considering this fact, a process that seems to be profitable with the 2010 prices, could become uneconomic with the prices of another year. It has been accordingly decided to study the profitability trend over time. The analysis has been conducted recalculating the economic parameter (payback period, IRR and NPV) for every 4-months period from the beginning of 2006 to the first quarter of 2010. This period showed wide variations of prices and, for this reason, results can be representative of a most wide period of time.

As a result, a process has been considered profitable when it has shown acceptable economic results for the whole period of time taken into account.

# Chapter 3

# Results and discussion

Given a 75 Ml/y ethanol plant, the engineering and economic performance comparison between different options is described in this chapter. Every option is the union of one process for ethanol production from corn and one process to obtain energy from corn stover. The two processes are linked and the energy produced by the treatment of corn stover is supplied to the ethanol plant as described in the previous chapter.
Three processes for ethanol production were taken into account (traditional dry milling, dry milling with recycle of distillers' grains and quick germ – quick fiber) and three for the treatment of corn stover (combustion for heat generation, combined heat and power generation and gasification).
A description of the models of individual processes is given first.

## 3.1 Models of processes for ethanol production

The model with mass and energy balance for each process is reported below and it has been built on the basis of the data described in the literature review and summarized in Table 1.1.
The model of the traditional dry milling process is given in Figure 3.1 and it has been defined considering the data reported in Section 1.1.1.

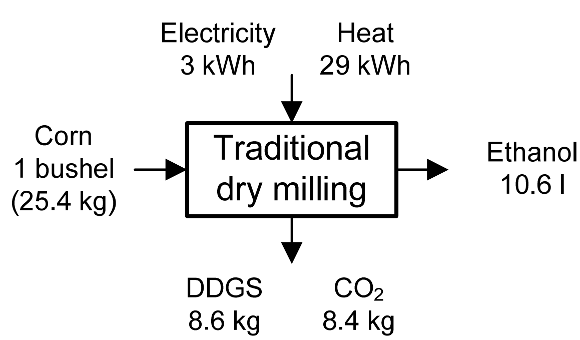


**Figure 3.1:** *Traditional dry milling's model*

The traditional dry milling model, as all the others, is scaled down to 1 bushel of corn (25.4 kg). In this kind of representation only input, output, side-products and energy

required are reported. In this process, the electrical energy required for each litre of ethanol is 0.29 kWh/l while the thermal one is 2.69 kWh/l.
Figure 3.2 shows the model of the dry milling with recycle of distillers' grains process based on the data reported in Section 1.1.2.

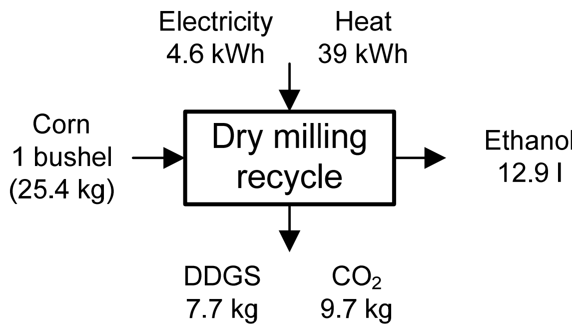


**Figure 3.2:** *Model of dry milling whit recycle process*

The consequence of the recycle of distillers' grains is an increased production of ethanol compared to traditional process (~21%) while the production of DDGS is lower than the one from traditional process (~10.5%). Moreover, the process with recycle requires more energy (both electrical and thermal) and produces a larger amount of $CO_2$ (~16%). The electrical energy required is 0.35 kWh/l and the thermal one is 3.03 kWh/l.
Analysing these data, the process with recycle seems to be better than the traditional one considering ethanol yield, while the traditional one seems to be better from the point of energy required and environmental emissions. The issue will be detailed when the two processes are combined with those for energy generation from corn stover.
Figure 3.3 shows the quick germ – quick fiber process model based on the data described in Section 1.1.3.

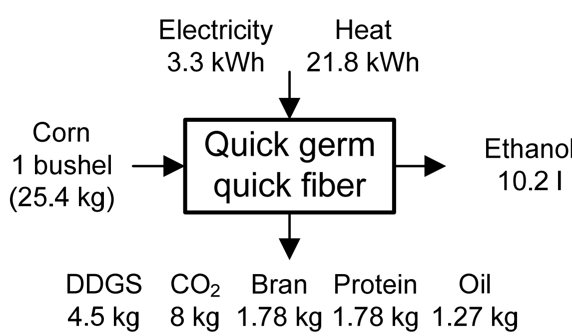


**Figure 3.3:** *Quick germ - quick fiber model*

This process seems to be better than those already described because it produces almost the same amount of ethanol than the traditional one (-3.77%; 10.2 l/bu instead of 10.6 l/bu), it requires less thermal energy (~24.8%) and almost the same amount of electrical energy (~10%) in comparison to the one with recycle. So, the electrical and thermal energy required are respectively 0.32 and 2.14 kWh/l. But the real strength of this process is the large number of valuables by-products (bran, protein and oil) that make it more flexible with respect to the others.

## 3.2 Models of processes to generate energy from corn stover

All the processes have been defined considering the data described in Section 1.2 and summarized in Table 1.2.
Figure 3.4 shows the model of the combustion process to generate heat (PH, Process Heat; data from Section 1.2.1).

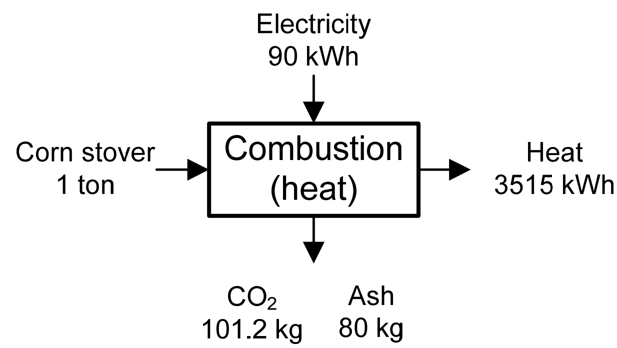


**Figure 3.4:** *Model of combustion process for heat generation*

The heat generated is steam at 0.5 MPa and temperature of 150°C. In every model data regarding the $CO_2$ emission are also reported because they will be used later to define quantity (in tonnes) of $CO_2$ emitted per litre of ethanol produced. Clearly, this will be done after the definition of the overall configurations.
Figure 3.5 shows the model of the combined heat and power generation process (CHP, Combined Heat and Power; data from Section 1.2.2).

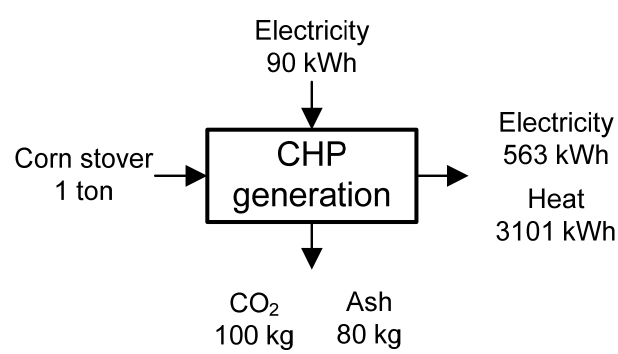


**Figure 3.5:** *Model of combustion process for heat and electricity generation*

The heat produced is steam at 0.5 MPa and 150°C as in the previous process. The overall CHP efficiency is 83.3%, that is greater than the one for PH, 80% (S. Mani et. al. 2009). Figure 3.6 shows the gasification process's model (data described in Section 1.2.3).

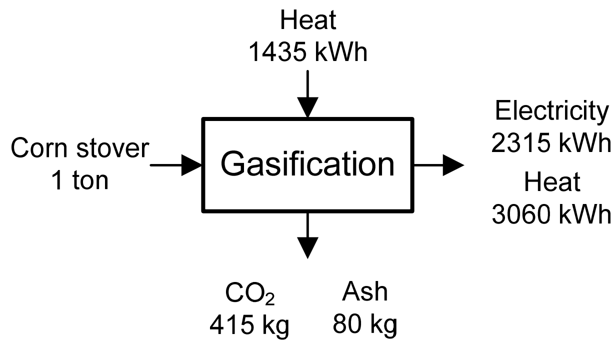


**Figure 3.6:** *Gasification's model*

The heat required by this process is used to generate steam and air at 400°C and 0.1 MPa (0.64 and 1.47 kg/kg of stover respectively). The gasification's main product is the electricity whereas the heat is a by-product. In fact the process is optimized to recover as much heat as possible in order to generate electricity. The remaining heat is the sensible energy of the hot water produced by condensing waste steam and by cooling the product gas. This hot water can be used for space heating.

## 3.3 Models of overall process

After the definition of the models, the different processes have been combined to define the overall configurations: ethanol production from corn linked to the energy generation process from corn stover. Corn stover is used to supply energy (heat and/or electricity) to the ethanol plant. In this way the consumption of energy from fossil sources is minimized making the most form energy crops. Therefore, to compare the different options the same amount of ethanol produced (75 million litres per year) has been set and, with the characteristics of Italian yields, the soil needed and all the others data (corn and corn stover production, by-products production and energy required) have been calculated. In this way it should be possible to determine the best process considering different aspects.
There are nine global processes that have been defined, which are described and discussed below.

### *3.3.1 Configuration n° 1*

Figure 3.7 shows the first configuration: combustion of corn stover to supply heat to the traditional dry milling process. For this case, as for all the configurations with a combustion process, the heat produced is set equal to the one needed by the ethanol process to produce 75 million litres per year. To obtain the right amount of thermal energy, only a part of the whole amount of corn stover available is burned, in this case the 91.3%. In this way it is possible to meet the thermal request of the ethanol plant while keeping the corn stover plant's scale and costs low.

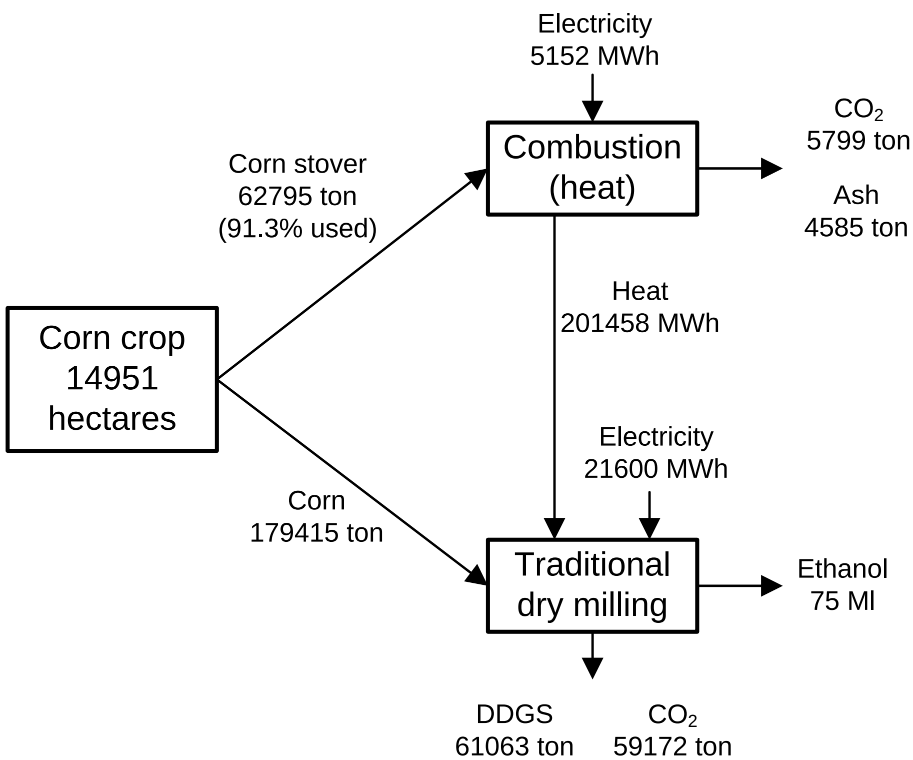


**Figure 3.7:** *Overall process - Configuration 1*

The combustion process requires 5152 MWh of electrical energy and produces a considerable amount of carbon dioxide and ash. However, the real result of this process is to have 100% of the thermal energy required, that usually comes from natural gas, replaced with a renewable source, the corn stover.

Regarding the environmental facet, the specific $CO_2$ emission per litre of ethanol is 0.87 kg/l. The ethanol process requires 21600 MWh of electrical energy so the global electrical consumption per litre of ethanol is 0.36 kWh/l, while the global specific thermal consumption is zero. To calculate this global specific consumption, only the externals sources of energy have been taken into account, but not the internal flows (from the corn stover treatment to the ethanol plant).

This first configuration can be considered as a *base process* and therefore it will be used as a reference.

### *3.3.2 Configuration n° 2*

Figure 3.8 shows the second configuration's model. The process for ethanol production is the dry milling with recycle of distillers' grains, and corn stover is burned to generate heat as in the previous configuration.

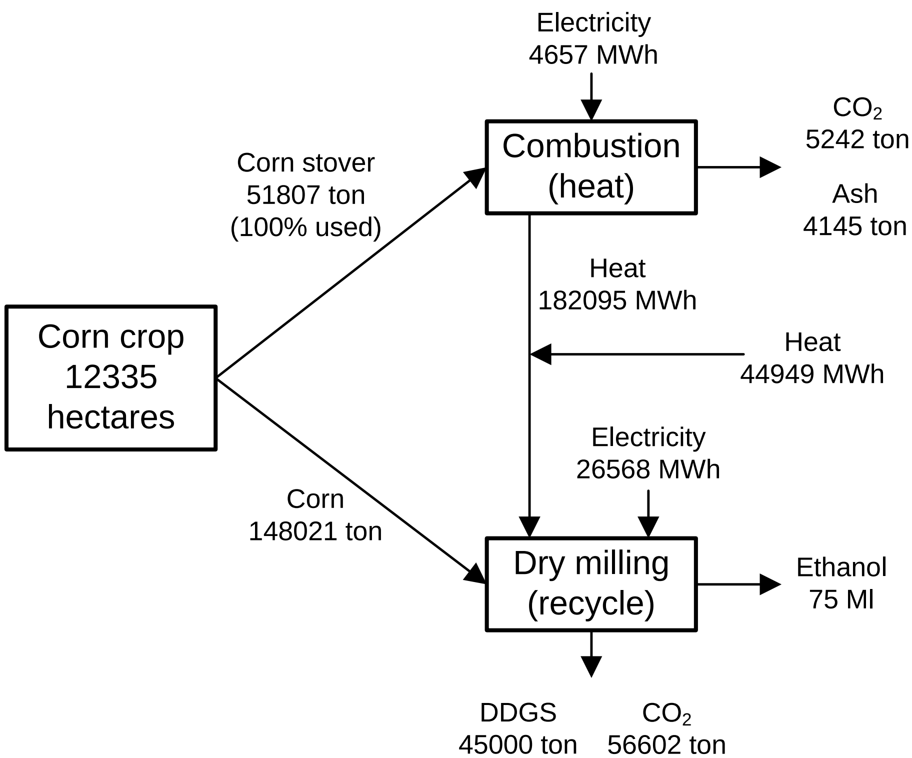


**Figure 3.8:** *Overall process - Configuration 2*

The process with recycle of distillers grains has a higher yield as compared to the traditional one (0.51 l/kg against 0.42 l/kg of traditional process). That means that the second configuration need less land in comparison to the first one (17.5%) to produce the same amount of ethanol. In turn, less land means a lower production of corn stover and heat from the combustion process. As a result, in this configurations, all the corn stover available is burned. However, the thermal energy generated is not enough to reach the ethanol plant thermal request, also because the dry milling with recycle process needs more thermal energy than the traditional one (12.7%).

The overall specific electrical and thermal energy consumptions are respectively 0.42 and 0.6 kWh/l.

The last important parameter is the specific $CO_2$ emission, which in this case is 0.82 kg/l.

### 3.3.3 Configuration n°3

Figure 3.9 shows the third configuration's model, where a quick germ – quick fiber process for the ethanol production is used and the corn stover is burned to produce heat as in the first and second options.

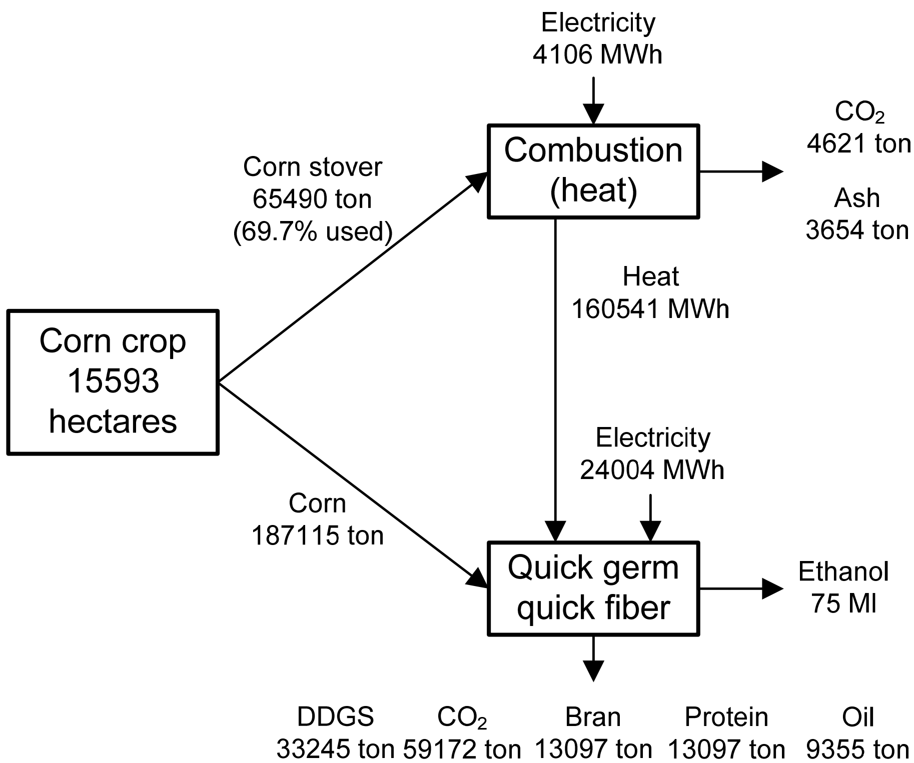


**Figure 3.9:** *Overall process - Configuration 3*

The quick germ – quick fiber process has a lower ethanol yield (0.4 l/kg) compared with the traditional process. So, this configuration needs more soil (~4.29%) compared to the base case, which means a larger amount of stover produced. In fact, the 69.7% of the corn stover produced is enough to meet the demand of thermal energy of the ethanol plant. Also in this case all the heat required by the ethanol process is generated using corn stover, a renewable source of energy. The electrical energy required is higher compared to the base case but lower than the one in the second configuration. The global specific electrical energy consumption is 0.37 kWh/l, while the thermal one is null. The specific $CO_2$ emission for litre of ethanol produced is 0.85 kg/l.

Finally, the quick germ – quick fiber has also the advantage of a large number of valuable by-products, but this affects only the economic analysis.

### 3.3.4 Configuration n°4

Figure 3.10 shows the model of the fourth configuration which uses a traditional dry milling process for ethanol production and a combustion process for heat and electricity generation.

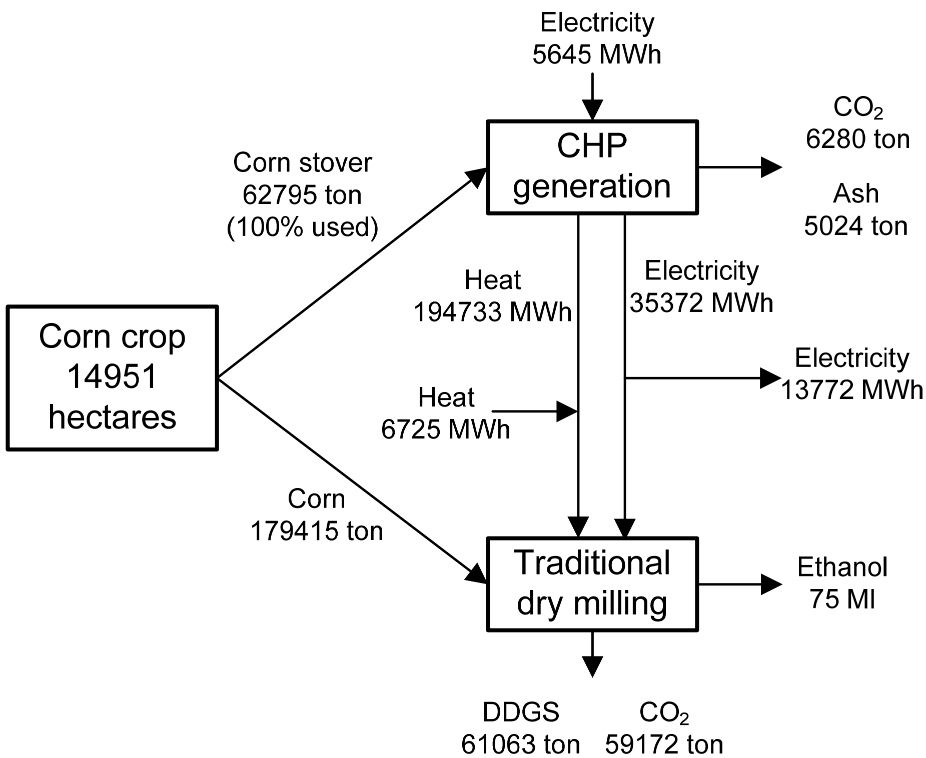


**Figure 3.10:** *Overall process - Configuration 4*

This process needs the same amount of soil as the first configuration but the process for energy generation from corn stover is different of the one of the first option. Also, in this configuration the whole amount of stover available is processed. In this way it is possible to produce 194733 MWh of thermal energy, that is the 96,7% of the heat required by the ethanol plant. At the same time, the CHP process generates more electricity than electrical energy demand of the ethanol process. As a result, considering also the internal energy consumption of the CHP plant, there is suffice of 8127 MWh of electricity that can be sold to the grid.

The global specific electrical consumption is zero, while the thermal one is 0.09 kWh/l. The specific $CO_2$ emission is 0.9 kg/l.

### 3.3.5 Configuration n° 5

Figure 3.11 shows the model of the option which uses a combustion process to generate heat and electricity supplied to a dry milling with recycling process.

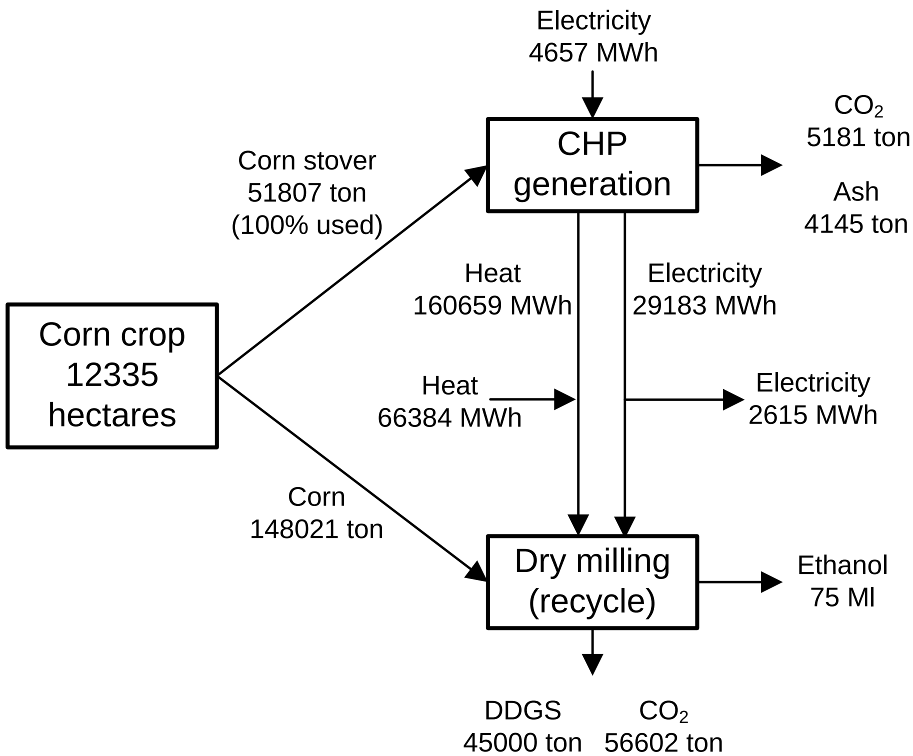


**Figure 3.11:** *Overall process - Configuration 5*

The dry milling with recycle has the highest ethanol yield among the processes taken into account in this work. It is the one that required less soil to produce 75 million litres per year and has also the lower production of corn and corn stover. For this reason the combustion process for heat and electricity generation, which is exactly the same as for previous configuration (number 4), produces a significantly smaller amount of thermal and electrical energy. In fact, the global specific electrical and thermal consumption are higher compared to previous process and they are respectively 0.03 and 0.89 kWh/l.

However, the combustion process produces 160659 MWh of heat, that is 70.8% of the total heat demand of the ethanol plant, and 2615 MWh of electricity are more than 100% of the ethanol plant request. Equally, the CHP process needs electrical energy, and as a result this configuration requires 2042 MWh of electricity.

The specific $CO_2$ emission in this configuration is 0.82 kg/l.

### 3.3.6 Configuration n° 6

Figure 3.12 shows the model of the sixth configuration, which has a combustion process for heat and electricity generation and a quick germ – quick fiber process for ethanol production.

In this case the ethanol process is the one with the lowest yield and then the biggest amount of land used. The result is a large availability of corn stover and then by processing the 79% of this corn stover it is possible to meet the energy request of the ethanol plant. The combustion process generates exactly the same amount of heat that is required by the ethanol plant, while the electricity produced is above the ethanol plant request (~121.5%). The global specific thermal and electrical consumptions are both zero. The specific $CO_2$ emission factor is 0.86 kg/l.

In this configuration the amount of electrical energy generated by the CHP process, and not used by the ethanol plant, is more than the internal energy consumption of the CHP plant. As a result, there is a suffice of 504 MWh that can be sold to the grid.

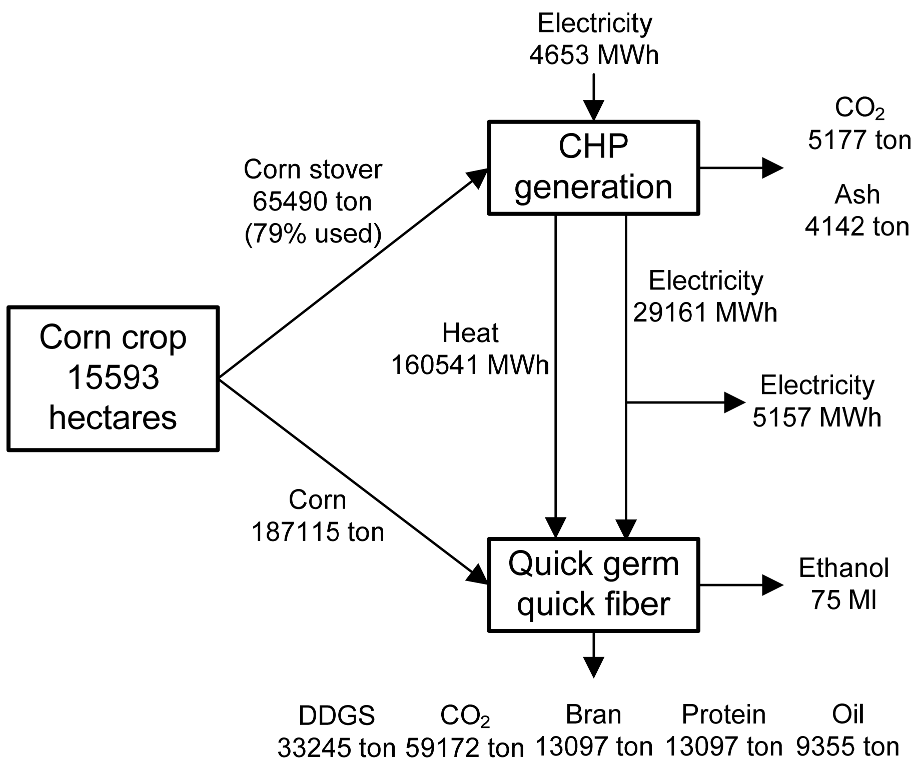


**Figure 3.12:** *Overall process - Configuration 6*

### 3.3.7 Configuration n° 7

Figure 3.13 shows the model of the seventh configuration. In this option the ethanol plant is the traditional dry milling while the process for energy generation is the gasification of corn stover. Gasification is an energy-intensive process compared to the combustion, and it requires 13389 MWh of heat in this configuration. This energy input is needed to obtain air at 400°C and steam at 400°C and 0.1 MPa. At the same time, the gasification process is able to generate 21600 MWh of electricity that is exactly the amount needed by the traditional dry milling. This result is reached by processing only 14.9% of the available corn stover, which has a positive effect on plant costs. The electrical energy required by internal consumptions of the gasification plant is already subtracted from the energy output. Moreover, they are almost negligible due to the fact that the compressor, which consumes the largest amount of energy, is driven by the gas turbine. In this way the energy required for the compressor is automatically detracted from the output.

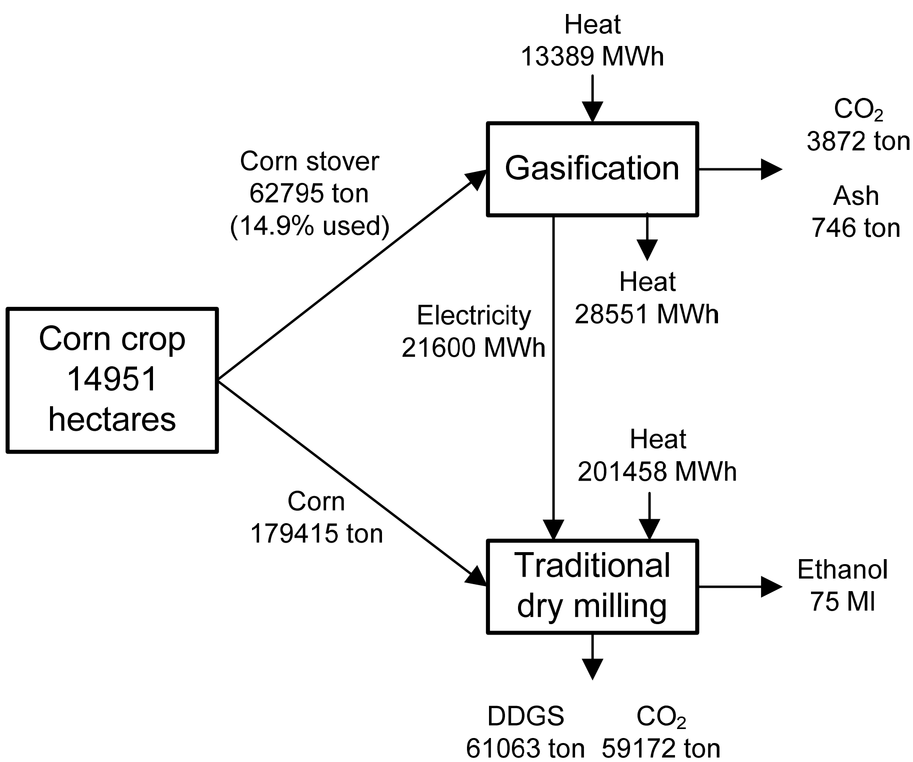


**Figure 3.13:** *Overall process - Configuration 7*

Regarding the heat, there is a considerable production (28551 MWh) but with a low value. In fact, this is hot water that cannot be used to supply heat to the ethanol plant, that usually needs steam at 0.4 ÷ 0.5 MPa and 110 ÷ 120°C. However, this hot water can be sold for space heating as suggest by Kumar et al. (2010).

The global specific electrical energy required can be considered zero because there are no input of electricity while the specific thermal energy consumption is 2.86 kWh/l. This number is really high compared to those described previously, but it could be offset by the erasure of the electrical energy demand. This facet will be analyzed and discussed later in the economic analysis.

The $CO_2$ specific emission is 0.84 kg/l.

### 3.3.8 Configuration n°8

The model of the eighth configuration is shown in Figure 3.14. The process for ethanol production is the traditional dry milling and the process for the treatment of corn stover is gasification. As already described, the dry milling with recycle has higher ethanol yield so the land required and the corn stover production are the lowest between the processes taken into account. Anyway, it is possible to meet the electrical energy demand of the ethanol plant (26568 MWh) by processing 22.2% of the corn stover available.

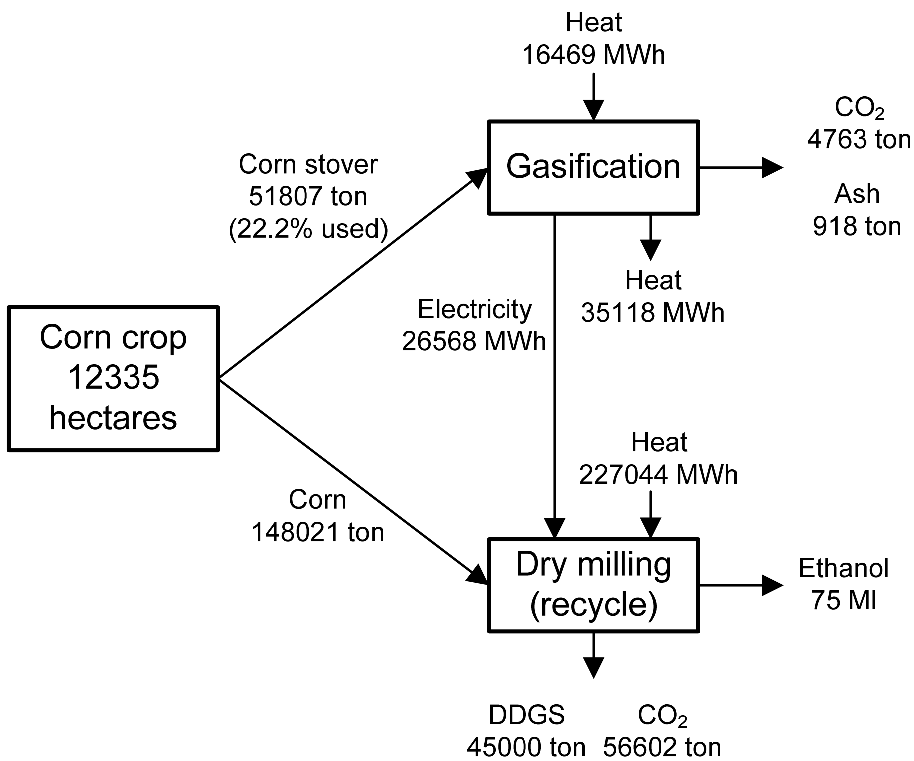


**Figure 3.14:** *Overall process - Configuration 8*

Similarly to the seventh configuration, the global specific electricity consumption can be considered zero, while the thermal one is 3.25 kWh/l. The $CO_2$ specific emission is 0.82 kg/l. Considering these data, it can noted that the specific thermal consumption the configuration number 8 is significantly greater than the one for configuration number 7, while the environmental emissions are almost the same. This is mainly due to the fact that dry milling with recycle requires more electrical and thermal energy in comparison to the traditional one.

### 3.3.9 Configuration n° 9

Figure 3.15 shows the model of the last option, which consists of quick germ – quick fiber process for ethanol production connected with a gasification process.
The global specific electrical consumption is zero and the thermal one is 2.34 kWh/l while the specific $CO_2$ emission is 0.85 kg/l.
The electrical consumption is the lower among configurations with a gasification process and the environmental emissions are very close to those for configurations 7 and 8.

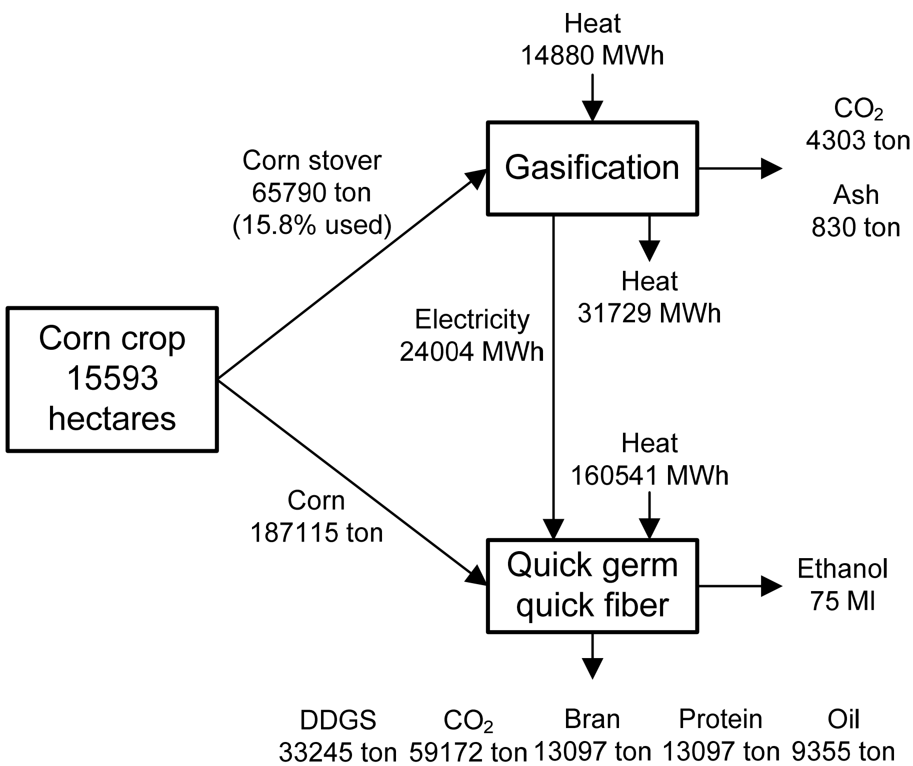


**Figure 3.15:** *Overall process - Configuration 9*

### 3.3.10 Overall processes' discussion

A number of parameters will be discussed. The first one is the extension of required soil, which depends only on which ethanol process is used and, more precisely, on its yield. The process with the highest yield (0.51 l/kg), among those taken into account, is the dry milling with recycle of distillers' grains, while the process with the lowest value (0.4 l/kg) is the quick germ – quick fiber. The traditional dry milling has a yield very similar to the quick germ – quick fiber (0.42 l/kg). Considering this facet, the configuration with the lowest soil request are number 2, 5 and 8.
The second parameter analyzed is the specific thermal energy requirement. Considering this facet, there are three configurations (1, 3 and 6) that have zero specific thermal

energy consumption. Besides, configuration number 4 has a small value, 0.09 kWh/l. At the same time, configurations with a gasification process show a comparatively high value of specific thermal energy required compared to other options. These is due to the intrinsic characteristics of the gasification process and it could be offset by the zero value of the specific electrical energy consumption. This question will be detailed in the economic analysis.

The third parameter taken into account is the specific electrical energy consumption. From this point of view the better configurations are those with a gasification process because they have a zero value for this parameter. However, the gasification process can only generate electricity because the heat produced cannot be supplied to the ethanol plant. In a different way, configurations number 4 and 6 are able to produce both electricity and heat for the ethanol plant and they have zero specific electrical energy consumption, as for configurations 7, 8 and 9. Moreover, the CHP processes of the configuration number 4 and 6 are also able to produce electricity that can be sold to the grid.

The last parameter taken into account is the specific $CO_2$ emission. The values for all configurations are between 0.82 and 0.9 kilograms per litre of ethanol produced. The configurations that show the lowest values (0.82 kg/l) are number 2, 5 and 8 while the configuration with the highest value (0.9 kg/l) is the number 4. Concerning this facet, it is important to emphasize that the emissions considered are only the emissions directly generated by the processes. The emissions due to the energy generation from external sources have not been taken into account.

In conclusion, number 6 is the best configuration, among those taken into account. In fact, this option has zero values for both specific electrical and thermal energy consumptions and it can also provide suffice energy to be sold to the grid. Moreover, the specific $CO_2$ emission is 0.86 kg/l that is a medium value among those calculated for all the configurations. Another good facet is that only the 79% of the available corn stover is processed to generate energy and that contributes to keep the plant costs low. However, the sixth configuration has a very high soil requirement (15593 hectares).

## 3.4 Economic analysis

This paragraph describes the results of the economic analysis. First, the operating cost and incomes to determine the profit for each configuration have been calculated on the basis of the data reported in the models described in Section 3.3.

Then, the plant costs have been determined and the results have been used as a base for the profitability and sensitivity analysis.

### 3.4.1 Operating costs analysis

In Table 3.2 all the costs taken into account are summarized. These costs include raw materials, energy and ash disposal cost. It is important to note that the purchase costs of corn assume only three values. This is because these values depend only on the type of ethanol process considered, not on the process used to generate energy from corn stover. At the same time, all others parameters show a set of different values because they depend on the structure of the overall process.

**Table 3.2:** *Operating costs for configurations (prices I four-month period 2010)*

| Configuration | Corn [M$] | Corn stover [M$] | Electricity [M$] | Heat [M$] | Ash [M$] |
|---|---|---|---|---|---|
| **1** | 24.16 | 1.13 | 4.72 | - | 0.46 |
| **2** | 19.93 | 1.02 | 5.51 | 1.82 | 0.41 |
| **3** | 25.19 | 0.90 | 4.96 | - | 0.37 |
| **4** | 24.16 | 1.24 | - | 0.27 | 0.50 |
| **5** | 19.93 | 1.02 | 0.36 | 2.69 | 0.41 |
| **6** | 25.19 | 1.02 | - | - | 0.41 |
| **7** | 24.16 | 0.18 | - | 8.72 | 0.07 |
| **8** | 19.93 | 0.23 | - | 9.88 | 0.09 |
| **9** | 25.19 | 0.20 | - | 7.12 | 0.08 |

Configuration number 6 seems to be the best one among those taken into account, as it is without both electrical and thermal energy costs. But it is also important to note that the last three configurations show a small corn stover and ash disposal costs. However this could be offset by a high thermal energy request.
Table 3.3 reports incomes for every configurations.

**Table 3.3:** *Incomes for configurations (prices I four-month period 2010)*

| | Incomes [M$] | | | | | | |
|---|---|---|---|---|---|---|---|
| **Configuration** | **Ethanol** | **DDGS** | **Bran** | **Protein** | **Oil** | **Electricity** | **Heat** |
| **1** | 32.30 | 6.45 | - | - | - | - | - |
| **2** | 32.30 | 4.75 | - | - | - | - | - |
| **3** | 32.30 | 3.51 | 1.21 | 5.24 | 8.35 | - | - |
| **4** | 32.30 | 6.45 | - | - | - | 1.43 | - |
| **5** | 32.30 | 4.75 | - | - | - | - | - |
| **6** | 32.30 | 3.51 | 1.21 | 5.24 | 8.35 | 0.09 | - |
| **7** | 32.30 | 6.45 | - | - | - | - | 0.62 |
| **8** | 32.30 | 5.97 | - | - | - | - | 0.76 |
| **9** | 32.30 | 3.51 | 1.21 | 5.24 | 8.35 | - | 0.69 |

It becomes apparent that the incomes from selling ethanol are the same for different configurations given that the production is set to the same value. Moreover, the number and the values of incomes is wide-ranging, as for the costs. That means significant different profits, as shown in Table 3.4.

**Table 3.4:** *Total cost, incomes and profit for each configuration (prices I four-month period 2010)*

| Profit [M$] | | | |
|---|---|---|---|
| **Configuration** | **Total cost** | **Total income** | **Profit** |
| **1** | 30.46 | 38.74 | 8.28 |
| **2** | 28.69 | 37.04 | 8.35 |
| **3** | 31.41 | 50.60 | 19.19 |
| **4** | 26.17 | 40.17 | 14.00 |
| **5** | 24.42 | 37.04 | 12.63 |
| **6** | 26.63 | 50.69 | 24.06 |
| **7** | 33.13 | 39.36 | 6.23 |
| **8** | 30.13 | 39.03 | 8.90 |
| **9** | 32.60 | 51.29 | 18.69 |

It is important to highlight that this is only order-of-magnitude estimate because only the main factors that determine the economic feasibility of the different configurations are taken into account. As an example, soil and labour costs were not considered.

As it can be seen from Table 3.4, the profit has a large variability from a minimum value of 6.23 M$ to a maximum of 24.06 M$. The biggest value is almost four times the smallest. The configuration that shows the better performances is the number 6.

It is also clear that the options with higher profits are those using a quick germ – quick fiber process for ethanol production. In fact, the three highest profits are number 3, 6 and 9. On the other hand, looking at the energy generation process, it is clear that the one showing the best results is the combined heat and power process (CHP). This is due to the fact that it produces both thermal and electrical energy, while the other processes are able to produce only one of this types of energy (heat for the combustion and electricity for the gasification).

Configurations with a gasification process, show low values of profit, except for number 9, whose profit is mainly due to the quick germ –quick fiber process for ethanol generation. The results of these configurations could be largely improved by increasing the amount of corn stover processed that, in order to meet the energy request of the ethanol plant, is never greater than 22.2% of the available corn stover. In this way it could be possible to significantly raise the amount of electricity that can be sold to the grid with positive effects on the profit. However, this is contingent on finding a use for the large amount of hot water produced together with the electricity.

Finally, it is important to remark that this is only an operating cost analysis and therefore it is crucial to analyze also the plant costs.

### *3.4.2 Plant costs analysis*

On the basis of the data taken from literature, the plant costs for each configuration have been calculated. In each case the plant costs from literature, related to different years, have been updated to 2010 using the Marshall & Swift cost index and then scaled to the ethanol production of 75 Ml/y, as in the previous analysis. In Table 3.5 the scales and the relative costs are reported as found in literature and also updated to 2010.

**Table 3.5:** *Plant scales and costs related to different year as found in literature. Cost is updated to the first four-month period of 2010 – Marshall & Swift cost index 1461.3*

| Process | Scale [MGal] | Scale [Ml] | Original cost [M$] | Year | M&S index | Updated cost [M$] |
|---|---|---|---|---|---|---|
| **Traditional dry milling** | 100 | 379 | 148.3 | 2007 | 1373.3 | 157.8 |
| **Dry milling with recycle** | 113 | 427 | 158.5 | 2007 | 1373.3 | 168.6 |
| **Quick germ quick fiber** | 42 | 160 | 111.1 | 2008 | 1449.3 | 112.1 |
| | **Scale [Ton]** | | | | | |
| **Combustion (PH)** | 121270 | | 18.9 | 2008 | 1449.3 | 19.5 |
| **Combustion (CHP)** | 137450 | | 38.2 | 2008 | 1449.3 | 38.5 |
| **Gasification** | 16300 | | 12.4 | 2007 | 1373.3 | 13.2 |

At this point the costs have been rescaled on the basis of the models described in paragraph 3.3. The results are reported in Table 3.6.

By analysing the data, it can be seen that there is a significant variability in the plant cost, from 70 to 92 M$. The configuration number 6 has the largest value.

The ethanol plants costs show only three values because the total production is set to 75 Ml/y for every configuration. The traditional dry milling and the dry milling with recycle of distillers' grains, have almost the same capital cost (~59 M$), while the quick germ – quick fiber process has a bigger one (~71 M$). For the energy generation processes, it is not possible to make the same comparison because their capital costs are closely related to the amount of corn stover processed and so to the scale of the plant. Anyway, it can be noted that the combustion and gasification processes show very close plant costs while the CHP processes have bigger values. Finally, it is important to note that by reducing the amount of corn stover processed by gasification, it is possible to keep the plant costs low, as demonstrated in Table 3.6.

Now, to decide which configuration has the best economical performances a profitability analysis is required.

**Table 3.6:** *Updated and rescaled plant cost for each configuration*

| Configuration | Processes | Scale | | Cost [M$] | Total cost [M$] |
|---|---|---|---|---|---|
| | | [Ml] | [Ton] | | |
| 1 | Traditional dry milling | 75 | - | 59.73 | |
| | Combustion PH | - | 57316 | 12.15 | 71.88 |
| 2 | Dry milling with recycle | 75 | - | 59.42 | |
| | Combustion PH | - | 51807 | 11.43 | 70.86 |
| 3 | Quick germ – quick fiber | 75 | - | 71.02 | |
| | Combustion PH | - | 45675 | 10.60 | 81.62 |
| 4 | Traditional dry milling | 75 | - | 59.73 | |
| | Combustion CHP | - | 62795 | 24.04 | 83.77 |
| 5 | Dry milling with recycle | 75 | - | 59.42 | |
| | Combustion CHP | - | 51807 | 21.42 | 80.84 |
| 6 | Quick germ – quick fiber | 75 | - | 71.02 | |
| | Combustion CHP | - | 51769 | 21.41 | 92.43 |
| 7 | Traditional dry grind | 75 | - | 59.73 | |
| | Gasification | - | 9330 | 9.44 | 69.17 |
| 8 | Dry milling with recycle | 75 | - | 59.42 | |
| | Gasification | - | 11476 | 10.69 | 70.11 |
| 9 | Quick germ – quick fiber | 75 | - | 71.02 | |
| | Gasification | - | 10369 | 10.06 | 81.08 |

### *3.4.3 Profitability analysis*

Several techniques have been used to analyze the profitability of different configurations. Four indexes are used: return of investment (ROI), discounted cumulative cash position (NPV), discounted payback period and discounted cash flow rate of return (IRR). Only the first technique is nondiscounted while the others are all discounted techniques and they are one for every base that can be used for the evaluation of profitability: time, cash and interest rate.

The results for the first four-month period of 2010 are shown in Table 3.7.

**Table 3.7:** *Economic performance for the first four-month period of 2010*

| Configuration | Fixed capital investment [M$] | ROI [%] | Payback period [years] | NPV [M$] | IRR [%] |
|---|---|---|---|---|---|
| 1 | 71.88 | 11.5 | 15.5 | 1.3 | 5.2 |
| 2 | 70.86 | 11.8 | 15.0 | 2.4 | 5.4 |
| 3 | 81.62 | 23.5 | 7.1 | 62.3 | 12.3 |
| 4 | 83.77 | 16.7 | 9.6 | 28.6 | 8.5 |
| 5 | 80.84 | 15.6 | 10.2 | 22.0 | 7.8 |
| 6 | 92.43 | 25.7 | 6.5 | 83.4 | 13.4 |
| 7 | 69.17 | 9.8 | 19.9 | -9.6 | 3.4 |
| 8 | 70.11 | 13.7 | 13.5 | 6.4 | 5.98 |
| 9 | 81.08 | 23.8 | 7.2 | 59.6 | 12.0 |

As it can be seen, there is one configuration, the number 7, that is uneconomic because of a negative value of NPV. Furthermore, there are other options that, for different reasons, cannot be considered profitable. Configuration number 1 and 2, for example, show a payback period and a return of investment acceptable but they have very small NPV and IRR. The last one is particularly important: if the interest rate was bigger than 5.2%, for the first configuration, and 5.4% for the second, the NPV would be negative. As a result, these configurations cannot be considered profitable. This also applies to numbers 4, 5 and 8. They have bigger value compared to configurations 1 and 2, but still not acceptable.

The options with acceptable results are number 3, 6 and 9. They have payback period shorter than 8 years, NPV greater than 60 M$ and IRR bigger than 10%. The best configurations, among all those considered, is again the number 6.

By analysing all of these economic results, it appears that the good economic performances are mainly due to the quick germ – quick fiber process that generates a large number of valuable by-products. On the other hand, the energy generation process seems to be less important. In fact, the three best configurations are examples of all three different processes. Anyway, the corn stover processes contribute to reaching good economic performances. As a result, number 6 is the best configuration, that is composed of a quick germ – quick fiber process and a CHP process. The second best configuration is number 3, with a combustion process, and a close third is number 9 which uses a gasification process.

### *3.4.4 Profitability trend over time*

The final analysis is aimed to verify whether configuration number 6 is sufficiently rigid when prices change. If a process is profitable in 2010, does not mean that it will be profitable when prices are changed. So, a sensitivity analysis to price changing was performed. The different sets of values taken into account were relative to the last four years, three sets for every year. The result is a set of tables with the economic performances of the different processes over time, since January 2006 to April 2010.

Table 3.8 shows results for 2006. The data shown in this paragraph are the most significant: discounted payback period, discounted cumulative cash position and discounted cash flow rate of return. The return of investment (ROI) is not taken into account because it is a nondiscounted parameter.

**Table 3.8:** *Economic performance for 2006*

| | I<br>4-months period 2006 | | | II<br>4-months period 2006 | | | III<br>4-months period 2006 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Config.** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** |
| **1** | 6.6 | 63.6 | 13.3 | 6.8 | 60.0 | 12.9 | 5.5 | 87.7 | 16.0 |
| **2** | 6.3 | 67.9 | 13.9 | 6.4 | 67.4 | 13.8 | 5.3 | 93.7 | 16.7 |
| **3** | 5.2 | 109.3 | 16.9 | 5.5 | 100.6 | 16.1 | 4.8 | 124.0 | 18.2 |
| **4** | 6.4 | 79.4 | 13.8 | 6.5 | 75.8 | 13.5 | 5.5 | 103.5 | 16.1 |
| **5** | 6.2 | 79.4 | 14.1 | 6.3 | 78.9 | 14.0 | 5.3 | 105.2 | 16.6 |
| **6** | 5.3 | 120.4 | 16.6 | 5.6 | 111.8 | 15.9 | 5.0 | 135.1 | 17.8 |
| **7** | 6.5 | 63.8 | 13.6 | 6.6 | 60.2 | 13.2 | 5.4 | 87.8 | 16.3 |
| **8** | 5.8 | 77.8 | 15.1 | 5.8 | 78.9 | 15.2 | 4.8 | 106.9 | 18.5 |
| **9** | 5.1 | 113.4 | 17.3 | 5.4 | 104.8 | 16.5 | 4.7 | 128.1 | 18.7 |

Each parameter follows a trend over configuration's number similar to the one for 2010, so that the three best configurations are 3, 6 and 9, as before. However, there is an exception; configuration number 9 shows IRR greater than configuration 6. This is true for each fourth-month period in 2006. As a result, for 2006 it is not so clear which is the best configuration: number 6 has a bigger NPV but number 9 shows a greater IRR. In any case, considering the performances and results described in the previous paragraphs, the preferred configuration is number 6.

Table 3.9 shows the economic results for the year 2007, while Table 3.10 shows the same for 2008.

**Table 3.9:** *Economic performance for 2007*

| | I<br>4-months period 2007 | | | II<br>4-months period 2007 | | | III<br>4-months period 2007 | | |
|---|---|---|---|---|---|---|---|---|---|
| Config. | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** |
| 1 | 6.7 | 61.4 | 13.0 | 7.2 | 52.4 | 12.0 | 10.4 | 18.3 | 7.7 |
| 2 | 6.4 | 66.9 | 13.8 | 6.8 | 58.1 | 12.8 | 9.8 | 22.2 | 8.2 |
| 3 | 5.3 | 107.1 | 16.7 | 5.4 | 103.0 | 16.3 | 7.0 | 64.4 | 12.5 |
| 4 | 6.4 | 79.6 | 13.8 | 6.7 | 70.6 | 12.9 | 8.8 | 36.5 | 9.4 |
| 5 | 6.2 | 79.9 | 14.1 | 6.6 | 71.1 | 13.3 | 8.8 | 35.2 | 9.4 |
| 6 | 5.3 | 120.4 | 16.6 | 5.4 | 116.2 | 16.2 | 6.8 | 77.6 | 12.9 |
| 7 | 6.8 | 56.7 | 12.8 | 7.4 | 47.8 | 11.7 | 11.3 | 13.7 | 7.1 |
| 8 | 5.9 | 76.2 | 14.9 | 6.4 | 65.6 | 13.7 | 8.8 | 31.5 | 9.5 |
| 9 | 5.3 | 107.8 | 16.8 | 5.4 | 103.6 | 16.4 | 6.9 | 65.0 | 12.6 |

**Table 3.10:** *Economic performance for 2008*

| | I 4-months period 2008 | | | II 4-months period 2008 | | | III 4-months period 2008 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Config.** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** |
| **1** | 9.2 | 28.0 | 9.0 | 9.8 | 22.2 | 8.2 | 18.0 | -3.5 | 4.5 |
| **2** | 8.2 | 38.0 | 10.3 | 8.2 | 38.0 | 10.3 | 15.3 | 1.7 | 5.3 |
| **3** | 5.1 | 115.5 | 17.4 | 5.3 | 107.5 | 16.7 | 5.8 | 92.3 | 15.3 |
| **4** | 7.4 | 57.4 | 11.6 | 7.9 | 50.0 | 10.8 | 9.3 | 30.9 | 8.8 |
| **5** | 7.2 | 60.3 | 12.1 | 7.2 | 59.0 | 12.0 | 9.5 | 28.1 | 8.6 |
| **6** | 4.9 | 138.1 | 18.0 | 5.1 | 128.7 | 17.3 | 5.4 | 118.9 | 16.5 |
| **7** | 8.8 | 30.4 | 9.4 | 9.6 | 23.4 | 8.5 | 14.8 | 2.8 | 5.4 |
| **8** | 6.8 | 59.1 | 12.9 | 6.8 | 58.0 | 12.8 | 9.5 | 24.5 | 8.6 |
| **9** | 4.8 | 124.0 | 18.3 | 5.1 | 114.7 | 17.4 | 5.4 | 104.8 | 16.5 |

As it can be seen from Tables 3.9 and 3.10, in both cases NPV show the same trend as in 2006. The biggest value is always the one for configuration number 6 and the second is for number 9. It can be also noted that the differences between the IRR of the three configurations (3, 6, and 9) seem to decrease from the first quarter of 2007 to the last one of 2008. The IRR of configurations 6 and 9 for the last fourth-month of 2008 are the same at 16.5%.

However, the most important result of this analysis is that the better configurations are always number 6 followed by number 9 and 3. This can be noted looking also at the results for the year 2009, as reported in Table 3.11.

**Table 3.11:** *Economic performance for 2009*

| | I 4-months period 2009 | | | II 4-months period 2009 | | | III 4-months period 2009 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Config.** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** | **Payback period** | **NPV [M$]** | **IRR [M$]** |
| **1** | 22.0 | -21.3 | 1.4 | 19.6 | -8.3 | 3.7 | 8.8 | 31.6 | 9.4 |
| **2** | 21.9 | -20.3 | 1.5 | 19.3 | -6.5 | 4.0 | 8.6 | 33.8 | 9.8 |
| **3** | 9.7 | 26.0 | 8.3 | 8.4 | 41.0 | 10.0 | 6.1 | 82.8 | 14.3 |
| **4** | 12.5 | 11.1 | 6.4 | 10.4 | 21.6 | 7.7 | 7.3 | 59.5 | 11.8 |
| **5** | 14.6 | 3.9 | 5.5 | 11.4 | 15.7 | 7.1 | 7.5 | 54.2 | 11.5 |
| **6** | 8.1 | 51.2 | 10.5 | 7.4 | 64.1 | 11.7 | 5.8 | 104.2 | 15.2 |
| **7** | 22.8 | -24.2 | 0.7 | 20.5 | -13.1 | 2.8 | 9.4 | 25.2 | 8.7 |
| **8** | 19.3 | -6.6 | 3.9 | 14.2 | 4.3 | 5.7 | 7.9 | 42.1 | 10.9 |
| **9** | 9.3 | 30.7 | 8.9 | 8.2 | 43.7 | 8.9 | 6.1 | 83.8 | 14.5 |

With reference to Table 3.11, it is possible to verify that the three configurations with the best economical performances are the number 3, 6 and 9, as for the previous years. Besides, it is possible to identify a period of time with very bad results. This corresponds to the first two quarters of the 2009 and it is mainly due to a combination of really high costs of energy and low values of products.

Another aspect of interest is the trend of the different parameters over time for each configuration. In this way is possible to analyze if a configuration generates profit in all the years taken into account. Once determined why a configuration is profitable or not, it will be possible to try to predict whether it will be profitable also in the future.

For every figure the limit for the parameter represented is reported. The payback period should be smaller than 20 years, that is the operating life of the plant. The NPV and IRR should be always greater than 0, otherwise the process cannot be considered profitable.

### 3.4.4.1 Configuration number 1

Figure 3.16 shows the payback period's trend over time.

The horizontal line in the figure is the limit of 20 years which is the operating life of the plant. The payback period of this first configuration is always smaller than the limit, except that for the first quarter of 2009. Also the values for the last fourth-month period of 2008 and for the second of 2009 are close to the limit.

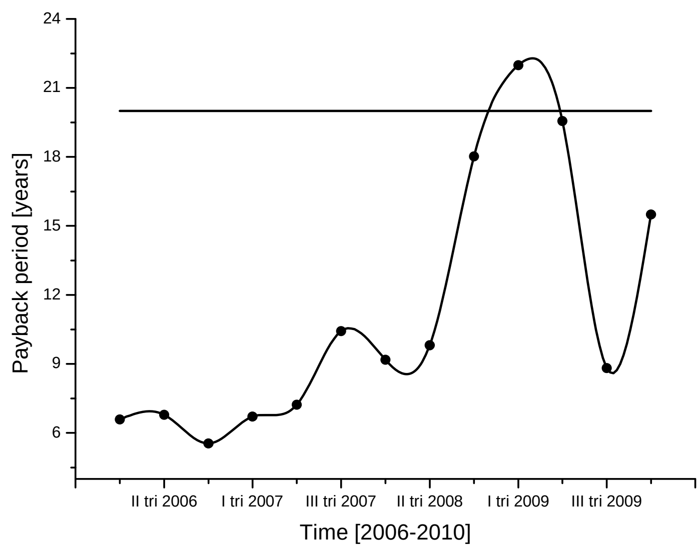


**Figure 3.16:** *Payback period over time - Configuration 1*

It is possible to draw the same conclusion looking at the trends of NPV and IRR over time respectively represented in Figure 3.17 and in Figure 3.18.

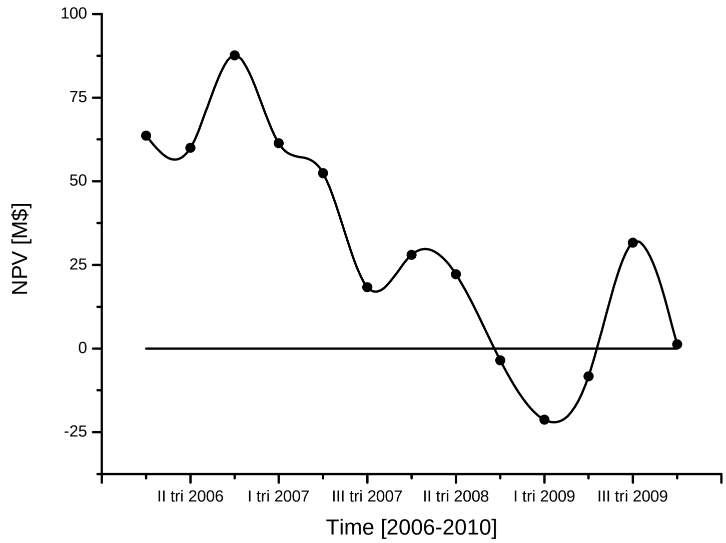


**Figure 3.17:** *NPV over time - Configuration 1*

For the NPV, there are three values lower than zero, corresponding to the three non acceptable values of the payback period.

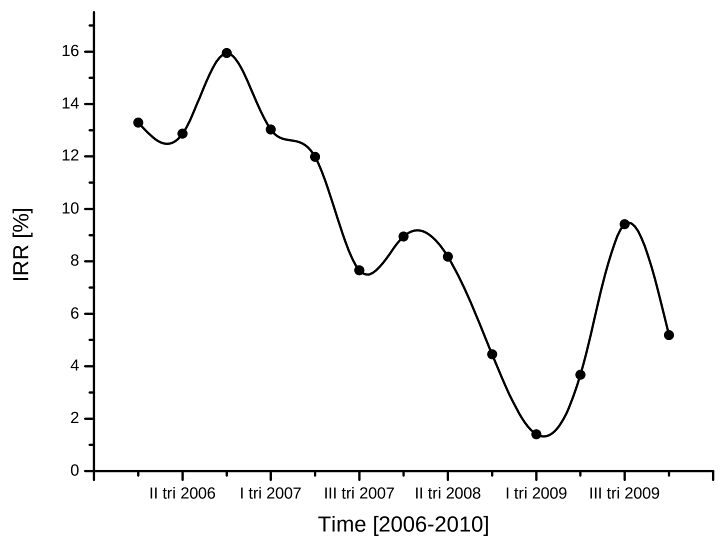


**Figure 3.18:** *IRR over time - Configuration 1*

The IRR for the first configuration is always bigger than zero also if the values at the beginning of 2009 are really small. In any case, the process cannot be considered profitable. In fact, as a general rule, if one parameter shows values outside the imposed limits, the process is reckoned as uneconomic, also if the other parameters suggest the opposite.

### 3.4.4.2 Configuration number 2

In Figure 3.19 the payback period's trend over time is represented.

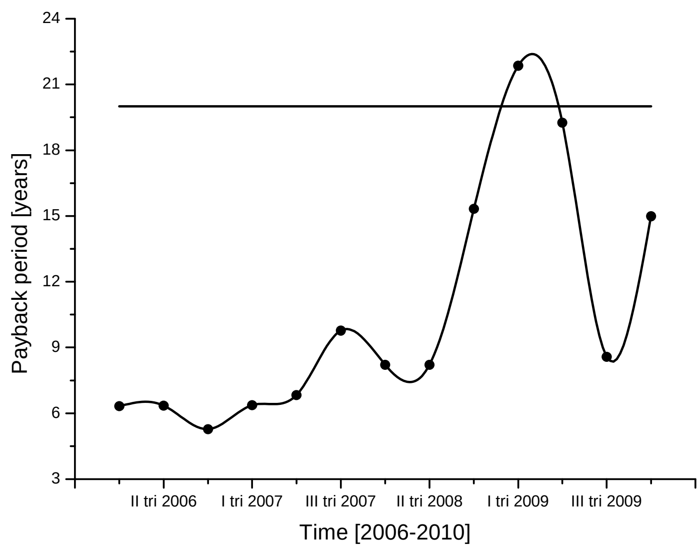


**Figure 3.19:** *Payback period over time - Configuration 2*

The second configuration is really similar to the first one considering both technical and economic aspects. For this reason also the trends of the economic parameters over time are almost the same as it can be seen in Figure 3.19 for the payback period, in Figure 3.20 for the NPV and in Figure 3.21 for the IRR.

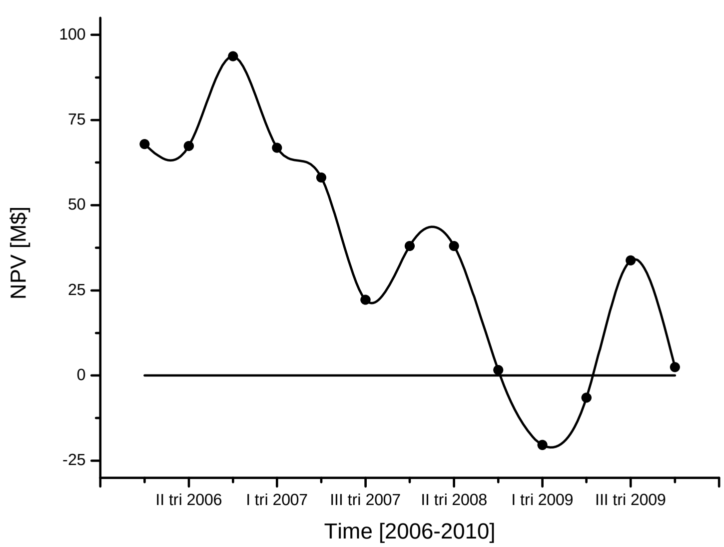


**Figure 3.20:** *NPV over time - Configuration 2*

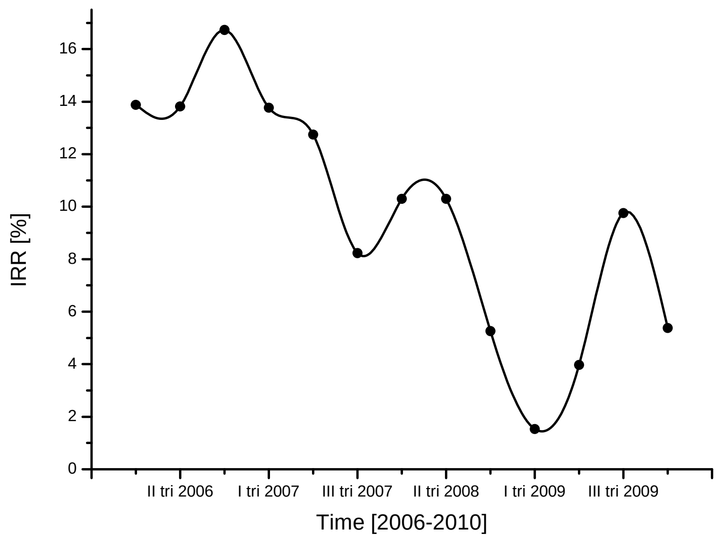


**Figure 3.21:** *IRR over time - Configuration 2*

Given that the trends are really similar it is possible to draw the same conclusion of the previous case: the process cannot be considered as profitable.

### 3.4.4.3 Configuration number 3

Figure 3.22 shows the payback period trends over time from January 2006 to April 2010 as in the previous figures.

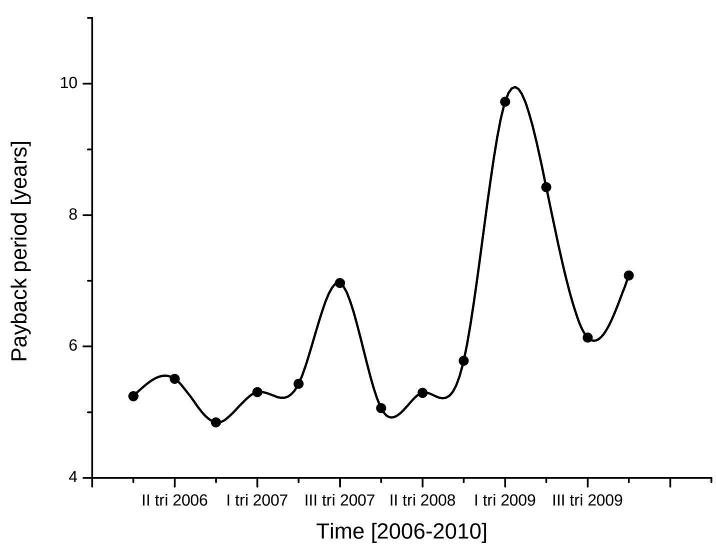


**Figure 3.22:** *Payback period over time - Configuration 3*

In this configuration the payback period is always shorter than the operating life of the plant. The biggest value occurs around the beginning of 2009, as in the previous cases, but is still inside the fixed limit.

In Figure 3.23 the NPV trend is reported and in Figure 3.24 the IRR one.

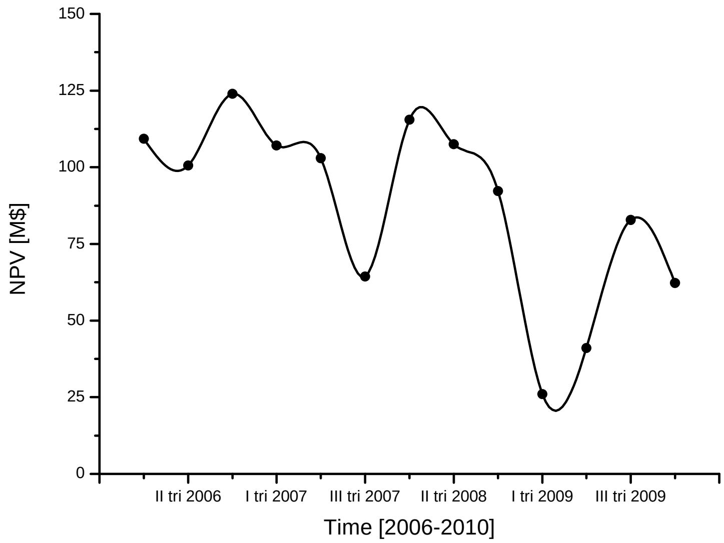


**Figure 3.23:** *NPV over time - Configuration 3*

The NPV is always greater than zero, meaning that the process generates profit in all cases. Only in the critic period, beginning of 2009, the profit is really small.

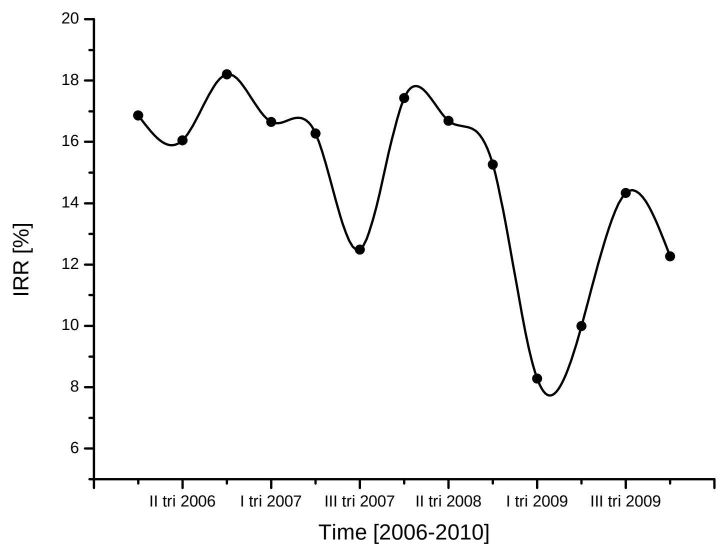


**Figure 3.24:** *IRR over time - Configuration 3*

Also the discounted cash flow rate of return, as well as the NPV, is always greater than zero. As a result, this configuration can be considered profitable. However the risk associated with an investment in this configuration, may be high because with one set of prices, the IRR is lower than 10%.

### 3.4.4.4 Configuration number 4

In Figure 3.25 is reported the payback period over time for the fourth configuration.

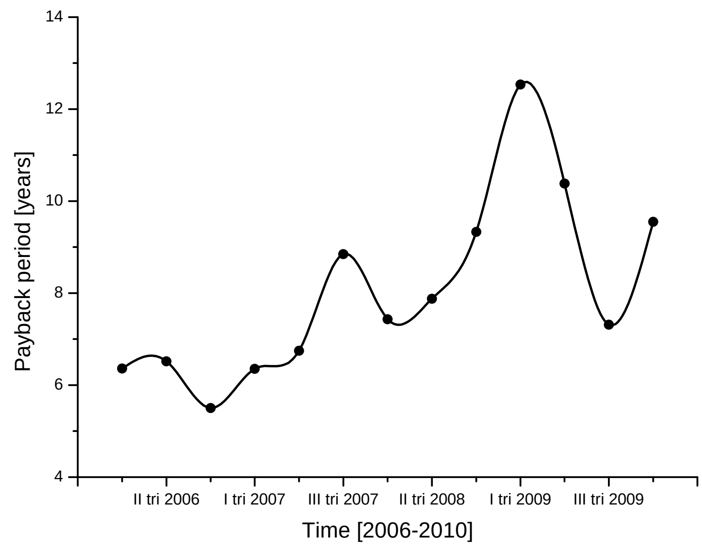


**Figure 3.25:** *Payback period over time - Configuration 4*

As it can be seen, the payback period of the fourth configuration is always broadly inside the imposed limit. The biggest values is around 13 years.

Figure 3.26 shows the NPV trend over time.

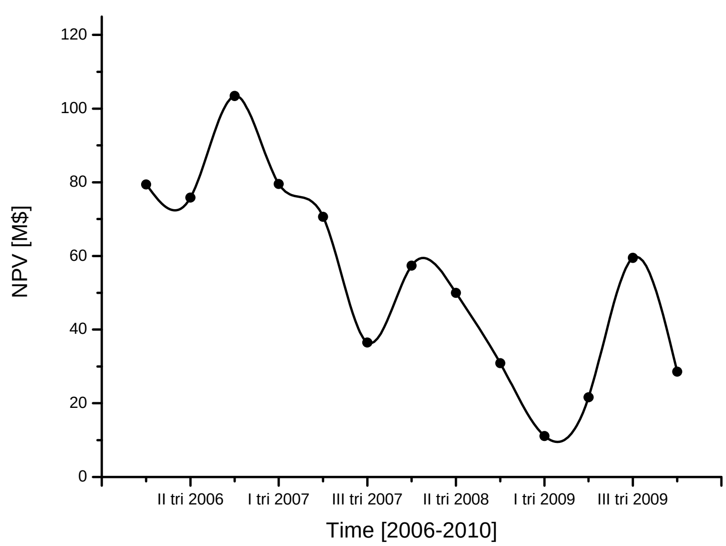


**Figure 3.26:** *NPV over time - Configuration 4*

The NPV has the same trend observed in the first two configurations, and about at the beginning of 2009 it has values really close to zero.

Looking at Figure 3.27, it can be noted that in this case the IRR is always greater than zero but this is not enough for consider this option profitable. If fact, the values of IRR and NPV for the beginning of 2009 are very close to zero.

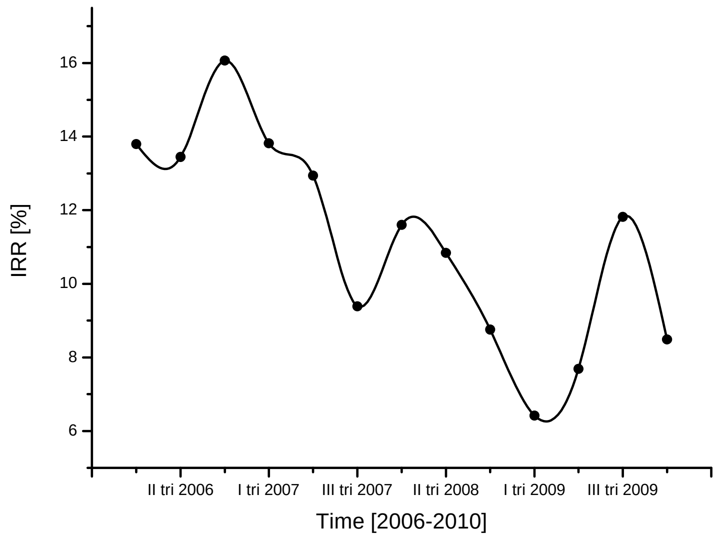


**Figure 3.27:** *IRR over time - Configuration 4*

### 3.4.4.5 Configuration number 5

In Figure 3.28 the payback period's trend over time for the fifth configuration is represented. The trend is the same of the previous options and the payback period is always inside the fixed limit.

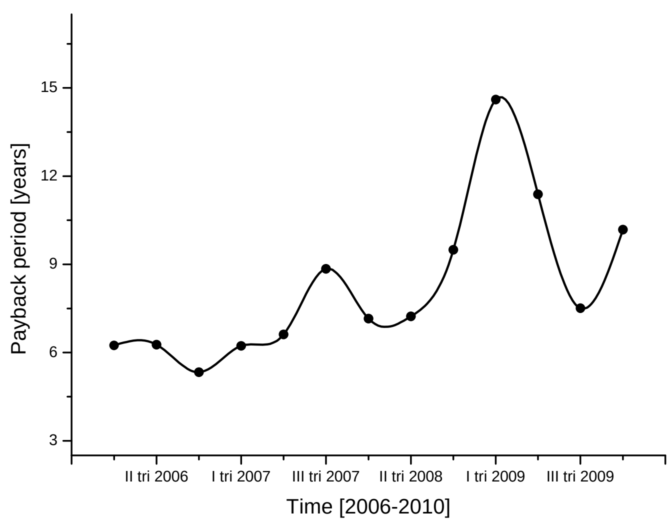


**Figure 3.28:** *Payback period over time - Configuration 5*

In Figure 3.29 is shown the NPV trend over time.

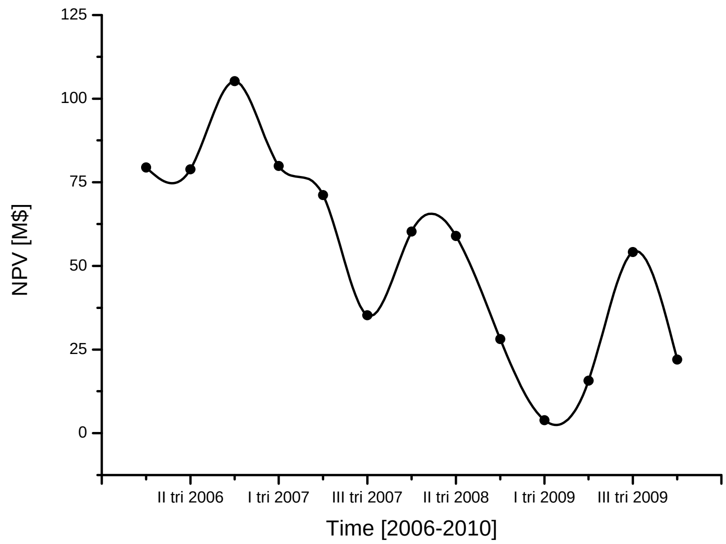


**Figure 3.29:** *NPV over time - Configuration 5*

Also this parameter has the same trend of the previous options and, as usual, the NPV calculated with the set of prices for the beginning of 2009, is almost null. The trend of the last parameter, IRR, is shown in Figure 3.30.

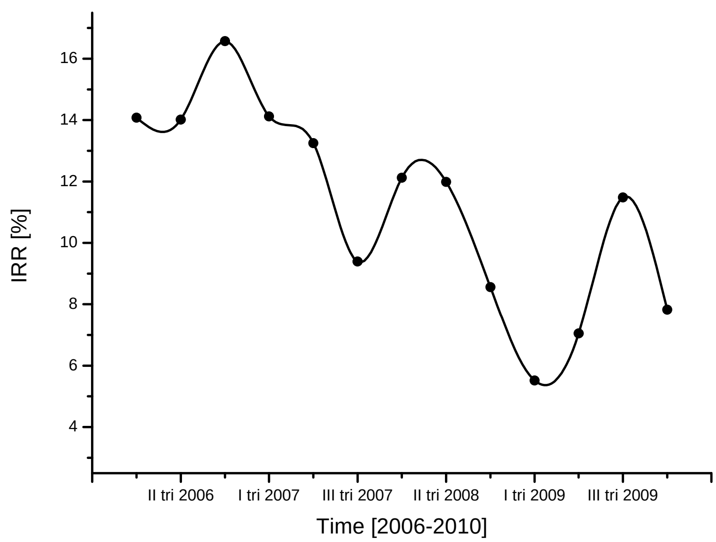


**Figure 3.30:** *IRR over time - Configuration 5*

The IRR gives a positive response because, in the considered period of time, it is always greater and zero. However, around the beginning of 2009, its values is around 6% that is unacceptable. Looking also at the others parameters, the process cannot be considered profitable.

### 3.4.4.6 Configuration number 6

Figure 3.31 shows the payback period's trend over time, in the considered range.

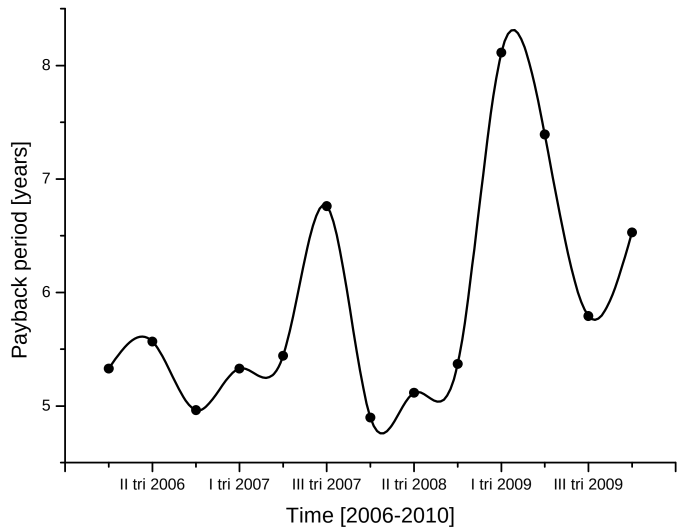


**Figure 3.31:** *Payback period over time - Configuration 6*

In this case the payback period is always shorter than the limit of 20 years and the biggest value is about 9 years. This a good result, so that the process could be profitable if the others two parameters will be inside the imposed limits.

In Figure 3.32 and 3.33 the NPV and IRR trends over time are reported.

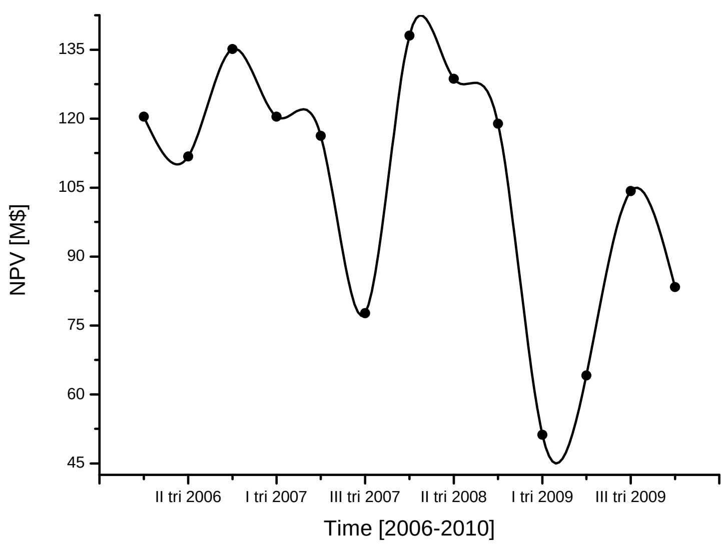


**Figure 3.32:** *NPV over time - Configuration 6*

Both parameters have values inside the fixed limits then the process can be considered profitable. Moreover, during the critical period, the lowest NPV is about 51 M$ that is a considerable value, and the corresponding IRR is 10.5%.

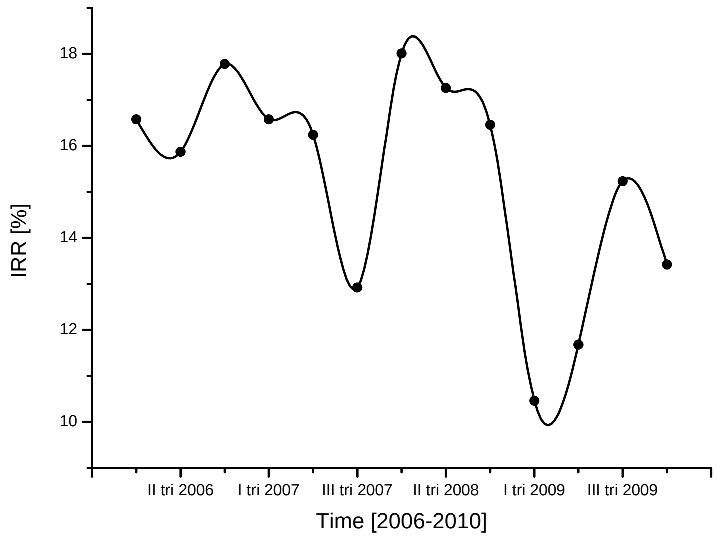


**Figure 3.33:** *IRR over time - Configuration 6*

### 3.4.4.7 Configuration number 7

Figure 3.34 shows the payback period over time for the seventh configuration.

As it can be seen, in the last part of the graph, the payback period is outside the fixed

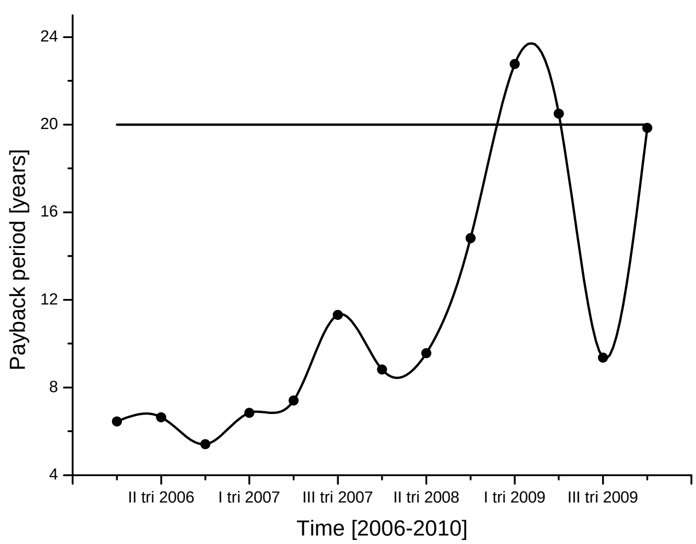


**Figure 3.34:** *Payback period over time - Configuration 7*

limit, not only for the beginning of 2009 but also for the last point, the first quarter of 2010.

In Figure 3.35 and Figure 3.36 the NPV and IRR trends over time are reported.

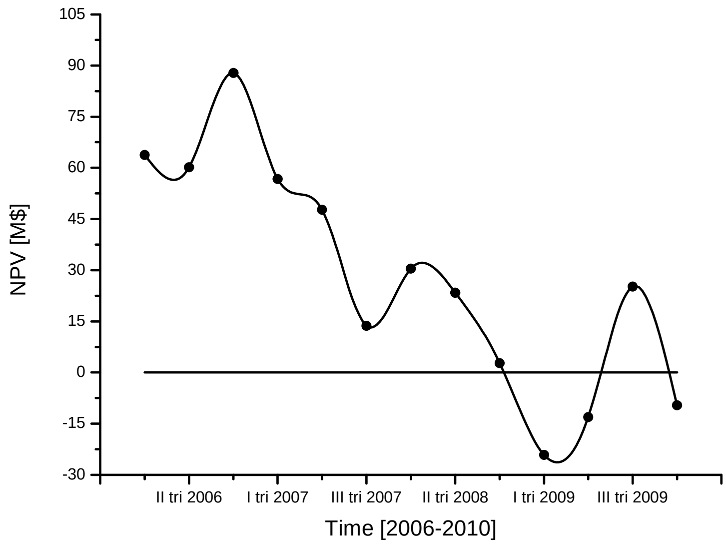


**Figure 3.35:** *NPV over time - Configuration 7*

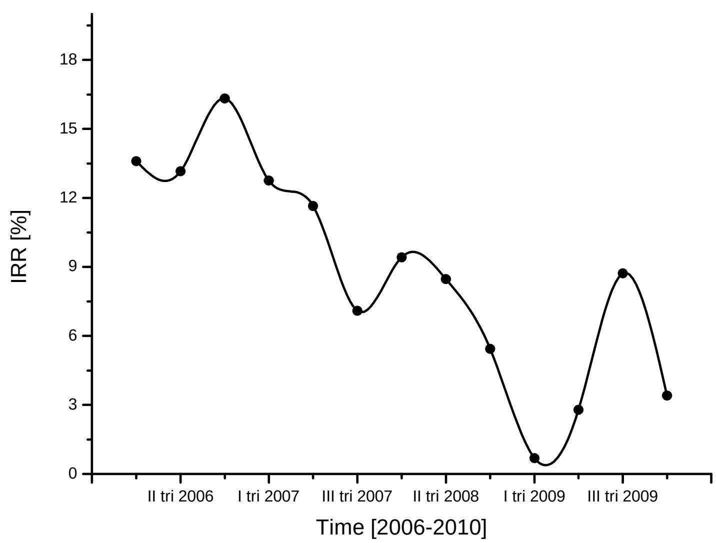


**Figure 3.36:** *IRR over time - Configuration 7*

The NPV is outside the fixed limit for almost all the last part of the graph, after the end of 2008. The IRR follows the same trend and, from the beginning of 2009 assumes values lower than 10%.

As a result, the seventh configuration is not profitable.

### 3.4.4.8 Configuration number 8

In Figure 3.37 the payback period's trend over time is represented.

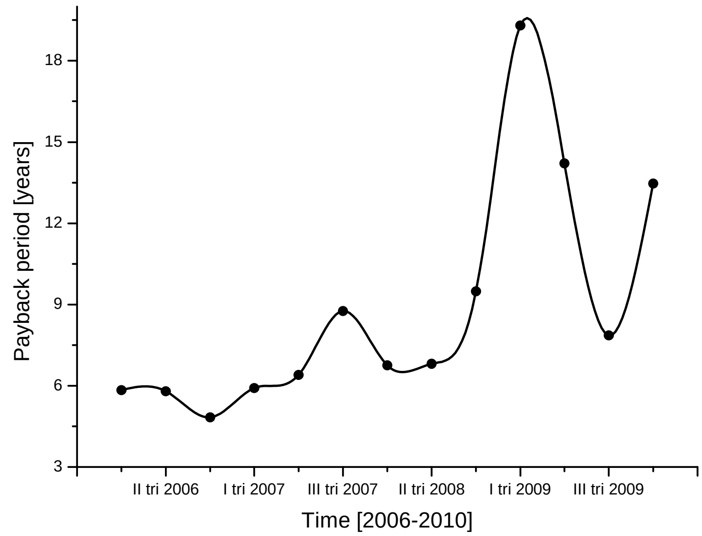


**Figure 3.37:** *Payback period over time - Configuration 8*

In this option, the payback period is inside the fixed limit but, at the beginning of 2009 it shows a value of about 19 years that is close to the operating life of the plant.

The NPV and IRR trends are reported in Figure 3.38 and 3.39, respectively.

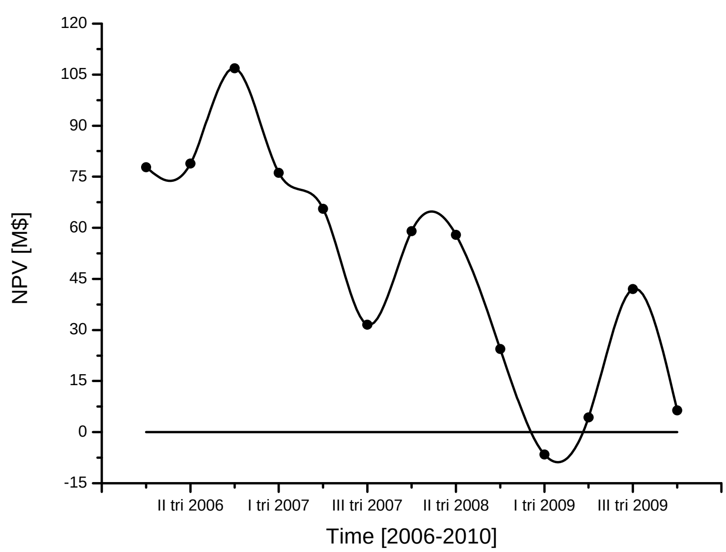


**Figure 3.38:** *NPV over time - Configuration 8*

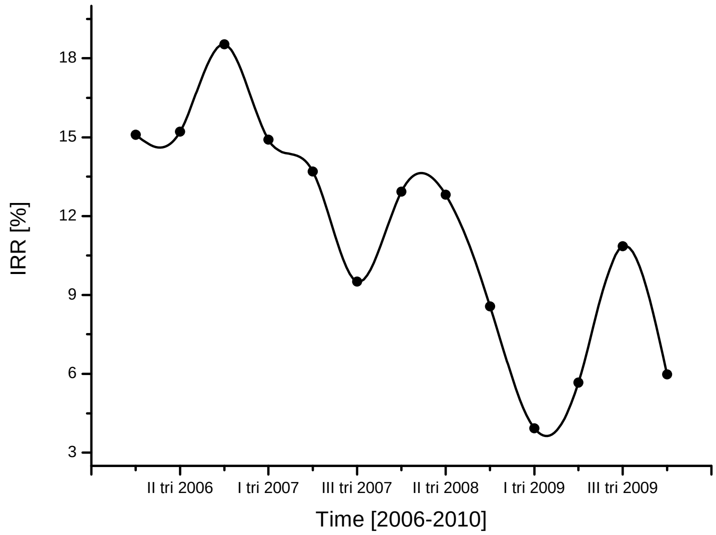


**Figure 3.39:** *IRR over time - Configuration 8*

The NPV and IRR trend, confirm the bad results observed before. In fact, at the beginning of 2009, the NPV is negative and the IRR is about 4%. As a result, this configurations is not profitable.

### 3.4.4.9 Configuration number 9

Figure 3.40 shows the trend over time for the payback period.

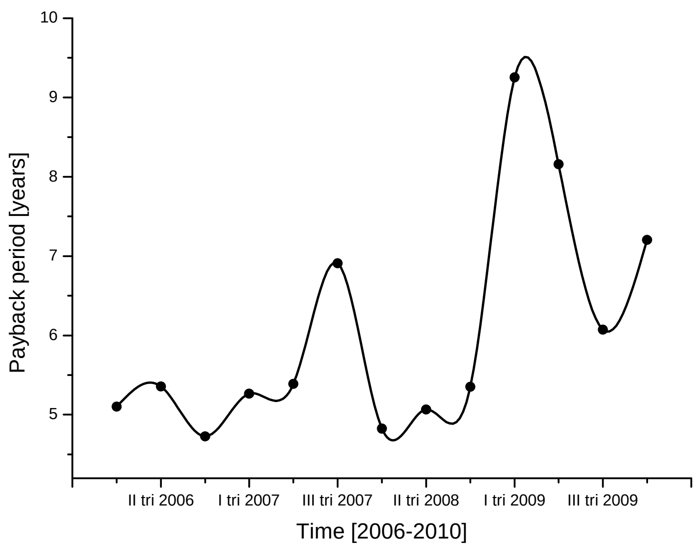


**Figure 3.40:** *Payback period over time - Configuration 9*

Looking at Figure 3.40, it can be noted that this is the configuration with the lowest payback period among those with a gasification process. The biggest value is less than 10 years.

In Figure 3.41 and Figure 3.42 the NPV and IRR trends over time are reported.

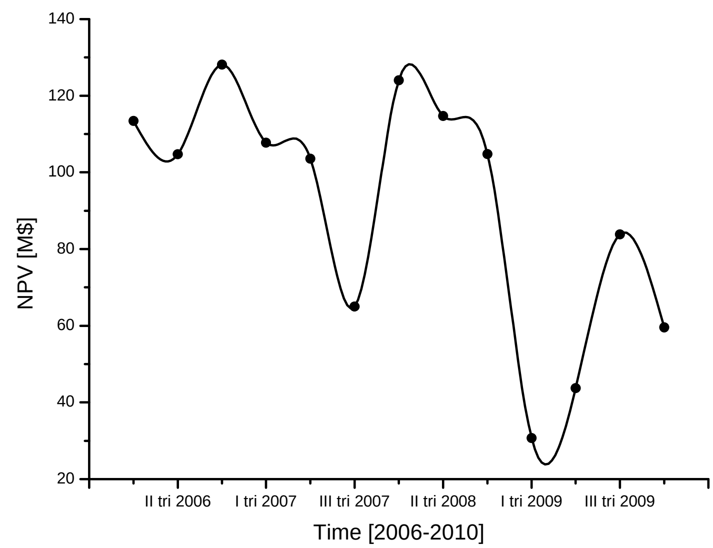


**Figure 3.41:** *NPV over time - Configuration 9*

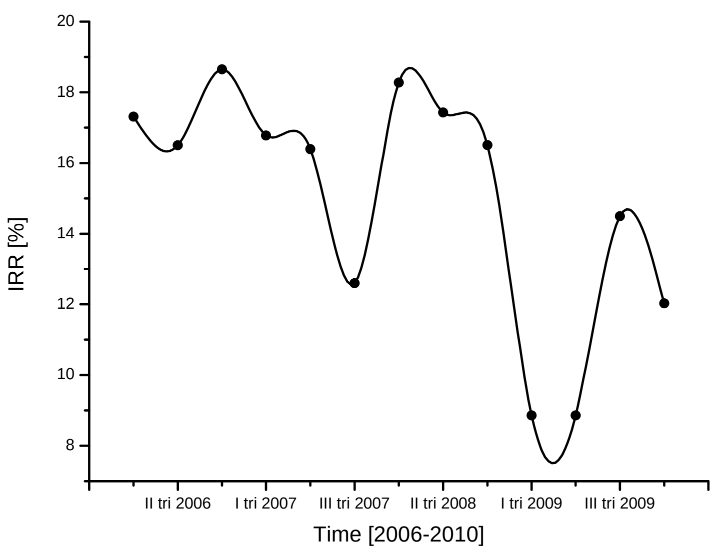


**Figure 3.42:** *IRR over time - Configuration 9*

Also the NPV and IRR are inside the fixed limits. The NPV values are broadly acceptable while those of the IRR are not so good. In fact they are about 9% that is an interest rate that have already been reached in past.

### *3.4.5 Discussion about the economic analysis*

An important facet to remember about the economic analysis is that it is only an order-of-magnitude analysis because there are aspects not taken into account as labour cost and soil cost. In addition, it has been chosen to make an economic analysis on the base of the prices of the last four years because it has not been possible to find detailed prices for all the products and by-products regarding years before 2006.

Looking at the parameters' trends, it is possible to identify a *critical period* at the beginning of 2009. During this period there is always a rise in the payback period, a sharp decrease in the NPV and a significant reduction of IRR. The reason of this sharp variations of the economic parameters depend on the set of prices for that period. In fact, between the end of 2008 and the beginning of 2009, the cost of corn has been of about 4 \$/bu that is very high (even thought not the highest value). The same holds true for the price of natural gas (0.34÷0.4 $\$/m^3$) while the electricity price has been the highest (~0.2 \$/kWh) among those relative to the range of time taken into account. Also for the outputs the prices were not favourable: the ethanol price has been one of the smallest (~1.5 \$/gal) while the DDGS, during this period, has been the only product with a high value (~126 \$/ton).

Number 6 is the configuration that better resists to the effects of the critical period: therefore, it results the configuration with the best economic performances. However, given that the sixth configuration has also the greater plant cost, it is important to mark that the economic results of the configurations 3 and 9 are not so far from those of number 6. Besides, the plant cost of the third and ninth configurations are about 11 M\$ less with respect to the number 6.

Another facet that should be analyzed are the results of the last three configurations. In fact, they could be broadly improved increasing the amount of corn stover processed. In this way, as already described, the electricity that can be sold to the grid can be largely increased, with very positive effects on the profit and so on the general economic performances. Moreover it is fundamental to remember that the greater the amount of electricity generated, the larger the amount of hot water produced, whose heat is however of low value.

# Conclusions

In this work the most important processes for ethanol production from corn and for energy generation from corn stover have been studied and compared. The aims were both to demonstrate that it is possible to significantly reduce the amount of energy from fossil sources using corn stover to generate energy, and to identify the most economical way, among those taken into account, to produce ethanol.

To achieve these two objectives, a set of simplified models, one for each process have been studied. Then, the single models have been combined to build different configurations where the energy produced by the treatment of corn stover was supplied to the ethanol plant. In this way nine configurations have been defined and compared on an engineering and economic base, setting the ethanol production to 75 million litres per year. For the technical comparison, we have taken into account parameters such as required soil, electrical and thermal energy request and environmental emissions while the profit has been the parameter for the economic comparison. Then, we have also evaluated the plant costs which have been the base, together with the operating costs, of the profitability analysis. With regards to this, three profitability indexes have been calculated: discounted payback period, discounted cumulative cash position (NPV) and discounted cash flow rate of return (IRR).

Given the prices broad variation, especially for electricity and natural gas, we have carried out also a profitability trend over time analysis, to verify if the configuration chosen as the better one remained the preferred choice also changing the prices.

The results of the technical analysis have shown quite big differences among the considered configurations, especially regarding the energy facet. So, it has been possible to clearly identify the best configuration (the number six) composed by a quick germ – quick fiber process for ethanol production and a combined heat and electricity generation process. In fact, this configuration has a null value of both electrical and thermal energy consumption because the CHP process, using about the 79% of the available corn stover, is able to produce the right amount of thermal energy required by the ethanol plant. At the same time, there are about 504 MWh of electricity that can be sold to the grid. The environmental emissions, 0.86 kilograms of $CO_2$ per litre of ethanol produced, are almost the same of the other configurations (0.82÷0.9 kg/l).

Regarding the profitability analysis, configuration number 6 has shown the biggest profit (~24 M$) and also the best profitability indexes. The payback period is of 6.5 years, the NPV is 83.4 M$ and IRR is 13.4%. Besides, the profitable trend over time analysis has confirmed the satisfactory technical and economic performances described above.

Unfortunately, the sixth configuration has the biggest soil and capital investment requests. So, it was noted that two others configurations have acceptable economic results but are less soil intensive and have capital costs of about 11 M$ smaller respect to number six. Both of these, use a quick germ – quick fiber process but different energy generation processes: combustion and gasification.

As a result, it can be assumed that the profitability is mainly related with the ethanol process, while the energy generation one plays a marginal role. However, it is fundamental to remember that the incomes of configurations with a gasification process, as number nine, can be largely increased treating a greater amount of stover and selling the excess electricity. Furthermore, it is also important to verify the profitability of this configurations because the gasification plant costs are really big compared with the others. The last facet about the gasification process is finding an utilization for the hot water produced, that cannot be used to supply heat to the ethanol plant (this needs steam at about 0.4÷0.5 MPa and 110÷120°C).

As a final result, it is clear that the best way to produce ethanol, among the existing and already commercial processes, is using a quick germ – quick fiber process that has a high ethanol yield and produce a large number of valuable by-products. At the same time it is possible to produce the thermal and electrical energy required by the ethanol plant, treating corn stover in a combined heat and power generation process.

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