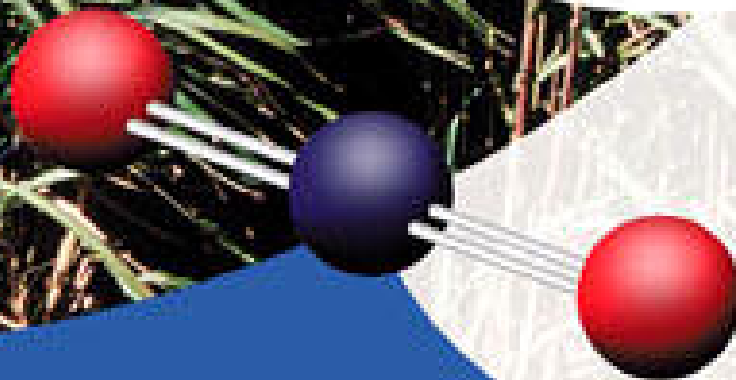




# Ligno Cellulosic- Ethanol

A second opinion

Report 2GAVE-03.11



***GAVE schakelt door***

# Colofon

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## Abstract

Up to now renewable energy sources are primarily used in the Netherlands for electricity production. At the end of the past decade the GAVE programme was launched to facilitate the introduction of climate neutral gaseous and liquid fuels. A comprehensive study by ADL evaluated a large number of options for the production of gaseous and liquid fuels. During the ADL study, the use of bioethanol - produced from lignocellulosic feedstock- as a substitute for gasoline was identified as highly attractive and promising for the reduction of Greenhouse gas emissions at a relatively low price.

The objectives of this study are: 1) to give an overview of the current technology available for production of ethanol from lignocellulosic feedstocks, and which companies are currently involved in lignocellulosic ethanol; 2) to identify major technological obstacles in the current production scheme, and to indicate which improvements have to be reached for a successful implementation of this technology, and 3) to estimate when and in what way large scale implementation of lignocellulosic ethanol in the Dutch transportation fuel market may be foreseen.

Finally, the prospects of reduction of Greenhouse gas emissions in the Netherlands by ethanol from lignocellulose are determined.

## Keywords

Bioethanol, cellulosic ethanol, pretreatment, lignocellulose, C5-fermentation, cellulase production, production costs, avoided CO<sub>2</sub> emissions, CO<sub>2</sub> reduction potential.

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# Summary

## Background

In 1998 Novem started the GAVE programme on behalf of the Ministry of Housing, Spatial Planning and the Environment and the Ministry of Economic Affairs. The objective of the GAVE program is to stimulate and speed up the market introduction of climate neutral gaseous and liquid fuels. One way to fulfil part of the climate and sustainability objectives of the Dutch government is the (partial) substitution of gasoline with bioethanol. In this scenario bioethanol will be produced from energy crops, and low-cost biomass residue stream (lignocellulosic feedstock). The use of this feedstock offers good perspectives for large-scale application of ethanol in transportation fuels. Moreover, bioethanol produced from this type of feedstock is identified as a highly cost effective option for CO<sub>2</sub> emission reduction in the transportation sector. However, currently the production costs of ethanol from lignocellulosic feedstock are too high, and current available technology results in high amounts of waste streams. Moreover, current technology for producing bioethanol from lignocellulose is nowhere in the world implemented.

## Objectives

The objectives of this study are to give an analysis of who are actively involved in the production of ethanol from lignocellulosic feedstock both national and international, which activities are currently taken place with respect to technology developments, and when and in what way is the large-scale implementation of bioethanol produced from lignocellulose expected in the Netherlands.

## Results

Currently (2002) 211 Mhl (450 PJ) bioethanol is produced world-wide (Brasil 59%, U.S.A 36%, Europe 2%, rest of the world 3%) from conventional feedstock (corn, sugarbeet, wheat) at a cost price of 0.34 €/l (=16.2 €/GJ), which is twice the cost price of gasoline (7.3 €/GJ). High feedstock cost (> 50% of the total cost price) and the limited availability of conventional feedstock pose a large obstacle to large-scale implementation of ethanol as a transportation fuel. Therefore alternative feedstocks are necessary. Lignocellulosic feedstock and low-cost biomass residue streams could be suitable feedstocks for the large-scale production of ethanol.

At this moment technology is available for producing ethanol from lignocellulosic feedstock. The current available technology follows largely the same path as the technology for producing bioethanol from sugarbeet, or other starch rich feedstocks. Major differences between ethanol production from conventional feedstock and lignocellulosic feedstock are: 1) pretreatment of the feedstock (liberation of glucose and xylose from the biomass), and 2) xylose fermentation to ethanol. Lignocellulosic

biomass is pre-treated with both physical/chemical methods and enzymatic methods to hydrolyse the sugar polymers to sugar monomers (glucose and xylose). These sugars are fermented into ethanol, and subsequent distillation of the fermentation broth yields the crude ethanol. Implementation of current technology is hampered by the generation of large amounts of inorganic waste (e.g. gypsum) and the high production costs (0.35 €/l). The major cost driver of bio-ethanol production is the enzymatic cellulose hydrolysis. The costs are about 50% of the net production costs per ton ethanol. Another large obstacle is the absence of economically feasible xylose fermentation technology. Despite substantial research efforts in the past decades, targeted among other things at *Zymomonas mobilis*, and *E.coli* no suitable micro-organism is as yet available for C5 fermentation, with sufficient robustness. Further reduction in production costs can be obtained by process optimisation and an efficient use of waste streams (e.g. heat and power generation).

Based on the above mentioned process improvements, a future potential cost price is estimated at 0.23 €/l (=11 €/GJ). The cost of CO<sub>2</sub> emission reduction using current technology will be between 73-108 €/ton. The cost of CO<sub>2</sub> emission reduction in the future (2010) will be between 27 – 38 €/ton. These cost are much lower than the CO<sub>2</sub> emission reduction cost for ethanol produced from conventional feedstock (550 €/ton) [32]. The total Dutch CO<sub>2</sub> emission reduction for a 5.75% gasoline substitution by cellulosic ethanol will be about 0.8 Mton CO<sub>2</sub>. This would require 1.7 Mton lignocellulose (345 kton ethanol). A complete substitution of all fossil transportation fuels in the Netherlands in 2010 would result in reduction of Greenhouse gas emissions with 39.3 Mton CO<sub>2,eq</sub>.

Although there is no commercial plant producing bioethanol from lignocellulose in the world today, two serious initiatives are on their way to commercialization: a pilot plant build by ETEK (Sweden, ethanol production capacity 400 l/day), and a demonstration plant build by Iogen (Canada, ethanol production capacity 880 l/day).

## Conclusions

1. Technology for producing ethanol from lignocellulose is available. However, this technology results in the generation of large amounts of inorganic waste (e.g. gypsum), and the xylose present in the feedstock is not converted to ethanol. Obviously, the available technology is not environmentally friendly. Therefore, improvements in current technology and new technology is needed. Major topics are: 1) pretreatment of the biomass, 2) enzymatic hydrolysis, 3) C5-fermentation, 4) process optimisation and efficient use of residue streams. On these four topics R&D is employed both at research institutes, universities as well as companies. Especially in those countries, where supporting regulations for fuel ethanol as a transportation fuel are in place (e.g. USA, Canada, Sweden and Spain). Substantial improvements in pretreatment technology and xylose fermentation are foreseen in the next decade. Such improvements will result in a rapid introduction of bioethanol produced from lignocellulosic feedstock.
2. It is likely that conversion of lignocellulosic biomass to ethanol will be commercially implemented through a number of gradual changes at current industrial facilities. These gradual changes include fermentation of xylose to increase conversion efficiency, and transition to less starch-containing feedstocks that contain cellulose as well. Two different types of industries are present in the

market. 1). companies currently producing ethanol from conventional feedstock (e.g. Nedalco). These companies have a minor interest in commercialisation of the residual biomass, that is not used for bioethanol production. The transition towards a lignocellulosic feedstock is directed by the availability of economical feasible technology. 2) another kind of companies shows interest in producing both heat and power from the residual biomass after ethanol fermentation, and the ethanol production itself (ETEK, Iogen, Abengoa). These companies either mix lignocellulosic feedstock with conventional feedstock (Abengoa) or use only lignocellulosic feedstock for producing ethanol (ETEK, Iogen). The latter companies have made the transition towards lignocellulosic feedstock. Improvements in technology will result in higher ethanol yields, and less generation of power and heat.

3. Currently ethanol is blended with gasoline (different percentages in different countries). In Europe only Sweden uses direct blending. In France and Spain the ethanol is converted to ETBE, and then blended with gasoline. This ethanol, however, is produced from traditional feedstock. When it is possible to produce ethanol from lignocellulosic feedstock in an environmentally friendly way at a competitive cost price, this ethanol can be directly applied as a transportation fuel, in the same way ethanol produced from conventional feedstock is nowadays applied. At this moment, environmentally-friendly technology is only available at lab scale. However, a lot of R&D is employed around the world (Spain, U.S.A., Canada, Sweden), and based on their efforts, an available mature technology for producing ethanol from lignocellulose feedstock is foreseen around 2010-2015. Then, the introduction of this new technology in the market depends largely on the establishment of markets and subsidy mechanisms. In those countries where at this moment, ethanol is blended with gasoline (e.g. USA, Sweden, Spain) a lot of technology driven research is employed and funding is available for constructing demonstration and pilot plants.

## Recommendations

In (the near) future ethanol will largely contribute to the total amount of fuels for transportation. Ethanol produced from conventional feedstock, today's mature technology, cannot fulfil the demand, and ethanol produced from lignocellulosic feedstock will be necessary. To develop a mature environmental-friendly technology, further R&D should focus on: 1) pretreatment of the biomass (both by physical-chemical methods as well as by enzymatic methods) 2) reliable robust C5-fermentation, 3) process optimisation and 4) efficient use of process residue streams (e.g. heat and power generation with BIG/CC).



# 1. Introduction

## 1.1 Background

The large-scale introduction of biomass in the Dutch energy-infrastructure is inevitable to fulfil the climate and sustainability objectives of the Dutch government. This large-scale introduction demands a broad application of biomass in the Dutch society. This means an introduction not only in conventional markets (the power production market, via co-firing and stand-alone initiatives), but also in other potential interesting markets like the transportation fuels market (gasoline and diesel substitution), the domestic market (natural gas substitution), and the industrial market (fossil fuels substitution).

In the 1990s various inventory studies, initiated by Novem as part of the GAVE-program, were performed studying the applicability of biomass as feedstock for the production of gaseous energy carriers (SNG<sup>1</sup> and Hydrogen) and liquid transport fuels (e.g. Fischer Tropsch-diesel, bioethanol from starchy material and bioethanol from lignocellulosic material, biomethanol, biodiesel etc.). Based on these studies different chains were defined, from feedstock to end-product. These chains were evaluated by Arthur D. Little on the basis of different analyses (technology, cost and amount of CO<sub>2</sub>-reduction potential). Twenty remaining chains, identified as potential interesting and relevant, were judged on a macro- and social-economic analysis, a stakeholders analysis, and a replication potential analysis. It appeared that one of the most attractive chain with respect to liquid transport fuels, is the chain in which lignocellulosic material is converted to bioethanol [1].

Bioethanol has been known as a fuel for well over 100 years. In 1860, German inventor Nicholas August Otto used ethanol as a fuel in an early prototype of an internal combustion engine. At the beginning of 1900 up to 1960, ethanol was mixed with gasoline and used as transport fuel in the USA, Brazil and European countries like Germany, France, Italy, Sweden, and England. By the early 1960s the production of ethanol as a fuel transport fuel disappeared due to the fact that abundant supplies of oil made the use of bioethanol uneconomical. The renewed interest in bioethanol is directed by factors as national energy security concerns, new gasoline standards, governmental incentives, technological developments and market forces. This interest started in Brazil in 1979, in the U.S.A around 1980, and in Europe at the beginning of the 1990s [4].

Currently fuel ethanol is produced in Brazil (125 Mhl/year), the U.S.A. (76 Mhl/year) and European countries (4.2 Mhl/year) from sugar cane or starch crops, including: corn, wheat and sugar beets<sup>2</sup>. The production cost of ethanol from these agro-feedstocks is approx. 0.34 €/litre (16.2 Euro/GJ) which is more than 2-fold the price of gasoline (7.3 Euro/GJ). The high feedstock costs (accounting for about 50% of the

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<sup>1</sup> Substitute Natural Gas

<sup>2</sup> 1 ton ethanol equals 12.5 hl ethanol

ethanol production costs) and the relatively limited contractability of starch and sugars, pose a major obstacle to large-scale implementation of ethanol as a transportation fuel. For the application of these feedstocks there is a strong competition with the feed and food industry [5].

The use of (ligno)cellulosic energy crops, and particularly low-cost biomass residue streams, offers excellent perspectives for large scale application of ethanol in transportation fuels [6]. The use of these materials will allow for a substantial increase of fuel ethanol production capacity, and a reduction of the ethanol production costs to a competitive level, due to relatively low feedstock costs.

Another major incentive for the development of technology for the production of bioethanol from lignocellulosic materials is the fact that bio-ethanol produced from lignocellulosic biomass was identified as a highly cost effective option for CO<sub>2</sub> emission reduction in the transportation sector [1,22,28,29].

## 1.2 Problem definition

FT-diesel and ethanol from lignocellulosic sources, as transportation fuels, are the most promising alternatives for substituting fossil fuels. However, the implementation of technology necessary for the production of ethanol from (ligno)cellulosic sources seems to be far away. Currently, production costs of ethanol from these sources are too high, and application of potentially interesting biomass residue streams in order to reduce total cost is nowhere implemented in a commercial way. A substantial RD&D-trajectory is needed for topics such as: the pre-treatment of the feedstock, C5-fermentation, thermal conversion of the organic side-product, the right formulation of the ethanol/gasoline blend, and total process integration and optimisation. This was an important conclusion of the Dutch EET-project 20117 "GF/WK-procedure: co-production of bioethanol, electricity and heat from (ligno)cellulosic rich organic residues via an integrated fermentation, and heat and power generation procedure" [7].

## 1.3 Objective

The objectives of this study are analyses of: 1) who is actively involved at this moment at both national and international level in the production of ethanol from lignocellulosic materials; 2) which activities are currently taken place in the market with reference to technology developments, and 3) when and in what way the large-scale implementation of ethanol from lignocellulosic sources can be realised in the Netherlands.

## 1.4 Outline of the report

In Chapter 2 an overview is given of the current technology for the production of bioethanol from lignocellulosic feedstocks, and which companies are currently involved. Chapter 3 deals with technology developments taking place at this moment, and technology breakthroughs that are foreseen in the (near) future. Chapter 4 describes the economic activities in the world and summarises recent developments for bioethanol from traditional feedstocks ("conventional bioethanol"). In Chapter 5 the CO<sub>2</sub> reduction potential for the Netherlands is estimated. In Chapter 6 the

introduction of bioethanol as transportation fuel in the market is discussed, and in which way the transition from conventional feedstock (starchy material) to lignocellulosic feedstock can take place. Conclusions and recommendations are given in chapter 7.

## 2. Description of the current technology and different companies involved

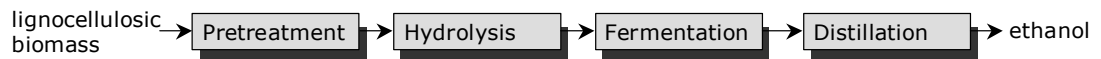
In this chapter a brief overview of the technology at this moment available for the production of ethanol from ligno(cellulosic) materials, and companies that are in some way involved in technological developments, are described .

### 2.1 Current Technology for producing ethanol from (ligno)cellulose materials

Fuel ethanol is currently produced in Brazil, the U.S.A. and several EU countries (Spain, France, Sweden) from sugar cane, sugar beet or starch crops, including: corn and wheat. Technology for the production of bioethanol from these feedstocks is well-established and mature. The process for corn as feedstock is shortly described as: 1) milling of the corn, 2) liquefaction of the corn meal with hot steam and the enzyme  $\alpha$ -amylase at elevated temperature (90-110 °C), 3) saccharification of the mash with glucoamylase at 60 °C, 4) fermentation of the sugars to ethanol by yeast, 5) distillation of the fermentation broth to crude ethanol (~45 vol%), 6) rectification of the crude ethanol (~96vol%), and 7) dehydration of ethanol to fuel specifications (>99.9%) by molecular sieves.

Lignocellulosic biomass differs in one aspect largely from starchy material, viz. the composition of the feedstock. Lignocellulosic biomass is composed among other things of cellulose, hemicellulose and lignin. Cellulose is a linear polymer of glucose monomers, and in contrast to amylose (the main feedstock component for the conventional ethanol production), not susceptible to the relative cheap amylase enzymes for hydrolysis to the monomeric sugars. Hemicellulose is a branched polymer of primarily glucose and xylose. Hydrolysis of hemicellulose is readily achieved under mild acid or alkaline conditions. The amount of hemicellulose and cellulose, and their subsequent monomeric sugars (mainly glucose and xylose), depends largely on the nature and source of the lignocellulosic biomass. However, both the cellulose and hemi-cellulose fractions are a potential source of fermentable sugars. Lignin cannot be fermented to ethanol, and as such is a residual material. In order to make an overall process economically feasible and competitive the lignin and other non-fermentables (e.g. fermentation residues) will have to be used in a biomass-CHP system to provide steam and electricity.

At this moment commercial production of ethanol from (ligno)cellulose does not take place anywhere around the world. However, a lot of industrial related R&D is implemented.



*Figure 1 Generic process scheme for bioethanol production from lignocellulosic biomass.*

The different process sections depicted in Figure 1 will include the following unit operations [7]:

#### Pretreatment

- Biomass treatment/handling (milling/chipping) for size reduction and opening up of the fibrous material for further treatment and production of a pumpable slurry.
- Thermo-chemical pretreatment for mobilisation of the lignin and (hemi)cellulose biopolymers and further breakage of structural components to optimise access for enzymes in further processing.

#### Hydrolysis

- Liquefaction of the highly viscous polysaccharide matrix to a liquid stream of sugar oligomers. This step can be performed in an acid/base and/or heat catalysed reaction with the possible aid of enzymes.
- Saccharification; enzymatic hydrolysis of sugar oligomers to fermentable monomeric sugars, mainly glucose (C6) and xylose (C5).

#### Fermentation

- Fermentation of both glucose (C6) and xylose (C5) to ethanol.

#### Distillation

- Distillation for separation and upgrading of ethanol from the fermentation broth to 'crude' ethanol (ca. 45 vol%).
- Rectification; concentration of 'crude' ethanol to approx. 96 vol%.
- Dehydration of ethanol to fuel specifications (> 99.9 vol%) by 'molecular sieves'.

In comparing the process for producing bioethanol from a traditional feedstock with the production of bioethanol from a lignocellulosic feedstock major differences are found in the pretreatment, and hydrolysis section, as well as in the C5-fermentation. C6-fermentation and recovery of the ethanol from the fermentation broth are proven technologies.

A historical overview of the developments regarding pretreatment, hydrolysis and fermentation is schematically shown in Figure 2.

Up to the 1950s acid hydrolysis was used to produce the glucose monomers. These monomers were fermented to ethanol and the hemicellulose was regarded as waste. In the 1970s cellulase enzymes became available for hydrolysing cellulose; higher yields were attained and unwanted side reactions eliminated. Still, hemicellulose could not be fermented to ethanol. In the 1980s enzyme performance drastically improved and first efforts were made to consolidate biological hydrolysis and glucose fermentation.

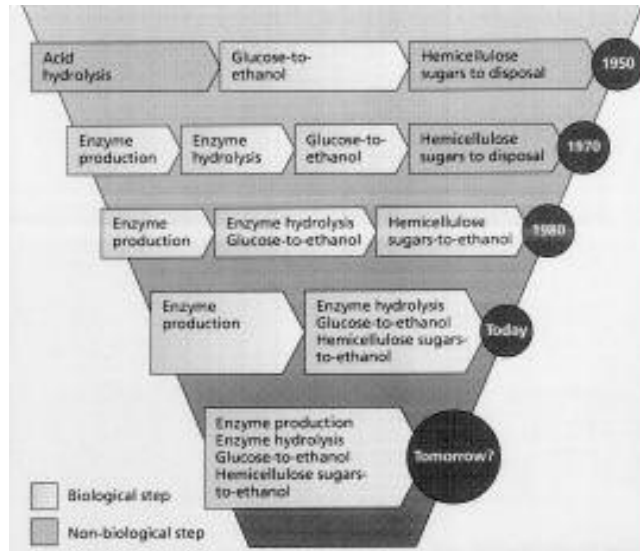


Figure 2 Historical overview of technological developments [8].

Micro-organisms were identified that could ferment the monomeric sugars in hemicellulose (C5-sugars). Today it is in principle possible to ferment both hemicellulose and cellulose to ethanol at a laboratory scale. Fermentation of C6-sugars (glucose) can be done in an economically feasible way, but fermentation of C5-sugars (xylose) is currently not economically feasible. Different processes have been developed, which will be shortly described below. Also, the major obstacles and drawbacks of these processes will be mentioned [8].

An outline of three technological options for co-production of ethanol, heat and electricity from lignocellulosic biomass that are currently under development are given below.

The NREL process (Figure 3) is a well-documented process design [9]. The process uses a combination of steam pre-treatment and mild acid hydrolysis of the hemicellulose fraction and subsequent enzymatic hydrolysis of the cellulose. Cellulose hydrolysis and fermentation of xylose and glucose monomers occur in the same reactor. The fermentation organism is a genetically modified strain from the bacterium *Zymomonas mobilis*.

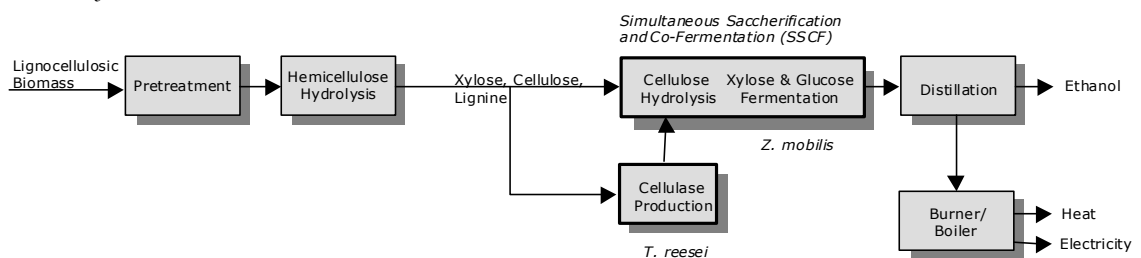


Figure 3 Biomass to ethanol process developed by the National Renewable Energy Laboratory (NREL), USA. [9].

The BCI process (Figure 4) uses a two-stage acid hydrolysis. The first stage releases the hemicellulose and the second the cellulose sugars. The xylose fermentation to ethanol is performed by a modified *E.coli* bacterium for ethanol fermentation.

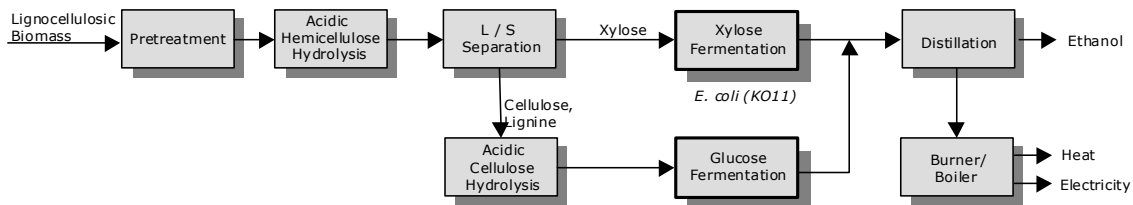


Figure 4 Biomass to ethanol process developed by BC International Corporation (BCI), Canada [10,11].

The process developed by Iogen Corporation (Figure 5) employs steam explosion with dilute acid for release of hemicellulose sugars and subsequent enzymatic hydrolysis of cellulose. Fermentation is performed by licensed technology. Lignin is removed prior to fermentation and could either be used for production of chemicals or as fuel for CHP production.

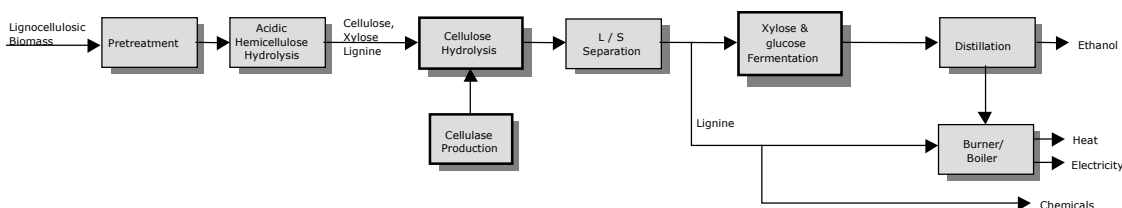


Figure 5 Biomass to ethanol process developed by Iogen Corporation, Canada [10, 11].

All processes use distillation (+ additional deep dewatering) and a conventional combustion/ steam boiler system for CHP production from the non-fermentable biomass fraction.

The major drawback of the NREL process and the BCI process are the high amount of residue material produced. For the NREL process, the acid hydrolysis uses 0.1 kg  $H_2SO_4$  / kg ethanol and subsequently 0.04 kg lime / kg ethanol. This lime is also used for removing fermentation inhibitors formed due to the acid hydrolysis. The total amount of gypsum generated is 0.13 kg/kg ethanol. At least similar amounts of residue material (gypsum) are produced in the BCI process. The pretreatment of the lignocellulosic biomass using steam explosion with dilute acid in the Iogen-process will definitely generate residues.

Obstacles in the existing processes include: insufficient separation of cellulose and lignin (which reduces the efficacy of subsequent enzymatic cellulose hydrolysis), the formation of by-products that inhibit ethanol fermentation (acetic acid from xylans, furans from sugars and phenolic acids from the lignin fraction), the high consumption of chemicals, and considerable residue production.

One large obstacle in all processes described is the C5-fermentation. Despite substantial research efforts in the past decades, targeted among other things *Zymomonas mobilis*, and *E.coli*, no suitable microorganism is as yet available for C6 and C5 co-fermentation, with sufficient robustness [12]. A large economic obstacle is the high cost of the cellulase enzyme. In Dutch EET<sup>3</sup>-project 20117 "GF/WK-procede" it is concluded that the major cost driver of cellulosic bioethanol production is the enzymatic cellulose hydrolysis. The costs are 40-55% of the net production costs per ton ethanol.

<sup>3</sup> EET: Economy, Ecology and Technology

Although there are no commercial plants in the world at this moment producing bio-ethanol from lignocellulosic material, three initiatives are one their way to commercialisation:

1. The National Renewable Energy Laboratory (NREL) of the USA developed a pilot plant to investigate integrated processes for the enzymatic conversion of lignocellulosic biomass to ethanol [13]. This pilot plant incorporates all the processes shown in Figure 3. Biomass with a feed rate of 1 ton dry material per day can be processed. The main fermentation equipment consists of four 9000 l stirred tanks. The pilot plant can use as pretreatment technology a continuous dilute acid system, a steam gun system, and a new developed counter-current shrinking bed system. Both glucose and xylose are fermented simultaneously in one vessel.
2. Iogen Corporation has built a demonstration plant, EcoEthanol™, capable of processing 25 tonnes of wheat straw per week into fermentable sugars. This will lead to an annual production of 320,000 liters of ethanol (press release 16 January 2003).
3. In the northern part of Sweden different regional energy companies (e.g. Skellefteå Kraft) started a new company ETEK (EthanolTeknik). This new company designed a complete industrial pilot plant capable of handling 2 tons dry feedstock per day and producing 400-500 litres ethanol per day. The design is based on the process developed by NREL (Figure 3). As pretreatment technology they use the counter-current shrinking bed technology development by NREL. The envisaged feedstock will be softwood residues. Operation of the plant is foreseen at the end of 2003. The total investment cost were 16 M€ [14].

To conclude this chapter, the major problems to be solved for a successful implementation of bio-ethanol from lignocellulosic biomass are:

- environmentally friendly pretreatment of the biomass with a minor amount of waste produced
- a large reduction in the cost of the cellulase enzyme production
- overall system optimisation, incl. using waste streams for CHP production, and
- reliable and robust C5-fermentation technology with a high ethanol yield

## **2.2. Companies involved in cellulose ethanol production**

At this moment ethanol is not commercially produced from lignocellulosic feedstock. So far there are few companies involved in R&D on cellulose ethanol. Stakeholders can be divided in: 1) enzyme companies, 2) ethanol producers and 3) research institutes. Stakeholders are located in countries where there are supportive regulations in place for use of ethanol as transportation fuel.

### **2.2.1. Enzyme companies**

*Novozymes* is market leader in the production of enzymes for converting starch (from maize) into fermentable sugars. *Novozymes* aims to defend its market leader position.



Therefore production of enzymes for converting cellulose into fermentable sugars is one of their main business development areas. Especially in the U.S.A., the ethanol industry is a booming market (20% increase of production annually).

In the U.S.A. the Department of Energy has included in its strategy to increase cost-efficiency of the production of bio-ethanol from biomass resources. The National Renewable Energy Laboratory (NREL) is running a three-year US\$ 14.8 million project with Novozymes, Abengoa High Plains, and VTT Finland to reduce the costs of cellulase enzymes, which is one of main barriers for cellulose ethanol production. The goal of the project is to reduce these costs 10-fold within defined milestones. Today enzyme costs are around 0.119 \$/litre and they should be reduced to 0.0119-0.0238 \$/litre to make it economically feasible for bioethanol production. Novozymes reached the second milestone (3 fold cost reduction).

Novozymes has been granted US\$ 2.2 million for participating in "Pre-Commercialisation of a Biomass-derived Process Technology" pilot plant demonstration. High Plains Corporation is leading the project (see 2.2.2, Abengoa).

*Genencor* is a company in the same league as Novozymes. They produce enzymes for converting starches into fermentable sugars. Genencor is the second company that is running a project with the NREL institute in order to reduce enzyme costs to a 10-fold. Genencor was awarded with a US 17M\$ contribution for reducing these costs. Thus far they reached the first milestone (1.5 fold cost reduction).

*Iogen* is a relative small-scale enzyme producer and combines its activities with design and engineering for production processes. Iogen's process combines pretreatment, enzyme technology, and fermentation technology (and optimisation of by-products use for electricity and animal feed purposes).

Iogen has been awarded for a year US\$ 5.4 million (50/50) cost shared project with the Canadian government. The project seeks to achieve a 10-fold improvement of enzyme efficiency.

Today Iogen operates at their site in Ottawa a US\$ 35 million bioethanol plant, which integrates cellulase enzyme R&D into production process of bioethanol. The facility processes 25 tonnes of wheat straw a week to produce 320.000 litres of ethanol annually. Iogen's bioethanol process reduces greenhouse gas emissions by 90% compared with gasoline. Iogen expects the first commercial facility for cellulose bioethanol to be in operation in 2006; construction is announced for mid 2004.

### ***2.2.2. Potential cellulose ethanol producers***

In 2002 *Shell* purchased an equity share in Iogen which fits its strategy to invest in promising breakthrough technology. Shell and Iogen will co-operate on the demonstration facility for bioethanol in Canada. Thus far Shell is the only known oil company involved in purchase of cellulose ethanol production. Shell's involvement will be a huge advantage for moving from conventional ethanol to (ligno)cellulosic ethanol. The availability of lignocellulosic ethanol on the market could be realised in relative short period of time.

*Abengoa* produces bio-ethanol for the Spanish market. It owns companies and conducts businesses around the world in engineering and construction in the energy sector. Thus far there are two bio-ethanol plants on stream. The third bio-ethanol plant is announced for 2004. The plant foreseen for 2004 will use lignocelluloses (up to 2,5%)

and barley as feedstock. There is also the intention to construct a fourth facility, which would be fully run on cellulose technology. Abengoa could become the first cellulosic bio-ethanol producer in Europe. In 2002 Abengoa acquired High Plains Co. in the USA. High Plains is a bio-ethanol producer on the basis of wheat. This is quite exceptional in the USA (90% of all feedstock is maize). High Plains participates in the USD 14.8 million research project with Novozymes. The main feedstock for Abengoa in Spain is wheat. Technology breakthrough in the U.S.A. at daughter company High Plains (wheat) could speed up the introduction of cellulose ethanol in Spain. Abengoa is in the front seat for starting production of cellulose ethanol in Europe. Especially, because Abengoa has for several years experience in producing ethanol and selling it to the Spanish market, due to supportive legislation (no duty on biofuels) in favor of conventional ethanol.

*Arkenol Inc.* is producer of biobased chemicals and fuels. Arkenol is in final development of its first commercial-scale biorefinery, a combined 1 million liters per year ethanol and 40.000 metric ton per year citric acid facility in Sacramento. Arkenol is also involved in a production facility for cellulose ethanol on the basis of concentrated acid treatment. Besides, Arkenol and National Renewable Energy Laboratory (NREL) compiled a co-operative research and development agreement to develop production of ethanol from rice straw by genetically modified yeast which ferments five and six-carbon sugars simultaneously.

*ADM, Cargill and Staley* (which control 60% of the ethanol market in the USA) have their own research programs and do not participate in large-scale governmental supported (and therefore public) projects. So far these companies report no technological breakthroughs. It's expected that if they do not succeed in own technological breakthroughs, they will use (new) enzymes licenses from companies like Novozymes and Genencore.

*Nedcalco* produces conventional alcohol for food and technical purposes. Nedcalco is not involved in bio-ethanol production for fuel purposes (there are no supportive regulations in place for bio-ethanol in the Netherlands). Nedcalco's production process fits possible (ligno)cellulosic bio-ethanol production in the future. Therefore Nedcalco participates in several (European) research projects. Compared to countries where biofuels are supported these R&D projects are on laboratory scale and do not include pilot plants. Research is done on: lignocellulose technology, C5-fermentation and pretreatment of biomass for CHP purposes in co-operation with TNO, ATO, ECN, Shell, TUD, WUR, Lund (Sweden) and VTT (Finland).

### **2.2.3. Research institutes**

*ETEK (Etanolteknik AB)* is a Swedish joint venture between several energy companies. The company's strategy is to build and operate a demonstration plant in 2006 where the production technology for ethanol and lignin from lignocellulose can be developed and verified. The lignin will be side-streamed from lignocellulosic biomass and will be used for heating/electricity purposes. The bio-ethanol from cellulose will be used for fuel purposes (commercially interesting because there is no duty charged for bio-ethanol in Sweden). Construction and investments are made for a 500 litre/day and 2 ton dry substance/day on basis of dilute-acid production and enzymatic hydrolysis. In 2008 production plants for ethanol and lignin from lignocelluloses are expected to start on a commercial base.

VTT is a general Finnish research institute in the field of electronics, IT, industrial systems, processes, building and transport, and biotechnology. VTT is an interesting institute for cellulose ethanol (specifically xylose fermentation), because it could combine experience of process engineering and biotechnology. VTT is partner in the USD 14.8 million NREL program with Novozymes and Abengoa High Plains.

Different Dutch research institutes (*ECN, TNO, TUD, ATO and WUR*) are involved in several projects dealing with the different topics in producing ethanol from lignocellulosic feedstock. A large consortium is formed to co-operate in a four year 6 M€ EET-project "Co-production of renewable transport fuels, green chemicals, power and heat from biomass residue".

The European directive on promotion of biofuels could mean a stepping stone to acquire more interest in cellulose ethanol in Europe and get involvement of several commercial partners more interestedly. Until now only companies (ethanol producers or enzyme producers) and research institutes have been seriously involved in (ligno)celluloses technology. Especially, where supporting regulation for fuel ethanol are in place in countries like the USA (NREL), Canada, Sweden (Lund university and Umea University) and Spain (CIEMAT). This could improve the technology knowledge position of Europe.

# 3. Technological developments

In the preceding chapter it is concluded that ethanol produced from lignocellulosic feedstock is promising. However, there are currently different obstacles identified for which mature, cost-effective and environmental friendly technology is not yet available. A key element in reducing the cost of bioethanol is improving pretreatment technology, including the use of cellulase enzymes in conversion of lignocellulosic feedstock. Recent innovations include: progress in pretreatment techniques, enzyme technology, pentose fermentation, and simultaneous saccharification and fermentation (SSF). Innovations on overall process optimisation are: 1) use of waste streams for CHP production (Biomass Integrated Gasification/ Combined Cycle), and 2) developments of alternatives for evaporation processes.

## 3.1. Current developments

### 3.1.1. Pretreatment

A key element in reducing the cost of bioethanol is improving pretreatment technology. Without effective pretreatment, sugar yields are low as cellulose is not readily accessible to cellulase enzymes [15]. The ideal pretreatment technology should lead to: 1) a high yield of fermentable sugars, 2) low or zero formation of side products, inhibiting the cellulose hydrolysis and ethanol fermentation, 3) absence or requirements for chemicals recycling, 4) low or zero residue production and 5) low capital investments. A review of pretreatment technology is given by Sun and Cheng [16].

Over the years, various biological, chemical, and physical pretreatment approaches have been studied. Dilute sulphuric acid pretreatment is one of the most commonly chosen routes nowadays because of low material costs and high hemicellulose sugar yields [17]. Steady progress over the years has been achieved in technology refining, which resulted in 80-90% sugar yields at reaction times of about 10 minutes with acid levels of 0.7% on dry weight basis. Weak acid hydrolysis however still suffers from major drawbacks -e.g. formation of inorganic side-streams and high capital costs due to corrosiveness and higher temperatures and pressures needed. Furthermore, formation of fermentation-inhibiting products is a key issue in acid pretreatment. Alternative pretreatment technologies include mechanical technologies (e.g. extrusion), supercritical oxidation, dissolution in organic solvents, alkaline pretreatment and acid hydrolysis using dissolved CO<sub>2</sub>. Recently, a consortium of Dutch companies and R&D institutes has launched a 4 year development program that is based on two of these alternative pretreatment technologies [7] (alkaline pretreatment and acid hydrolysis using dissolved CO<sub>2</sub>). A recent development in pretreatment technology is the so-called pressurised hot wash treatment that removes solubilised lignin and hemicellulose immediately after pretreatment, leaving the cellulose fraction more "digestible" for the subsequent enzymatic hydrolysis [21]. Major research institutions involved in developing state-of-the-art pretreatment

processes of lignocellulosic biomass include the National Renewable Energy Laboratory (USA), Lund University (Sweden), CIEMAT (Spain), the Royal Veterinarian Agricultural University (Denmark), TNO, ATO as well as other universities and institutes.

### **3.1.2. Enzyme technology**

Besides pretreatment technology, the use of cellulase enzymes is a key issue in conversion of lignocellulosic feedstocks. Cellulase is produced commercially but current production is directed at low-volume, high-value, speciality products. As a result, the current available industrial cellulases are not effective enough and too costly for wide-scale industrial application. Key enzyme producers such as Novozymes, Genencor and Iogen are involved in extensive R&D to increase the cost-effectiveness of enzymes for lignocellulosic biomass conversion. The most commonly researched conversion route is the hydrolysis of the field residue of maize production (corn stover) that is pretreated by dilute acid technology, however other lignocellulosic biomass such as cereal straw is being studied as well. Nevertheless, cellulase action is still low, with reaction times of about 5-7 days to achieve modest ethanol concentrations, compared to 2 days for conventional starch-derived ethanol. Among others, studies are carried out to evaluate the application of enzymes to the whole fermentation broth (mixed solid/liquid hydrolysate), rather than the liquid, which will reduce capital costs by eliminating extra separation steps.

### **3.1.3. Pentose utilisation and fermentation**

Despite substantial efforts, no current fermentation system exists that can utilise the entire cellulose fraction from lignocellulosic biomass. Monomers derived from the hemicellulose fraction include substantial amounts of xylose and arabinose, five-carbon sugars (pentoses), which cannot be fermented with the ordinary strains of baker's yeast. Without a profitable use of these pentoses, cellulosic bioethanol is too expensive to compete in commercial markets. Three approaches that have been attempted to enable fermentation of pentoses are: genetic modification of baker's yeast, co-culture of different strains from *Zymomonas mobilis*, and cloning of pentose-utilising genes into ethanol-resistant strains of *E. Coli*. In addition, there is some research experience with anaerobic micro-organisms that convert the entire lignocellulose fraction directly into ethanol. Despite the reported progress in research journals, there is a lack of experience with these micro-organisms at industrial scale. Major European research organisations involved in fermentation of C5 sugars derived from ligno-cellulose include: VTT Biotechnology (Finland), the Danish Biofuel Centre (Denmark), ATO (the Netherlands), and several other universities, organisations and biotech companies.

### **3.1.4 Simultaneous saccharification and fermentation**

A process that generally has been viewed as favourable for cellulosic ethanol fermentation application, is simultaneous saccharification and fermentation (SSF). Since high concentrations of simple sugars can inhibit the enzymatic hydrolysis of cellulose, there are advantages to continuously removing them from the reaction vessel by using SSF. A major problem with this technology is that the optimal temperatures for saccharification (50 – 60 °C) and fermentation (30°C) are different.

Recent research is carried out to evaluate so-called thermo-tolerant micro-organisms, which can convert sugars into ethanol at higher fermentation temperatures. Most of the research and technology development on SSF to date has been initiated and carried out in the United States, which comprises the work that is co-ordinated by the three federal research laboratories concerned with liquid biofuels -i.e. the National Renewable Energy Laboratory, the Oak Ridge National Laboratory, and the Pacific Northwest Research Laboratory.

### **3.2. Cellulose ethanol: costs and technological breakthroughs needed**

As was outlined in the previous paragraphs, two key issues for making ethanol from lignocellulosic biomass more competitive are: the pretreatment technology used, and the cost-effectiveness of enzyme technology [15,17,18]. Although production costs of bioethanol are site and organisation specific, some general remarks can be made with regards to future production costs of (ligno)cellulosic bioethanol. Two recent studies evaluated the costs of producing ethanol from ligno-cellulosic biomass and provide ample information on what cost factors need to be reduced to result in a competitive price for bioethanol. These studies are summarised below.

A joint study by the U.S. Departments of Energy and Agriculture [19] investigated the likely price development of ethanol derived from the lignocellulosic residue from maize production (corn stover), and compared it with the current maize-to-ethanol industry. Figure 6 presents the cost estimates from this study (represented in 1999 US\$ l<sup>-1</sup> ethanol), and assumes an equally sized facility with on-site propagation of enzymes. Although feedstock and utility costs for bioethanol are significantly lower than for starch-derived ethanol, lower feedstock costs are more than offset by the higher costs for labour, supplies, and capital depreciation costs for bioethanol. As a result, the estimated production cost for lignocellulosic ethanol exceeds that of starch ethanol by 75 to 80%. Two factors that play a major role here are the differences in feedstock handling and pretreatment (washing and grinding of ligno-cellulose is much more time and energy intensive compared to starch crops), and the residence time of the lignocellulose in the hydrolysis and fermentation process (e.g. complete enzymatic and fermentation based on dilute-acid hydrolysis pretreatment takes roughly 7 days, compared to 2-3 days for starch). These two factors increase both labour costs and capital costs for lignocellulosic ethanol considerably. The cost differences give a good indication at what scale improvements are needed in pretreatment and enzymatic/fermentation technology to make (ligno)cellulosic bioethanol more competitive in the future. The authors further indicate that there are important other opportunities for cost reduction of bioethanol, including replacing on-site enzyme production and developing new applications for co-products.

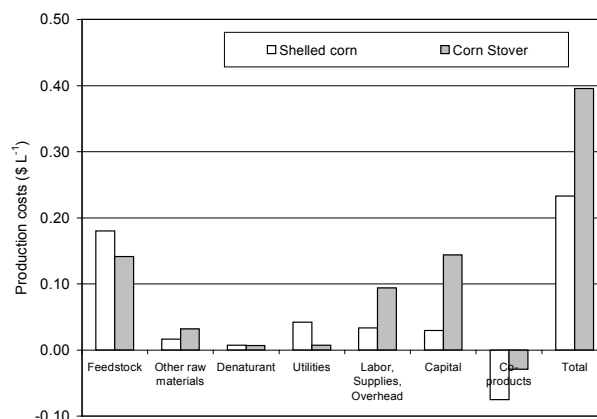


Figure 6 Comparison of production costs of ethanol from starch and lignocellulose biomass (adapted from [19])

A second study that evaluated the costs of bioethanol was carried out recently by a consortium representing Dutch companies, R&D organisations and universities [7].

Table 1 presents estimated costs for producing ethanol in a 195,000 m<sup>3</sup> per annum facility in the Netherlands, based on two feedstocks that show promise for bioethanol development in the Netherlands (grass from roadside and nature parks, and willow from short-rotation forestry). In this evaluation, Operation and Maintenance costs included costs for acquiring cellulase enzyme, which at the current price (6000 €/ton) is a major contributor to ethanol production costs (40 - 49 % of net production costs). Further, a sensitivity analysis based on these data showed that enzyme costs need to be reduced by a factor 10, and total capital costs by 30% to achieve ethanol production costs that are competitive with the currently starch-to-ethanol costs. Besides improvements in pretreatment and enzyme technology, further cost reductions could be made by: 1) reducing the total water consumption in the process, which could in turn reduce capital and operating costs for the distillation step, and 2) overall process optimisation.

Feedstock	Grass <sup>1</sup>	Willow <sup>1</sup>	Corn stover <sup>2</sup>	Corn (starch) <sup>2</sup>
Feedstock price	0.06	0.19	0.13	0.18
Cellulase (enzyme make-up)	0.51	0.48	0.05	0.00
Other O+M	0.09	0.07	0.10	0.10
Capital	0.37	0.34	0.14	0.03
Electricity	-0.11	-0.10	-0.03	-0.08
Total	0.92	0.98	0.40	0.23

Table 1 Production costs of bioethanol (€ l<sup>-1</sup>)

<sup>1</sup> study of Reith focussed on the Netherlands [7]

<sup>2</sup> study of McAloon focussed on the USA [19]

The large difference in production cost between both studies follows directly from the costs allocated to pretreatment through enzymatic hydrolysis of the feedstock (cellulases). This large difference in cost might originate from the fact that Reith [7] used current data for cellulase hydrolysis activity and McAloon [19] used data for cellulase hydrolysis activity to be reached in the future. A higher activity results in a lower amount of enzyme, and therefore cost reduction. Reith [7] mentions that in order to be competitive with ethanol produced from starch, the activity of the cellulase enzyme has to be increased tenfold. The production cost, with a 10-fold increase in enzyme activity, will drop to 0.46 € l<sup>-1</sup>, and is comparable with the production cost of McAloon [19].



# 4. Analysis of the commercial activities

In this chapter a short overview will be given of the commercial activities for ethanol production. As there are no plants producing ethanol from lignocellulosic feedstock, the figures are based on the production of ethanol from starchy feedstock. The information is gathered from F.O.Licht's two-monthly report "World ethanol and Biofuels report" volume 1, No. 4-9 (October 2002 -January 2003), Agra Europe, London.

## 4.1. Today's activities

Bio-ethanol is currently made by large-scale yeast fermentation of sugars that are extracted from crops including corn, sugar cane, wheat, barley, and sugar beets. Figure 7 shows world production of bioethanol in 2002. The America's (Brazil and USA) developed a mature ethanol market, whereas Asia and Europe is only at the beginning of this development.

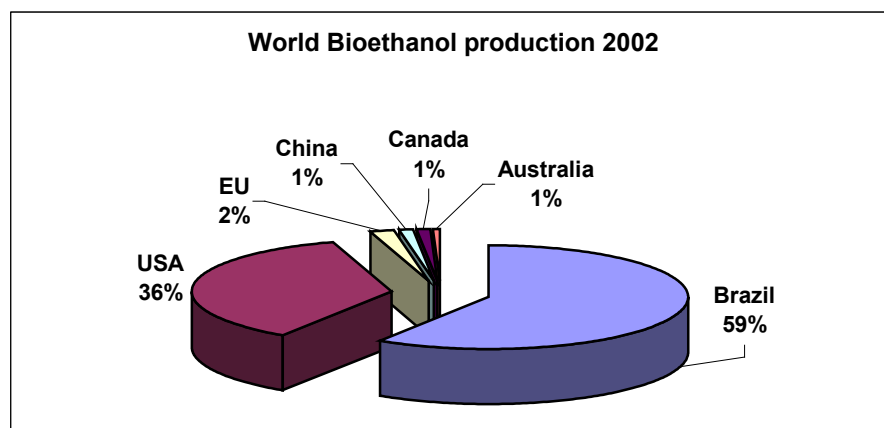


Figure 7 World Bioethanol production 2002. Total production 211 Mhl.

In Europe, the largest producer of bio-ethanol is France, which replaces 0.6% of its gasoline consumption by ethanol. The current production in Spain represents 1.0% of gasoline consumption replacement. Today, the major use of ethanol is as an oxygenated fuel additive that reduces emissions of carbon monoxide, oxides of nitrogen (NO<sub>x</sub>), and unburned hydrocarbons. Bio-ethanol can be used in a two of ways, 1) as a mixture in gasoline (at various percentages) and 2) as component in the fuel oxygenates ETBE. Table 2 summarises bio-ethanol types used by country, including primary feedstock used.

Country	Volume (million hectoliter)	Feedstock	Fuel-type with Ethanol % in ()
Brazil	125	Sugar cane	Hydrous alcohol (95.5%) Anhydrous gasoline (20-25%)
U.S.A.	76	Corn (90%), wheat, side streams food industry	E 10 or Gasohol (10%) Reformulated gasoline (5.7%), E 85 (85%)
China	2.5	Grains	Unknown
Canada	2.35	Wheat, corn	E85, E10 (see above)
Spain	2.26	Wheat, Barley, Wine	ETBE (up to 4%)*
Australia	1.3	Sugar cane, wheat	E10
France	1.19	Sugar beets, wheat	ETBE (3.7%)
Sweden	0.5	Barley	E85, E5 (5%)

Table 2 Bio-ethanol use and fuel-type by country in 2002

\* note: common ETBE percentage in fuel is 7.6%; ETBE contains 48% ethanol

## 4.2. Recent developments

### 4.2.1. Europe

As shown in Figure 7 bioethanol production is dominated by the Americas. A few European countries are producing bio-ethanol: Sweden, Spain and France. In 2001 the European Commission published the "European Directive on the Promotion of Biofuels". Fuels for transport purposes should be substituted with biofuels: 2% in 2005 and 5,75% in 2010 (each year an additional 0,75%). Current producing countries are planning to expand their production from 2005. For Spain this will lead to an additional volume of 2 Mhl (in 2004) and for France an additional volume of 3.85 Mhl. Germany and United Kingdom, which produce no bio-ethanol at the moment, announced new production facilities (total of 6 Mhl by 2005). It is generally expected that in the next decade European production of bio-ethanol will increase significantly.

The development of commercial ethanol production in the EU countries is largely driven by tax exemption of biofuels (in some countries the exemption is 100%) and other policies related to either land-use (set-a-side policy of agricultural land which prohibits use for food production) or regional development. According to the IPTS<sup>4</sup> [22] a full implementation of set-a-side land in the EU (10% or 5.5 Mha) to produce raw materials for ethanol would produce enough fuel-ethanol to replace 5.8% to 18.3% of current gasoline consumption, depending on feedstock used. This estimate does not include the conversion of (ligno-) cellulosic raw materials to ethanol. For

<sup>4</sup> Institute for Prospective Technological Studies

comparison, the current land-use for fuel-ethanol in France amounts to roughly 30,000 ha.

The European Union will be enlarged with a number of new member states in 2004. The European Biofuel directive will be one of the European directives which have to be implemented by these candidate states. In preparation to the enlargement Hungary will exempt bio-ethanol from duty from 2003 onwards for gasoline blends with 2% bio-ethanol. The Czech government has also announced a biofuel program. In 2003, Polish parliament will come forward with a biofuel program which includes obligatory blending percentages (and duty exemption).

#### ***4.2.2. Recent developments in the world***

The government of the United States has forwarded proposals to the Senate and the House of Representatives of a New Energy Bill. These proposals for the American energy policy for the coming years include stimulating measures for increasing ethanol use. Ethanol production in 2002 reached to 1.2% of gasoline consumption. The Energy Bill will mandate the use of renewables to 4% in 2016 (AUS consultants, J.M.Urbanchuk, November 2002). One of the major issues in this Energy Bill is a federal ban on the use of MTBE as oxygenate. In California (and 16 other states) such a ban already will be in place from 2004 on. All major oil companies in California have voluntarily announced to ban MTBE from 2003 on. MTBE will be substituted by (blended) bioethanol (or ETBE) as oxygenate.

Japan is phasing out the use of MTBE. In 2002 ethanol has been exported to Japan to fill in the oxygenate demand.

Canada is using 3.25 Mhl of ethanol per annum. 1.0 Mhl/a is imported from the United States. As part of Kyoto measures the Canadian government in 2002 has set a target to increase production to 13.0 Mhl/a in 2010. 35% of the petrol sold on the Canadian market will then contain a 10% ethanol blend.

India will blend 5% bio-ethanol into gasoline in 9 states. This first phase will come into force from 2003 and onwards. Promotion of bioethanol fits India's strategy to become less depend of oil in order to improve the net trade balance. Production facilities are located in sugar cane producing states. During the second phase (from 2004 onwards) all states will use ethanol and, if feedstock is sufficient, be blended at percentages to 10%.

In 2002 China (Nanyang) produced 2.5 Mhl/a with stored (old) grains as a feedstock. Production capacity will be increased to 10.0 Mhl in 2003 and to 13.75 Mhl in 2004. Feedstock will vary from wheat, rice and corn. Coming decades the demand for energy will be enormous, in this way the dependence on oil will be somewhat less. It is expected that bio-ethanol will be used in cities with high density of people where the Olympic Games in 2008 will take place. Bio-ethanol will therefore mainly be used to improve air quality in these cities.

Thailand is increasing its production rapidly. Mid 2003 production will rise till 5.5 Mhl/a. Sugar Cane and tapioca will be the major feedstock. Bio-ethanol is used as a blending component with gasoline up to 5%. The government is discussing to rise this percentage to 10%, which will double production on to 11.0 Mhl/a.

Since 2000 Australia is producing bio-ethanol. Sugar cane is used as feedstock. Existing ethanol production totals about 1.3 Mhl/a. Gasoline with 10% blends is on the market in Queensland.

# 5. Reduction of Greenhouse gas emissions

## 5.1. Greenhouse gas emissions per km driven and costs of emission reduction

The costs of reduction of Greenhouse gasses have been calculated according to the methodology used in the GAVE/ADL study:

At this moment nowhere in the world ethanol is produced on a commercial scale

$$\text{Costs emission reduction (€ /ton CO}_2) = \frac{\text{Extra costs (€/km)}}{\text{CO}_2 \text{ savings (g/km)}} \times 10^6$$

using lignocellulosic feedstock. Therefore different economic studies were used for estimating the cost of ethanol. Those studies gave also different scenarios for reducing the production cost in the future. Table 3 summarises different estimated cost prices found in literature. A detailed description of the cost prize is given in § 3.2.

Source	Price (€/l)	
	current estimate	future estimate
Novem GAVE/ADL[2,3]		
poplar wood SSF-process <sup>3</sup>	0.19 (0.28) <sup>5</sup>	0.12 (0.19) <sup>5</sup>
poplar wood BCP-process <sup>4</sup>		
NREL[9]		
poplar wood <sup>1</sup>	0.30	0.20
NREL [17]	0.40	
corn stover		
ECN [5]		
Biomass residues	0.26	0.18
Imported biomass	0.38	0.23
ECN [7] <sup>2</sup>	0.92	0.33
verge grass	0.99	0.35
willow tops		
BAFF [26]		
Softwood	0.45	0.36
ETEK [14]		
Softwood residues	0.41	
EUBIA [27]		
Lignocellulose (acid hydrolysis)	0.45	
Lignocellulose (enzymatic hydrolysis)	0.18	

*Table 3 Cost price of ethanol produced from lignocellulosic feedstock*

<sup>1</sup>A study undertaken by NREL in close co-operation with industry-knowledgeable turnkey companies.

<sup>2</sup>A study undertaken by a Dutch consortium of industry, R&D- institutes and universities

<sup>3</sup>SSF is simultaneous saccharification and fermentation (see also Figure 3)

<sup>4</sup>CBP is consolidated bioprocessing (hydrolytic enzymes, micro-organisms and ethanol are produced in a single tank).

<sup>5</sup>As pointed out in the GAVE report Conventional transportation fuels [32], the cost price has been incorrectly calculated. The price between brackets is the original cost price.

Production cost depend largely on feedstock price and the scale of the production plant [5]. The large difference in cost price estimated in both ECN studies, originates from the cost allocated to pretreatment via enzymatic hydrolysis. In ECN [5] data were used from the NREL study [9], and these data were translated to the Dutch situation. The data used for enzymatic hydrolysis were probably based on cellulase hydrolysis activity to be reach in the next decade. In ECN [7] data were used for current cellulase hydrolysis activity. Based on Table 3 a cost price for ethanol of 0.35 €/l is used as a current estimate whereas for a future estimate a cost price of 0.23 €/l is used.

For Greenhouse gas emissions an assessment of the complete chain is required. A possible schematic chain is depicted in Figure 8.

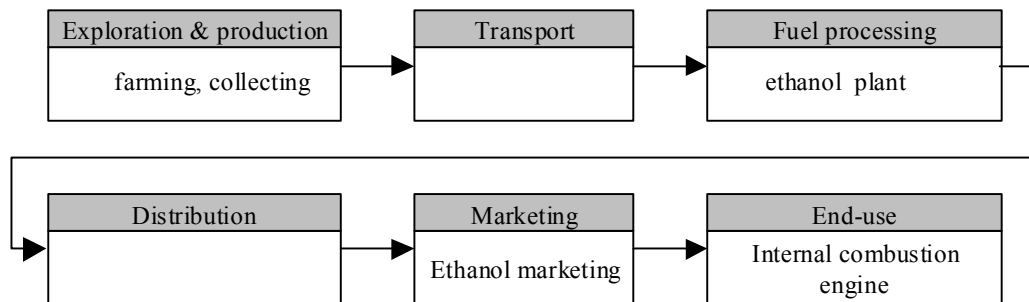


Figure 8 Fuel chain for producing and processing ethanol from lignocellulosic feedstock

An overview of different studies estimating greenhouse gas emission is given in Table 4. The values between brackets are the emission reduction in percentage compared with conventional gasoline.

Greenhouse Gas Emissions	Short Term	Long Term
ADL [2,3] <sup>1</sup>		
Poplar wood SSF process		-20.5 (108.9)
Poplar wood BCP process		-27.8 (112.0)
Wang (1999) E95 blend [28] <sup>2</sup>		
Woody Biomass	-42.0 (118.2)	-11.6 (105)
Herbaceous Biomass	47.8 (79.3)	49.2 (78.7)
GM WTW (2002) [29] <sup>3</sup>		
Residual side streams		65 (52.6)
Poplar plantation		91 (33.6)

Table 4 Greenhouse Gas reduction in g CO<sub>2</sub>/km

<sup>1</sup>The power train used was an internal combustion engine

<sup>2</sup>The power train used was a Ford Taurus ethanol FFV (flexible fuel vehicle)

<sup>3</sup>The power train used was a fuel cell hybrid car (CO<sub>2</sub> emission for gasoline is 137 g/km)

The GAVE/ADL study assumes a negative emission of CO<sub>2</sub> for ethanol as transport fuel. A negative emission is also calculated by Wang (1999) for using ethanol in a 95% blend with 5% gasoline. The GM European Well-to-Wheel analysis (2002) does not estimate negative CO<sub>2</sub>-emissions. A negative emission results from the GHG offsets in electric power generation. The offsets are from the reduction of excess electric power generated by the biomass (ligno)cellulosic ethanol technology.

Fuel efficiency of the engine is another aspect to be looked at for estimating the cost of emission reduction. For a conventional internal combustion engine a use of 7.5 l ethanol/100 km is assumed, and for the fuel cell hybrid car a use of 4.6 l ethanol/100 km is assumed. The cost of CO<sub>2</sub> emission reduction using current technology is 73 €/ton for the production ethanol from woody biomass and 108 €/ton using herbaceous biomass. The cost of CO<sub>2</sub> emission reduction in the future (2010) will range from 27 to 29 for the production ethanol from woody biomass and 38 €/ton using herbaceous biomass (the price of gasoline used is 0.018 €/km, CO<sub>2</sub> emission using gasoline is 231 g/km). Using fuel cell hybrid cars for transportation the cost of CO<sub>2</sub> emission reduction will be 27 – 113 €/ton.

## 5.2. Amount of avoided Greenhouse gas emissions

There is a considerable potential for substitution of petroleum based transportation fuels by bio-ethanol from lignocellulosic feedstocks. It is difficult to determine whether these feedstocks can be contracted for the production of bio-transportation fuels, and more importantly at which price they can be contracted. Furthermore expansion of the European Union as well as financial incentives can considerably influence the market for bio-transportation fuels.

Considering the factors given above, it is difficult to estimate the amount of Greenhouse gas emissions that can be avoided by using bio-ethanol. In this chapter estimates are made based on the targets on fuel substitution proposed by the European Union. Furthermore, similar to the GAVE/ADL study, the CO<sub>2</sub> reduction obtained by complete substitution of petroleum based transportation fuels by bioethanol is given below.

The European Union has proposed the following targets for substitution of petroleum based transportation fuels:

2005	2%	(EU, 2002)
2010	5.75%	(EU, 2002)
2020	8%	(EU, 2001)

In 2000 the consumption of gasoline in the Netherlands was 177 PJ [30]. Based on these data the required amount of bio-ethanol and the amount of avoided Greenhouse gas emissions can be calculated, see Table 5. Furthermore, just like in the GAVE/ADL, study it has been assumed that use of ethanol results in a 10% increase in end-use efficiency.



	Bio-ethanol		
	2005	2010	2020
Percentage substitution (%)	2	5.75	8
Bio-fuel consumption (PJ/year)	3.2	9.3	12.9
(million liter/year)	151	434	604
(kton/year)	120	345	480
Emission reduction (Mton/year)			
woody biomass (100% CO2 reduction)	0.31	0.89	1.24
herbaceous biomass (79% CO2 reduction)	0.24	0.70	0.97

*Table 5: Bio-ethanol consumption and emission reduction for different percentages substitution*

In the GAVE/ADL study (ADL, 1999b) also the amount of Greenhouse gas emissions avoided when all transportation fuels are substituted was calculated. ADL estimated the transportation fuel consumption in the Netherlands in 2010 to be 125071 bbl/day gasoline. Assuming that bio-ethanol results in 100% reduction of Greenhouse gas emissions complete substitution of all fossil transportation fuels in the Netherlands in 2010 by bio-ethanol from ligno(cellulose) would result in reduction of Greenhouse gas emissions with 39.3 Mton CO<sub>2,eq</sub> (for 78.9% reduction the reduction in Greenhouse gas emissions is 30.5 Mton CO<sub>2,eq</sub>).

In the Netherlands 12 million tons (dry weight) of highly variable feedstocks are available as feedstock for production of 2.5 million tons of fuel ethanol per year. An 8% percentage substitution of petroleum based transportation fuels would require 2.3 Mton/year lignocellulosic feedstock. This is a substantial part of the available amount of feedstock (20%). It would require 53 Mton feedstock (11 Mton ethanol) per year to completely substitute transportation fuels with bioethanol produced from lignocellulosic feedstocks. This amount is far more than the amount of feedstock available and import would be necessary.

# 6. Introduction of bioethanol in the liquid transport fuels market. Transition to less conventional feedstocks

For traditional bio-ethanol production several starch-rich feedstocks are available. Although availability and climate characteristics generally determine feedstock production, there are also some policy based reasons to choose for specific feedstock. Europe, the United States and Brazil all promote domestic production and protect these products from imports (mainly with tariff barriers at the border). So the choice of feedstock for ethanol production (and their market prices) is also influenced by regional production policy and trade issues. Traditional feedstocks include: sugarbeet, sugar cane and grain (wheat, barley, rye and corn).

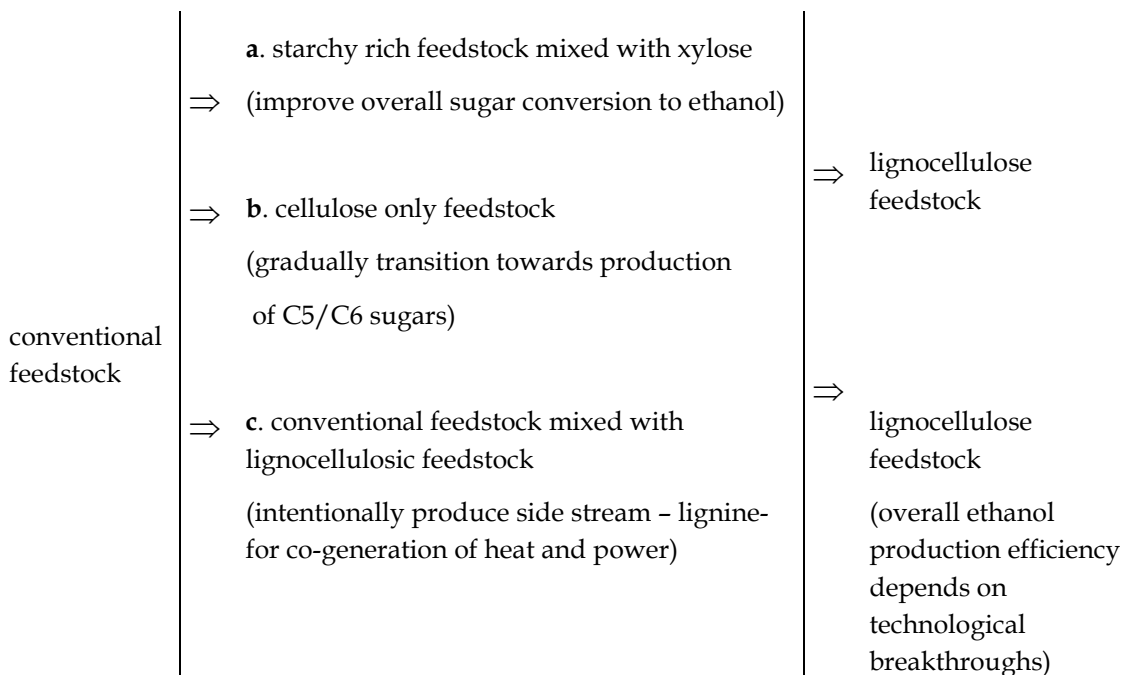
Side-streams of the agri-processing industry contain valuable sugars, which can be used as a feedstock for bio-ethanol production. In 2002 the Rabobank studied the agri-processing (potato, grain, sugar) industry and its side-streams [31]. Figures from this study show that there is potential ethanol production of 2,18 million hectoliter from side-streams alone. Prices of these side-streams are under a lot of pressure due to a declining animal (especially pig) sector. It is expected that this decline will continue in the coming years. Side-streams are therefore considered to be an interesting feedstock for bio-ethanol production in the Netherlands. Royal Nedalco produces at this moment only ethanol from two side streams. The first side stream is molasses which is a sugar rich side stream from the sugar industry. For the sugar industry it is not economically possible to extract all sugars from the sugar beet, but the residue is still a very interesting fermentation feedstock for ethanol production. The second side stream is so called C-starch which is supplied by Cargill. For milling of wheat huge quantities of wheat are being processed. Cargill's "A-stream" of starch is used for food purposes. Cargill's B-stream is also a side stream and is sold to the animal feed sector. The C-stream of starch is a feedstock for the ethanol production.

The EU has its own prices for feedstock and heavily depends on the Common Agriculture policy. For the coming years reforms of this historical long evolved policy could be crucial to this aspect. In addition, the World Trade Organization (WTO) round which will be concluded in 2004 will have an impact on possible feedstock prices for ethanol. How will European prices of grain develop? How will the sugar regime continue? All of these issues heavily depend on political decisions. Generally expected changes will develop very slowly, and until 2007 no major changes are expected for the feedstock market for bio-ethanol. Technology developments could speed up this transition process, but this is not yet an economic certainty.

As discussed above, nowadays ethanol is only produced from sugars (molasses) and starchy feedstock. An update on the status of ethanol, produced from conventional feedstock, as a substitute for gasoline in transportation fuels is given in the recent published GAVE-report "Conventional Bio-transportation fuels; an update" [32]. A large increase in production capacity, necessary for fuel production, will result in usage of different feedstocks; the amount of current available feedstock is limited, cost of the current feedstock is relative high and current feedstock has to compete with food applications.

Future feedstock will be (ligno)cellulose based. As described and discussed in the previous chapters mature technology is not yet available for producing ethanol from lignocellulosic feedstock. Current technology is hampered by incomplete conversion of the total sugar content (lack of commercially feasible xylose fermentation), the generation of huge amounts of side streams (among other things gypsum), and high cost for cellulose hydrolysis (pretreatment by physical/chemical methods and enzymatic degradation by cellulase). Existing ethanol producing companies (e.g. Nedalco) are mainly focussed on increasing overall sugar conversion efficiency of the feedstock and increase the availability of feedstock. For these companies commercialisation of large amounts of side products is of minor interest (i.e. thermal conversion of unconverted cellulose, hemicellulose and lignine to heat and power). A different type of companies also shows initiatives for producing ethanol (Abengoa in Spain, and Skellefteå Kraft, as part of the ETEK consortium and Iogen in Canada). These companies show interest in producing heat and power from the unconverted biomass. Abengoa has started a planning for a production facility in Spain on the basis of 85% conventional raw material mixed with 15% straw residues. Construction is planned for 2005. ETEK has foreseen a production plant in 2008 for production of ethanol and lignine (capacity is 600.000 hl/year, feedstock is 300 kton dry mass). The unconverted biomass is either sold as chemicals or burned to produce heat and power. Iogen has build a demonstration plant (capacity is 3.200 hl/year, feedstock is 1.3 kton wheat straw). The unconverted biomass is used for heat and power generation.

So, two different types of companies are present in the market, for which different transition paths from starchy feedstock to lignocellulosic feedstock can be drawn. Ethanol producing companies, focusing on the highest possible conversion of feedstock to ethanol, will show a gradual replacement of conventional feedstock with lignocellulosic feedstock; transition will take place in small steps, and depends on feedstock availability. This replacement depends heavily upon breakthroughs in commercial feasible xylose fermentation, and low cost cellulose hydrolysis (to increase availability of new feedstock). These breakthroughs are foreseen in the coming decade. A possible feedstock transition path could be :



For companies with a high interest in side products the transition can follow two different paths. The first path follows the ideas of ETEK: producing ethanol from lignocellulosic feedstock (e.g. softwood residues) and generating heat and power from the unconverted biomass. Improvements in xylose fermentation technology and hydrolysis technology will result in higher ethanol yields and less unconverted biomass. The second path follows the strategy of Abengoa: co-mixing conventional feedstock with lignocellulose feedstock (Abengoa and its American daughter company received an award in 2002 of 32M\$ research program for biomass (cellulose) fermentation for cellulose ethanol. In 2002, the U.S. Department of Energy awarded a number of substantial R&D grants that include projects to study new Biorefinery concepts, which combine conventional starch or sugar-derived fuel-ethanol with the conversion of lignocellulose biomass (e.g. stover, straw)). The unconverted biomass is used for heat and power generation. Improvements in xylose fermentation technology and hydrolysis technology will result in more and more replacement of conventional feedstock with lignocellulose and improve the availability of (new) feedstock.

At this moment there are different initiatives for constructing pilot plants for production ethanol from lignocellulose. Based on these initiatives it is expected that around 2005-2007 a lot of technological hurdles will have been taken. Plants commercially producing ethanol from a lignocellulosic feedstock are expected to run around 2010-2015. The introduction of this new technology in the market depends largely on the establishment of markets and subsidy mechanisms. In those countries where ethanol is blended with gasoline (e.g. USA, Sweden, Spain) a lot of technology driven research is employed and funding is available for constructing demonstration and pilot plants.

## 7. Conclusion

Currently (2002) 211 Mhl bioethanol is produced from conventional feedstock (corn, sugarbeet, wheat) at a cost price of 0.34 €/l (=16.2 €/GJ), which is twice the cost price of gasoline (7.3 €/GJ). High feedstock cost (> 50% of the total cost price) and the limited availability of conventional feedstock pose a large obstacle to large-scale implementation of ethanol as a transportation fuel. Therefore alternative feedstocks are necessary. Lignocellulosic feedstock and low-cost biomass residue streams could be suitable feedstocks for the large-scale production of ethanol. Although it is possible to produce ethanol from lignocellulosic feedstock with current technology, the resulting cost price is high (0.35 €/l) and large amounts of residues are produced.

Technological hurdles to be taken for a successful and economically feasible implementation of bio-ethanol produced from lignocellulosic feedstock are: 1) development of an environmentally friendly pretreatment technology for biomass with a minor amount of waste produced, 2) a large reduction in cost of cellulase enzyme production, and 3) reliable and robust xylose fermentation technology with a high ethanol yield. Further reduction in costs can be reached by process optimisation and an efficient use of waste streams (e.g. heat and power generation). Based on the above mentioned process improvements a future potential cost price is estimated at 0.23 €/l (=11 €/GJ). The cost of CO<sub>2</sub> emission reduction using current technology will be between 73-108 €/ton. The cost of CO<sub>2</sub> emission reduction in the future (2010) will be between 27 - 38 €/ton. The total Dutch CO<sub>2</sub> emission reduction for a 5.75% gasoline substitution by cellulosic ethanol will be about 0.8 Mton CO<sub>2</sub>. This would require 1.7 Mton lignocellulose (345 kton ethanol)

The following conclusions can be given:

- 1 At this moment technology for producing ethanol from lignocellulose is available but this technology is hampered by the generation of large amount of residues and this technology is not environmentally friendly. Major topics for research are: 1) pretreatment, 2) enzymatic hydrolysis, 3) C5-fermentation, 4) process optimisation and efficient use of residue streams. On these four topics a lot of R&D is employed both at research institutes, universities as well as companies. Improvements on pretreatment technology, reduction in cellulase production cost, and improvement of pentose fermentation will reduce the cost price of ethanol and the amount of residual material generated. Further reduction in cost price can be obtained by process optimisation and efficient use of residue streams. These improvements are foreseen in next decade. Though, until now only companies (ethanol producers or enzyme producers), research institutes and universities have been seriously involved. Especially in those countries, where supporting regulations for fuel ethanol as a transportation fuel are in place (e.g. USA, Canada, Sweden and Spain).
- 2 At this moment there is no commercial plant anywhere around the world producing ethanol from lignocellulosic biomass. However, two serious initiatives are on their way towards commercialisation: 1) a pilot plant build and owned by ETEK in Sweden; capacity is 400 litres ethanol per day, operation is foreseen at the

end of 2003, 2) Iogen Corporation is running a demonstration plant, EcoEthanol™; capacity is 880 liters ethanol per day.

- 3 At this moment two different type of companies are present in the market. 1.) Companies with the sole focus on producing ethanol with the highest possible overall sugar efficiency and increasing the availability of feedstock (e.g. Nedalco). These companies have a minor interest in commercialisation of large amounts of side streams (co-generation of heat and power from unconverted biomass). Their transition from conventional feedstock (starch, sugar beet, corn, wheat) towards lignocellulosic feedstock will take place gradually; transition will take place in small steps directed by breakthroughs in commercial feasible xylose fermentation and low cost cellulose hydrolysis. 2.) Companies producing ethanol with an interest in using the unconverted biomass for co-generation of heat and power (Abengoa, ETEK, and Iogen). For these companies the transition from conventional feedstock to lignocellulosic feedstock can follow two ways. 1) mixing conventional feedstock with lignocellulose and conversion to ethanol, heat and power (Abengoa). Improvements in current technology will lead to a larger amount of lignocellulose used. 2) only using lignocellulose for producing ethanol, heat and power. Improvements in current technology will lead to a higher conversion of feedstock to ethanol and less generation of heat and power.
- 4 Based on current initiatives for constructing demonstration plants and pilot plants, production technology of ethanol from lignocellulose is foreseen around 2005-2007. Plants producing ethanol on a commercial basis are expected to run around 2010 - 2015.

In order to stimulate the use of ethanol as a transportation fuel, governments should be actively involved in stimulating the use of ethanol. This could be done by partially tax exemption (which makes this fuel competitive with gasoline) and by informing the public on the benefits of ethanol as fuel. To make the current available technology environmental-friendly and to reduce the cost price substantially, further R&D should focus on:

- pretreatment of the biomass (both by physical-chemical methods as well as by enzymatic methods).
- reliable robust C5-fermentation.
- process optimisation
- valorisation of residue streams either by production of heat and power (BIG/CC) or extracting valuable products.

Establishing markets for bio-ethanol based transportation fuels and introducing subsidy mechanisms can result in an increase of R&D activities and realising funding for construction of pilot and demonstration plants (examples here of are observed in Sweden, Spain, Canada and the USA).

## 8. References

- 1 Novem, ADL (1999a): Analyse en evaluatie van GAVE ketens: Management summary. Arthur D. Little International Inc., Rotterdam, GAVE-rapport 9908
- 2 Novem, ADL (1999b): Analyse en evaluatie van GAVE ketens: Final report (sheetpresentation). Arthur D. Little International Inc., Rotterdam, GAVE-rapport 9909
- 3 Novem, ADL (1999c): Analyse en evaluatie van GAVE ketens: Appendices. Arthur D. Little International Inc., Rotterdam, GAVE-rapport 9910
- 4 FO LICHTS (2001): World ethanol markets, analysis and outlook, Agra Europe, London
- 5 J.H. Reith, Veenkamp, J.M., Van Ree R., De Laat W.T.A.M., Niessen, J.J., De Jong, E., Elbersen H.W. and P.A.M. Claassen (2001): Coproduction of bioethanol, electricity and heat from biomass wastes: potential and R&D issues. Paper First European Conference on Agriculture & Renewable Energy, 6-8 May 2001, Amsterdam.
- 6 Den Ridder, J. (2000): Presentation for the closing meeting of IEA task 26: Biotechnology for the conversion of lignocellulosics to ethanol.
- 7 Reith et al. (2002): Co-production of bioethanol, electricity and heat from biomass residues. 12 th European Conference and Technology Exhibition on Biomass from Energy, Industry and Climate Protection 17-21 juni 2002, Amsterdam, The Netherlands.
- 8 Wooley R, (2001): Bioethanol – moving into the marketplace, Newsletter from the National Renewable Energy Laboratory, <http://www.afdc.doe.gov/pdfs/4836.pdf>
- 9 Wooley, R., et al., (1999): Lignocellulosic Biomass to Ethanol Process Design and Economics, Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis, Current and Futuristic Scenarios, Final Report NREL/TP-580-26157, July 1999.
- 10 Technology review. Wood-Ethanol: A BC value added opportunity. (1999): Internet document, available on [www.pyr.ec.gc.ca/ep/wet/section16.html](http://www.pyr.ec.gc.ca/ep/wet/section16.html). A review of biomass-to-ethanol processes developed by Iogen Corporation, BC International Corporation, Arkenol Inc., Paszner ACOS and Bioengineering Resources
- 11 Arkenol: [www.arkenol.com](http://www.arkenol.com); BCI: [ww.bcintlcorp.com/](http://ww.bcintlcorp.com/); Iogen: [www.ioegen.ca/fuels.htm](http://www.ioegen.ca/fuels.htm); US DOE National Biofuels Program: [www.ott.doe.gov/biofuels/](http://www.ott.doe.gov/biofuels/)
- 12 Raamsdonk, L (2001): Xylose as a substrate for bioethanol production: the microbial hurdles, Confidential.
- 13 Nguyen QA et al. (1996): NREL/DOE ethanol pilot-plant: current status and capabilities, Bioresource Technology 58 189-196

- 14 Fransson G (2002): A pilot plant for ethanol from wood waste, oral presentation at Biomarket held in Skelleftea, Sweden 5-7 November 2002.
- 15 C.E. Wyman (2001): Twenty years of trials, tribulations and research progress in Biotechnology, *Appl. Biochem and Biotechnology* 91-93.
- 16 Sun Y and Chen J (2002): Hydrolysis of lignocelulosic materials for ethanol production: a review, *Bioresource Technology* 83 1-11
17. M. Galbe and G. Zacchi (2002): A review of the production of ethanol from softwood, *Appl. Microbiol Biotechnol* 59: 618-628.
- 18 Jeewon L (1997): Biological conversion of lignocellulosic biomass to ethanol, *Journal of Biotechnology* 56:1-24
- 19 A. McAloon, F.Taylor, W. Yee, K.Ibsen, R.Wooley (2000): Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks, NREL report 580-28893
- 20 J.R. Hettenhaus, R. Wooley and A. Wiselogel (2000): Biomass commercialisation prospects in the next 2-5 years, *Biomass Colloquies 2000*, NREL report 580-28886
- 21 Washing away Bioprocessing cost, Pressurized hot wash improves cellulosic ethanol technology (2002): US DOE/GO-102002-1625, September 2002
- 22 IPTS Joint Research Centre European Commission, Techno-economic analysis of Bio-alcohol production in the EU: a short summary for decision-makers, May 2002
23. A.E. Wheals, L.C. Basso, D..M.G. Alves, H.V. Amorim (1999): Fuel ethanol after 25 years, *TIBTECH* December 1999 vol 17 p.482 - 487
24. IEA Task 27 Country Reports
25. Biorefinery Project Awards , U.S. Department of Energy 2002, <http://www.ott.doe.gov/biofuels/>
- 26 Information from the Bioalcohol Fuel Foundation (BAFF) <http://www.baff.info/english/ohbilder/3%20Production%20technique.pdf>
- 27 G. Grassi (EUBIA) (2000): Bioethanol Industrial World Perspectives, *Renewable Energy World*, issue may-juni, on-line article: Download at [http://www.jxj.com/magsandj/rew/2000\\_03/bioethanol.html](http://www.jxj.com/magsandj/rew/2000_03/bioethanol.html)
- 28 Wang, M., Saricks, C. and Santini, D. (1999): Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. Argonne National Laboratory, Centre for Transportation Research, Energy Systems Division, ANL/ESD-38
- 29 GM Europe (2002): GM Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems a european study, 27 september 2002, Download at: <http://www.lbst.de/gm-wtw>
- 30 ECN (2003): Energie in cijfers. Energieonderzoek Centrum Nederland, [www.energie.nl](http://www.energie.nl)
- 31 Rabobank, M.van Vaals, P.Braks (2003): industry note Food & Agribusiness Research; "Ethanol from biomass: a Dutch case study"
- 32 Den Uil et al. (2003): Conventional Biotransportation Fuels, an update, GAVE-report in preparation.



## GAVE-PROGRAMMA

GAVE staat voor Gasvormige en Vloeibare Klimaatneutrale Energiedragers. Novem voert het GAVE-programma uit in opdracht van de Ministeries van Volkshuisvesting, Ruimtelijke Ordening en Milieu, Economische Zaken en Verkeer en Waterstaat. Hoofddoel van GAVE is om voor het jaar 2010 demonstraties te realiseren van gehele ketens voor de productie tot en met de toepassing van klimaatneutrale gasvormige en vloeibare energiedragers. Het traject dat GAVE doorloopt om dit te bereiken, is als volgt opgebouwd. Ondersteund door GAVE zijn in 2001 en 2002 allianties gevormd die nodig zijn om gezamenlijk een keten voor klimaatneutrale brandstoffen op te zetten. In 2002 is partijen de mogelijkheid geboden hun plannen uit te werken tot een blauwdruk voor demonstratie. Met ingang van 2003 kunnen partijen voor het eerst het ontwerp feitelijk realiseren door middel van demonstratieprojecten.

## BEDRIJFSPROFIEL VAN NOVEM NEDERLANDSE ORGANISATIE VOOR ENERGIE EN MILIEU

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