

CO-PRODUCTION OF BIO-ETHANOL, ELECTRICITY AND HEAT FROM BIOMASS WASTES: POTENTIAL AND R&D ISSUES

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ABSTRACT

Large-scale application of bio-ethanol as a transportation fuel can contribute substantially to the reduction of CO₂ emissions and other emissions (SO₂, NO_x) from the transport sector. Worldwide, 17 million tons/year of fuel ethanol are currently produced from agro-feedstocks such as corn, sugar cane, sugar beet and wheat. Current production costs are about 0.34 Euro/liter (16.2 Euro/GJ) which is 2 fold the price of gasoline (7.3 Euro/GJ). The use of agricultural residues and biomass wastes from agro-industry, forestry or other origins as a feedstock is expected to greatly enhance world fuel ethanol production at reduced cost, thus promoting large scale application. The projected costs for large scale ethanol production from biomass wastes are 0.26 Euro/liter (12.4 Euro/GJ). Through technological developments, the cost of ethanol may be further reduced to approx. 0.18 Euro/liter (8.6 Euro/GJ) in the longer term.

Biomass is composed of cellulose, hemi-cellulose and lignin. Both the cellulose and hemi-cellulose fractions can be fermented to ethanol after suitable pre-treatment and hydrolysis. The remaining, non-fermentable fraction can be thermally converted to electricity and heat, which are used for the ethanol production process and for export to the public grid.

Intensive R&D on biomass-to-ethanol processes in the past two decades has led to substantial industrial developments mainly in the USA and Canada. In the Netherlands there is a rapidly growing industrial interest for production of potentially low cost ethanol from biomass wastes and its application in fuels. The Dutch government intends to support further development to accelerate commercial implementation. A consortium from industry and the R&D sector is currently being formed in the Netherlands to assess the possibilities for further development and commercial implementation. The first step is to evaluate the technical state-of-the art, the economic feasibility and the ecological performance in order to identify the R&D required for commercial implementation. A preliminary outcome of this evaluation is presented in this paper.

1. POTENTIAL OF BIO-ETHANOL AS A RENEWABLE TRANSPORTATION FUEL

In a study performed for the Dutch government in 1999, bio-ethanol produced from lignocellulosic biomass is identified as a highly cost effective option for CO₂ emission reduction in the transportation sector [1]. The use of ethanol as a substitute for fossil fuels will reduce other emissions as well, incl. SO₂, NO_x, which contribute to acidification, and other hazardous emissions (particles, soot).

Fuel ethanol is currently produced in Brazil, the U.S.A. and several EU countries from sugar cane or starch crops, including: corn, wheat and sugar beets. The total amount of fuel ethanol produced worldwide from these crops is approx. 15 – 17 Million ton/year [2]. The production price of ethanol from these agro-feedstocks is approx. 0.34 Euro/liter (16.2 Euro/GJ) which is over 2-fold the price of gasoline (7.3 Euro/GJ). The high feedstock costs (accounting for about 50% of the 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.

The use of (ligno)cellulosic energy crops, and particularly low-cost biomass waste streams, offers excellent perspectives for large scale application of ethanol in transportation fuels [3]. The use of these materials will allow 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.

An evaluation of the international 'state-of-the-art' indicates a number of R&D issues that need to be addressed to enable large scale implementation. Both the R&D issues and the economic potential and applicability of the technology in the Netherlands are discussed in this paper.

2. R&D ACTIVITIES IN THE NETHERLANDS

The biomass-to-ethanol route has been researched intensively for the past two decades. Particularly in the USA and Canada this has resulted in substantial industrial development efforts [4,5,6,7]. In Europe, Sweden and Finland play a leading role [8]. In the Netherlands there is a rapidly growing industrial interest in alternative feedstocks for bio-ethanol production. The Dutch government is stimulating accelerated implementation by funding of R&D and demonstration projects. A consortium from industry and the R&D sector is currently being formed in the Netherlands to assess the possibilities for further development and commercial implementation of the technology. The first step -which is now in progress- is to evaluate the technical state-of-the art, the economic feasibility and the ecological performance in order to identify the R&D required for commercial implementation.

3. TECHNOLOGY OVERVIEW

In *Figure 1*, the classical ethanol production from starch crops and molasses (residue from beet sugar production) is compared with the innovative route for co-production of ethanol, electricity and heat from lignocellulosic biomass.

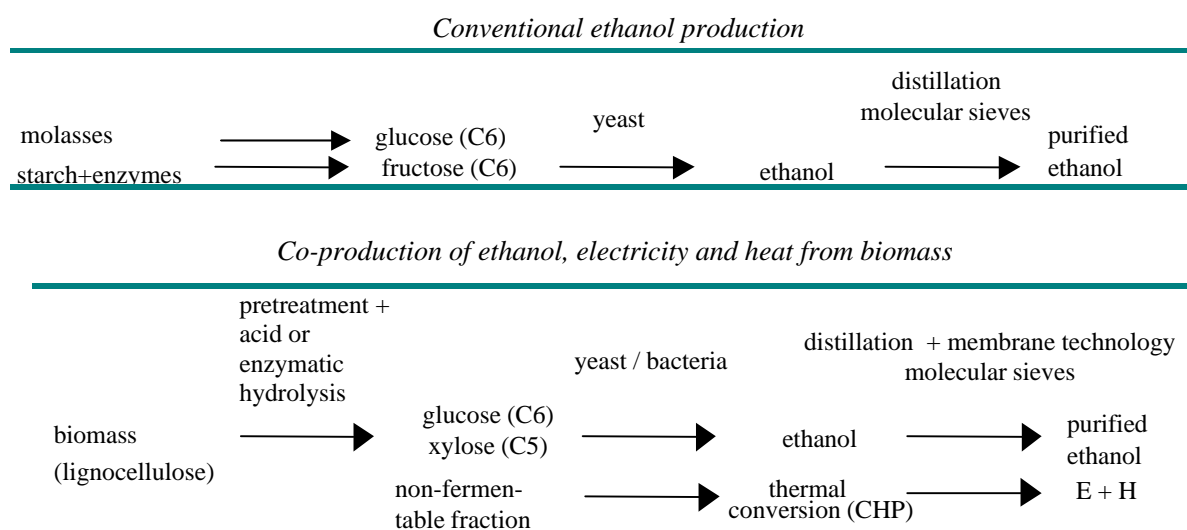


Figure 1. Outline of conventional ethanol production (above) and the innovative route for co-production of bioethanol, electricity (E) and heat (H) from lignocellulosic biomass (below).

The central element in ethanol production biotechnology is the fermentation of sugars by micro-organisms. In conventional ethanol production the sugars are directly derived from molasses or sugar cane or through hydrolysis (the conversion of starch to sugar) of starch containing crops such as corn. The production of sugars from these feedstocks is a simple and effective process. The resulting sugars can be readily fermented by yeasts. Deriving fermentable sugars from lignocellulosic biomass is more difficult. Biomass is predominantly composed of cellulose, hemi-cellulose and lignin. Both the cellulose and hemi-cellulose fractions are a potential source of fermentable sugars which are less easily accessible and therefore require suitable pre-treatment and hydrolysis steps. The hydrolysis produces a variety of sugars. The C5 sugars (mainly xylose) cannot be fermented with the standard yeast used in the ethanol industry. Ethanol production from these sugars requires the use of specially selected or genetically modified micro-organisms. Both in the conventional and the new process the ethanol product is recovered from the fermentation broth, and subsequently dehydrated by distillation and final deep dewatering by molecular sieves, to the required fuel specifications (< 0.1 wt% water). The non-fermentable, lignin-rich fraction and other organic wastes from the process (e.g. water treatment sludge) are used for Combined Heat & Power (CHP) production. For this purpose a conventional relatively low efficiency combustion/steam boiler system, or a more advanced high efficiency Biomass-Integrated-Gasification/Combined-Cycle system (BIG/CC) could be applied. The

produced electricity and heat (steam) are used to a large extent within the ethanol production process, whereas the surplus of electricity is fed to the public grid.

4. TECHNOLOGY STATUS AND R&D ISSUES

Figures 2., 3. and 4. present an outline of three technological options for co-production of ethanol, heat and electricity from lignocellulosic biomass that are currently under development. The NREL process (Figure 2.) is a well documented process design, that was used as a reference case in this study [5]. 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 bacterium: *Zymomonas mobilis*. The BCI process (Figure 3.) uses a two-stage acid hydrolysis. The first stage releases the hemi-cellulose and the second the cellulose sugars. The process uses a modified *E.coli* bacterium for ethanol fermentation.

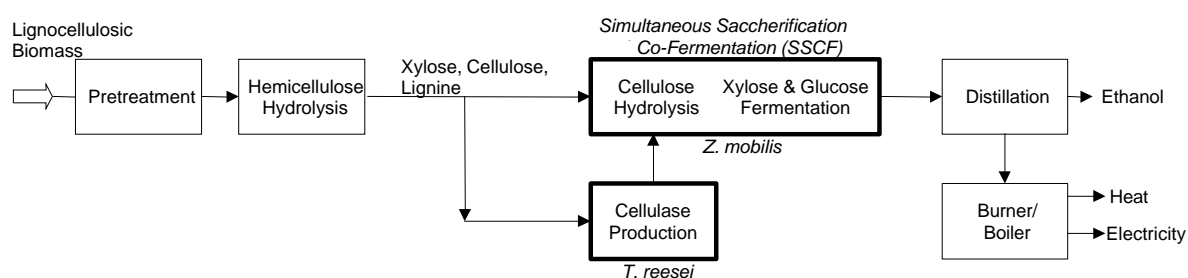


Figure 2. Biomass to ethanol process developed by the National Renewable Energy Laboratory (NREL), USA. [5].

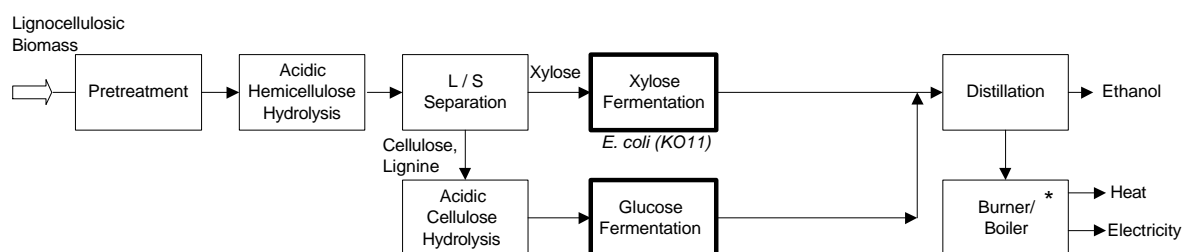


Figure 3. Biomass to ethanol process developed by BC International Corporation (BCI), Canada [4,6].

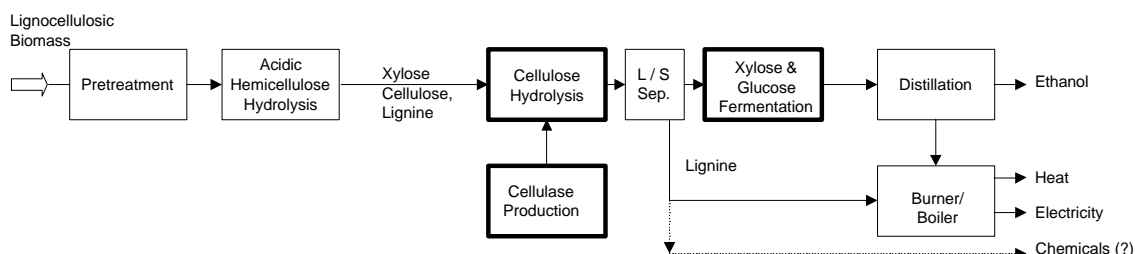


Figure 4. Biomass to ethanol process developed by Iogen Corporation, Canada [4,6].

The process developed by Iogen Corporation (Figure 4.) employs steam explosion with dilute acid for release of hemicellulose sugars and subsequent enzymatic hydrolysis of cellulose. Fermentation is performed by (to be) licensed technology. Lignin is removed prior to fermentation and could either be

used for production of chemicals or as fuel for electricity and heat production. Another process is being developed by Arkenol (USA) which uses concentrated sulfuric acid pretreatment/hydrolysis [4,6]. All processes use distillation (+ additional deep dewatering) and a conventional combustion/steam boiler system for CHP production from the non-fermentable biomass fraction.

Although considerable progress has been made in the past two decades, scaling up still proves difficult and commercially unattractive. The R&D issues to be addressed to enable large scale commercial implementation are discussed in more detail in the following sections. Major issues –for which no mature technology is available- concern the development of cost effective and environmentally sound pre-treatment/hydrolysis technology, cost effective fermentation of sugars derived from hemicellulose, and fuel formulation and logistics. The recovery and (deep) dehydration of ethanol, and CHP from non-fermentable biomass are less critical and can in principle be performed with conventional technology. Clear opportunities exist however for improvement of these process steps, and in overall process integration, resulting in an increased energetic efficiency and economic performance of the overall bio-ethanol production process.

4.1 Development of cost effective and environmentally acceptable pre-treatment and hydrolysis technology

Lignocellulosic biomass is predominantly composed of three components:

- cellulose, a polymer of C6 sugars (glucose);
- hemicellulose, a co-polymer consisting of C5 + C6 sugars (mainly xylose and mannose);
- lignin, a 'random' polymer consisting of mainly aromatic compounds (e.g. cinnamyl derivatives).

Effective release of sugars from hemicellulose and cellulose is technically complex. It requires decomposition of the complex intermeshment of the sugar polymers with each other and the lignin fraction in the fibrous plant material, as well as breaking the chemical bonds between the sugars in the polymer chains. Hemicellulose hydrolysis can be achieved under relatively mild process conditions. The cellulose fraction is more resistant and requires more rigorous treatment.

Several technological options are under development for pre-treatment and hydrolysis [4,5,6,7,9,17,18], including:

- steam explosion + dilute acid pre-treatment followed by enzymatic hydrolysis (Iogen);
- steam pre-treatment combined with dilute acid hydrolysis of hemicellulose, followed by enzymatic hydrolysis of cellulose (NREL), and
- two stage acid hydrolysis of hemicellulose and cellulose (BCI).

The NREL process -for example- uses a combination of steam pre-treatment and dilute acid hydrolysis for recovery of hemicellulose monomers and cellulose. This requires a relatively high consumption of H_2SO_4 (0.10 kg/kg ethanol) and $Ca(OH)_2$ (0.04 kg/kg; for neutralisation), whereas a large amount of waste gypsum (0.13 kg/kg ethanol) is produced. The cellulose fraction is subsequently hydrolyzed enzymatically by cellulase produced in the process (*Figure 2.*). The BCI process (*Figure 3.*) uses a two stage dilute sulphuric acid hydrolysis, with at least similar demand of acid and waste gypsum production. The Iogen process (*Figure 4.*) uses steam explosion with dilute acid, also generating wastes. Obstacles in the existing processes include: insufficient separation of cellulose and lignin (which reduces the effectivity of subsequent enzymatic cellulose hydrolysis), the formation of byproducts that inhibit ethanol fermentation (acetic acid from xylans, furans from sugars and phenolic acids from the lignin fraction), high use of chemicals, and considerable waste production.

An interesting, novel approach for hydrolysis of hemicellulose and pre-treatment for cellulose hydrolysis is the 'carbonic acid' process. This process employs hot compressed liquid water saturated with carbon dioxide as a reagent for promoting hemicellulose hydrolysis and breaking up of the (ligno)cellulose structures, to enhance subsequent cellulose hydrolysis [10,11,12]. This approach prevents the use of mineral acids and associated waste production and recycles some of the CO_2 produced during the fermentation.

Enzymatic hydrolysis of cellulose is clearly preferred both from a process oriented and an environmental point of view. The currently available cellulases are not cost effective. Furthermore their (in process) production shows a high energy demand (>50% of internal electricity consumption in the NREL design). Economic viability requires the development of cellulases active at higher temperatures, tolerant to low pH, with higher specific activity and resistance to inhibition by glucose. An alternative approach to the latter obstacle is the use of yeast capable of ethanol fermentation of cellobiose, a breakdown product of cellulose consisting of two glucose molecules [13].

Another issue that needs to be resolved is the removal (or prevention of formation by milder process conditions) of inhibitory breakdown products from the lignin fraction. These compounds inhibit the subsequent ethanol fermentation, thus reducing the effectivity of the process and increasing the production costs. A possible approach is removal (by precipitation) of the lignin prior to fermentation (Logen process) and use of the lignin as feedstock for chemicals or as a fuel for CHP.

4.2 Development of effective C5 fermentation

In order for ethanol production from ligno-cellulosic feedstocks to become viable, effective fermentation of both the cellulose (C6) and hemicellulose-derived sugars (C5) is required. The yeast *Saccharomyces cerevisiae* is used in the ethanol industry for large scale production of ethanol from molasses and starch crops. These industrial yeasts are capable of effective fermentation of the C6 sugars glucose and fructose and can tolerate high ethanol concentrations (up to 17 vol%) in the fermentation broth [14,15]. They are not capable of fermentation of C5 sugars (xylose), derived from hemicellulose. R&D to date has focused on genetic modification of *Saccharomyces* yeasts [16] which has so far not led to efficient C5 fermentation to ethanol. Other R&D has focussed on C5 fermentation by genetically modified bacteria including recombinant *Zymomonas mobilis* (NREL process) and *E. coli K011* (BCI process). Other options are the use of *Clostridia*, which are capable of C5 fermentation, although at relatively low rates, or the use of naturally occurring *Pichia ssp.* yeasts, which are capable of xylose fermentation [25]. Disadvantages of the latter are the O₂ requirement during fermentation and the limited ethanol tolerance. Unexplored options of the other organisms are a decreased sensitivity against inhibitors.

Although the R&D progress is encouraging, most processes are difficult to scale up. Further R&D is needed guided by criteria for industrial application, viz.: high ethanol production rate (short fermentation times), suitable metabolite profile (few side products esp. organic acids) and a high ethanol tolerance. The latter enables a high final ethanol concentration in the fermentation broth, which has a large influence on production costs and on the energy requirement for subsequent ethanol recovery [14].

4.3 Improved ethanol recovery and dehydration

Purification of ethanol to fuel specifications is an energy intensive process. Technological improvements are needed to optimise the overall energy balance and economics. The current industrial technology for ethanol recovery and purification is distillation of the filtered fermentation broth, in which the ethanol is concentrated from an initial concentration of approx. 10 vol% to 95 vol%. The energy consumption for distillation is a function of the ethanol concentration in the fermentation broth and the process configuration. By improvement of the latter, the energy requirement for distillation has been reduced by the industry to approx. 4 MJ/liter ethanol, about 20% of the ethanol fuel value (21 MJ/liter) [14].

For fuel applications the water content of the bioethanol must be further reduced to < 0,1 wt%. Available technologies for this final, 'deep' dehydration are: azeotropic distillation (using cyclohexane as entrainer), the use of 'molecular sieves', or (low temperature) membrane separation (pervaporation, vapour permeation). New technological developments for dehydration include the application of high temperature membrane separation processes for pervaporation or vapour permeation, which can be integrated with the distillation process. A central requirement for these new technologies is the development of robust, cost effective (ceramic) membranes [14]. An alternative option for applying membranes is direct recovery of ethanol from the fermentation process [20]. Fermentation batches may be maintained for much longer periods, reducing production costs.

4.4 Thermal conversion of non-fermentable biomass

Conversion of the non-fermentable biomass and surplus organic wastes generated in the process (e.g. sewage sludge) to electricity and steam is expected to cover the total energy requirement of the ethanol production process. The most obvious choice is a conventional combustion/steam boiler system, which is included in all developed processes. The base case NREL design [5] is for a wood-to-ethanol plant with a processing capacity of 700 kton wood (dry basis) or 408 MW_{th}/year per year and an ethanol output of 156 kton/year (139 MW_{th}). An energy analysis shows that the boiler produces 95 MW_{th} of steam, all of which is consumed in the production plant [19]. The plant further produces 44 MW_e of electricity, of which 33 MW_e (75%) is used internally, mainly for the blowers in the cellulase production section (18 MW_e), and 11 MW_e is available for export to the public grid. The overall energetic efficiency of the plant is 40% (Table 1.).

Table 1. Enthalpy balance (LHV basis) of ethanol plant integrated with a steam boiler [19].

IN	MW _{th}	OUT	MW _{th}	MW _{el}
Wood	408	Ethanol	139 (34%)	10,9
		Electricity	24 (6%) ¹⁾	
		Losses	245 (60%)	
	408		408	

1) The thermal equivalent of 10.9 MW_e is 24.2 MW_{th} for an e-conversion efficiency of 45%.

The current price of renewable, ‘green’ electricity in the Netherlands is about 0,06 Euro/kWh_e (0.14 Dfl/kWh_e). Export of electricity from the process to the public grid thus contributes to the economy of the process. The use of a Biomass-Integrated-Gasification/Combined-Cycle system (BIGCC) is expected to increase the overall energetic conversion efficiency to 65% (Table 2.), mainly due to a higher power production efficiency. A preliminary analysis indicates however that the higher power production efficiency, is annulled to a large extent by the relatively high specific investment costs of the BIG/CC, concerning the bio-ethanol production costs [19].

Table 2. Enthalpy balance (LHV) of an ethanol plant integrated with a BIGCC [19].

IN	MW _{th}	OUT	MW _{th}	MW _{el}
Wood	408	Ethanol	139 (34%)	57
		Electricity	127 (31%) ¹⁾	
		Losses	142 (35%)	
	408		408	

1) The thermal equivalent of 57 MW_e is 127 MW_{th} for an e-conversion efficiency of 45%.

Since the BIGCC technology is still under development, R&D is required in order to assess the technical applicability for the specific biomass streams in the biomass-to-ethanol process; particularly the requirements for syngas cleaning, emissions and the quality and applications of produced ashes.

4.5 Formulation and performance of ethanol fuel blends

Blending of bio-ethanol with fossil fuel based transportation fuels is expected to accelerate large scale market introduction [21]. In addition to the reduction of CO₂ and other emissions, ethanol has a higher fuel efficiency than gasoline due to its oxygen content, and the resulting cleaner combustion at relatively low temperature. Issues that need to be resolved for the ‘blending’ approach include:

- development of formulation specifications and technology;
- effects on long term engine performance, and
- questions relating to distribution and safety.

4.6 Process integration and ecological evaluation

Selecting a suitable feedstock is essential to accelerate demonstration of the technology. In order to establish the feasibility, and further definition of the R&D focal points, an overall technical, ecological and economic system analysis for selected biomass feedstocks is required. For example, in the current designs, the pre-treatment/hydrolysis and cellulase production sections are the major energy consumers. Optimal process integration will evidently have a large effect on the overall energy balance of the process, the amount of net electricity production for exportation to the public grid, and consequently on ethanol production costs. A thorough ecological evaluation (LCA methodology) is required to establish the net ecological effects. The analysis should have a broad scope and include issues such as applicability of byproducts and generated wastes, effects on land use and other societal impacts. Also, an ecological (and cost) comparison is required with alternative uses of biomass for energy generation, including the production of Fischer Tropsch fuels from syngas [22].

5. ECONOMIC EVALUATION

5.1 Feedstock availability

The use of low or zero cost agricultural and other biomass wastes is most attractive from an economic point of view. *Table 3* gives an impression of the potential scale of ethanol production from a number of waste feedstocks produced in the Netherlands. It should be stressed that *Table 3* only serves to give an impression of the potential order-of-magnitude of ethanol production from biomass wastes in the Netherlands. The actual contractibility of some listed streams (esp. food industry residues) is certainly limited due to other uses (e.g. in animal feeds), while other wastes -not included in *Table 3*- may be a suitable feedstock as well.

Table 3. Estimate of potential production of bio-ethanol, electricity and heat from a number of biomass wastes produced in the Netherlands. The listed amounts of waste streams are based on data from [23,24]. The estimates of potential ethanol production from each stream are based on their assumed cellulose + hemicellulose contents. Electricity and heat production from remaining biomass were estimated for conversion efficiencies of 40% and 50% respectively.

Waste stream			Bioethanol production		Heat and electricity production ³ BIGCC		
Type	[kt/yr]	[kt dry/yr]	[PJ _{th} /yr]	[ton/yr]	Electricity [GWh _e]	[MW _e]	Heat [PJ _{th}]
ODW ¹	3,340	1,340	3.2	122,000	1,400	196	6.2
Straw	700	600	4.9	186,000	270	38	1.2
Verge grass	460	180	0.9	32,900	170	24	0.7
Forestry residue ²	2,690	1,350	12.0	458,400	660	94	3.0
Food industry residues	50,000	10,000	49.5	1,887,500	9,500	1357	42.8
Total:	57,190	13,470	70.5	2,686,800	12,000	1709	53.9

¹ODW: organic domestic waste (Dutch: GFT).

²Residues from forestry, fruit sector, horticulture.

³In the NREL process design all of the produced heat and 75% of the produced electricity is used for ethanol production.

Table 3 shows that sufficient waste streams are –in principle- available to allow large scale ethanol production. Especially streams with a relatively high water content can be converted more efficiently via co-production of ethanol and electricity than by direct thermal conversion.

At present, many of the listed streams are not utilised for energy production. Some are processed by composting in which no useful energy is generated. Others are used for animal feed. It is certain that in the future there will be several competing processes for production of renewable energy from these wastes, as well as other applications. If the total amount of biomass wastes potentially available in the Netherlands is estimated at 120 PJ_{th}/year, replacing 1% of the yearly consumption of motor fuels in the Netherlands (400 PJ) with ethanol (4 PJ; 150.000 ton) would require the use of approx. 12 PJ_{th} or 10% of these streams. The above implies that in the longer term contractibility, price and logistics on the

national level may form an obstacle for large scale implementation. In the longer term the use of (imported) waste biomass and/or energy crops could therefore be needed for large scale application.

5.2 Ethanol production costs

A preliminary economic evaluation was performed using the NREL process design [5] as a reference case, with minor modifications for the situation in the Netherlands [19]. Values used where : 1 US\$ = Dfl. 2.30; 1 Euro = Dfl 2.20371. *Figure 5.* shows the ethanol production costs as a function of plant scale and biomass feedstock costs.

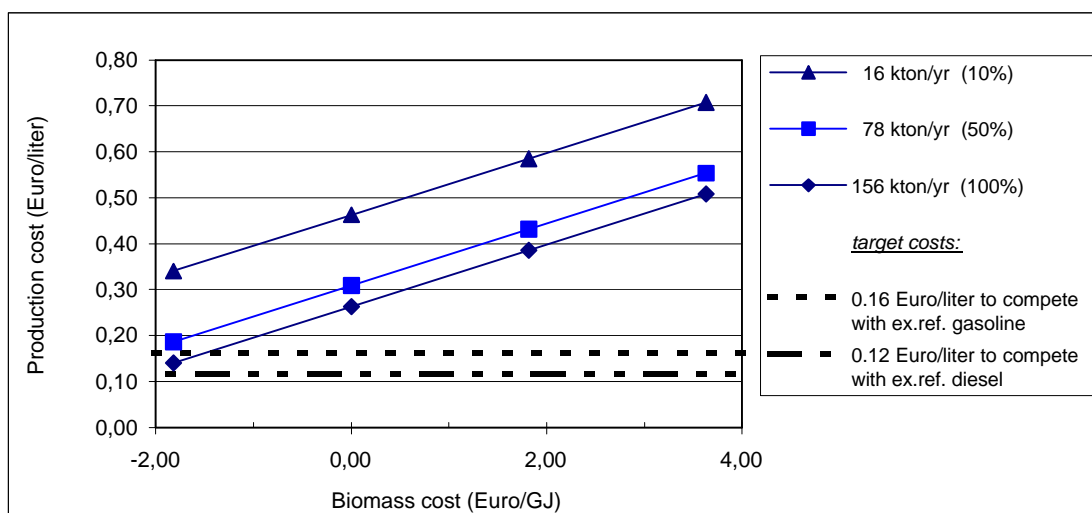


Figure 5. Ethanol production costs for 3 plant scales as a function of biomass feedstock costs [19]. Base case: NREL biomass to ethanol plant design [5], with an ethanol output of 156 kton/yr. Target cost are indicated for ethanol to be fully competitive with ex refinery gasoline and diesel based on the average price of these fuels over the past 3 years [26]. A 20% better fuel efficiency (km/MJ) of ethanol compared to gasoline was taken into account. The assumed price for exported electricity is 6 Euroct/kWh_e.

Figure 5. shows that for currently designed technology, zero or negative feedstock costs and large scale production are required to approach a competitive ethanol price. For a large scale production plant (156 kton ethanol/year), the ethanol cost would be 0.38 Euro/liter (18.1Euro/GJ) for energy crops (1.8 Euro/GJ), which is similar to the current cost of fuel ethanol from agro-feedstocks. For biomass wastes (assumed 0 Euro/GJ) the costs are reduced to 0.26 Euro/liter (12.4 Euro/GJ). A breakdown of the ethanol costs produced from biomass wastes is provided in *Table 4.*

Table 4. Breakdown of ethanol production costs from biomass wastes (0 Euro/GJ) in a plant according to the current NREL design [5,19].

	Dfl/liter	Euro/liter
biomass	0.00	0.00
chemicals, nutrients	0.11	0.05
Electricity credit	<u>-0.07</u>	<u>-0.03</u>
chemicals, nutrients – electr.credit	0.05	0.02
fixed costs	0.09	0.04
capital costs	0.45	0.20
total	0.58	0.26

It is expected that ethanol costs can be reduced by technological developments, including more efficient pre-treatment/hydrolysis, improved cellulases, and increased effectiveness of the ethanol fermentation process. According to an assessment by NREL these improvements could lead to a 40% reduction of the ethanol costs by 2010 [5]. The projected costs for ethanol from energy crops (1.8

Euro/GJ) would then become 0.23 Euro/liter (10.9 Euro/GJ). For biomass wastes (0 Euro/GJ) the costs could be reduced to 0.16 Euro/liter (7.6 Euro/GJ). This is in line with the longer term projected costs of the ethanol industry of 0.18-0.26 Euro/liter (8.6 – 12.4 Euro/GJ) [14].

6 CONCLUSIONS

Through successful technology development for co-production of bio-ethanol, electricity and heat from agricultural residues and other biomass waste streams, the use of ethanol as a renewable transportation fuel can be greatly increased, leading to a substantial reduction of CO₂ emissions. An evaluation of the international 'state-of-the-art' indicates a number of R&D issues that need to be addressed to enable large scale implementation.

Based on the currently designed technology, bio-ethanol can be produced from biomass wastes at a projected cost of 0.26 Euro/liter (12.4 Euro/GJ), assuming zero costs for the feedstock and a large scale production plant (160 kton ethanol/year). Through technological improvements, the cost of ethanol produced from biomass wastes may be reduced to 0.18 Euro/liter (8.6 Euro/GJ) in the longer term.

Replacing 1% of the annual transport fuel consumption in the Netherlands (400 PJ) with ethanol (4 PJ; 150.000 ton) would require the use of approx. 12 PJ or 10% of the estimated total amount of potentially available biomass waste streams in the Netherlands. In the longer term the use of (imported) biomass or energy crops could therefore be needed for large scale application. The projected ethanol costs from imported biomass (assumed cost 1.8 Euro/GJ) are 0.38 Euro/liter (18,1 Euro/GJ), with a possible reduction to 0.23 Euro/liter (10.9 Euro/GJ) by technology improvements in the longer term.

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