



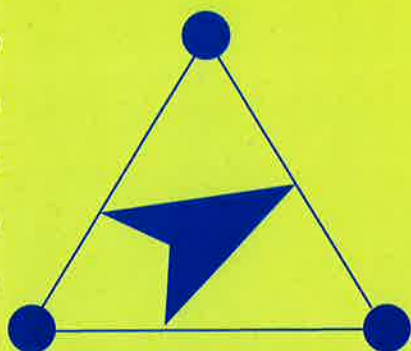
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# **STAP Technical Workshop on**

## **“Liquid Biofuels”**

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New Delhi**

# **BACKGROUND PAPERS**

**Life Cycle Analysis (LCA), GHG  
and Energy Balances of Biofuels:  
Synthesis Paper of Existing Studies**

**Eric D. Larson**

**Life Cycle Analysis (LCA), GHG and Energy Balances of Biofuels: Synthesis Paper  
on Existing Studies**

Eric D. Larson

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**1 Introduction**

This report presents a summary and synthesis of a number of recent publications focusing in part or in whole on lifecycle assessment (LCA) of one or more liquid biofuel production/use systems for transportation. The report limits itself to consideration of liquid fuels – “conventional” biofuels (biodiesel and bioethanol) and “future” biofuels (Fischer-Tropsch fuels and dimethyl ether) – produced from a variety of biomass sources.<sup>b</sup> The publications include several major studies that review and synthesize others’ LCA-related work on biofuels [1, 2, 3, 4], several major studies that report original LCA results comparing biofuels among themselves and/or with non-renewable fuels [5, 6, 7, 8, 9, 10, 11, 12, 13], a number of studies that develop LCAs in great detail for biodiesel [14, 15, 16, 17] and bioethanol [18, 19, 20, 21, 22, 23, 24, 25, 26], and a lesser number of studies on fuels derived via biomass gasification (Fischer-Tropsch and DME) [27,28]. Additional studies relevant to biofuels LCA were also reviewed, including studies focusing on LCA of alternative biomass production systems [29,30,31,32,33,34], studies of alternative motor vehicle systems [35,36], and LCAs of applications of biomass other than biofuels [37,38].

The above set of studies does not represent the complete literature on biofuel LCAs, but it does provide a substantial and representative cross section of reported work. This report focuses on biofuel LCA energy and GHG balances, which is the focus of most of the studies in the literature. Only a few studies have examined lifecycle impacts in other environmental areas, including local air pollution, acidification, eutrophication, ozone depletion, etc. Such impacts depend even more on site specific factors than do GHG emissions, which complicates drawing general conclusions. However, studies that have examined these other environmental issues in detail have generally, but not universally, concluded that biofuels substituting fossil fuels will often lead to increased negative impacts. Thus, the positive impacts on GHG emissions (where they exist) may carry a cost in other environmental areas and careful analysis is needed to

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<sup>b</sup> Neither biohydrogen nor biomethanol are addressed here. A general consensus on hydrogen is that it will not become a significant fuel for at least 2 to 3 decades. Methanol is considered by some analysts as a potential biofuel (a few of the studies reviewed here include biomethanol in their LCA comparisons), but the environmental problems (and related liability concerns of oil companies) encountered by use of methanol-based MTBE (at least in the United States), makes methanol a generally less favored liquid fuel option.

understand the tradeoffs in any particular situation. Economics of biofuels are not discussed here, though some of the studies reviewed in the course of this work address economics. Salient features and key results from a number of the studies reviewed for this report are included as an appendix.

## 2 Biofuels Addressed in LCA Studies in the Literature

LCAs are reported in the literature for the following biofuels and originating crops:

- Biodiesel (fatty acid methyl ester, FAME, or fatty acid ethyl ester, FAEE) from rapeseed (RME), soybeans (SME), sunflowers, coconuts, and recycled cooking oils.
- Pure plant oil from rapeseed
- Bioethanol (E100, E85, E10, ETBE) from grains or seeds: corn, wheat, potato,
- Bioethanol (E100, E85, E10, ETBE) from sugar crops: sugar beets, sugarcane
- Bioethanol (E100, E85, E10, ETBE) from lignocellulosic biomass: wheat straw, switchgrass, short rotation woody crops
- Fischer-Tropsch diesel from lignocellulosic materials: waste wood, short-rotation woody crops (poplar, willow), switchgrass
- Dimethyl ether (DME) from lignocellulosic materials: waste wood, short-rotation woody crops (poplar, willow), switchgrass

Almost all biofuel LCA studies have been undertaken in a European or North American context. With the exception of one excellent study on energy and GHG balances for sugarcane ethanol in Brazil [21], another study on ethanol from sugarcane in India [20], and a study on biodiesel from coconut (mentioned in [3], but not independently reviewed here) no LCA studies set in a developing country context were found in the course of the literature search for this report.<sup>c</sup> Palm biodiesel, which is the focus of considerable interest in Thailand, Malaysia and other palm-growing countries, apparently has not been the subject of comprehensive LCA. Nor have there been LCAs for other “conventional” (near-term) biofuels (biodiesel or bioethanol) from locally-relevant crops such as jatropha, cassava, etc. Neither have locally-relevant lignocellulosic energy crops in a developing country context been the subject of biofuel LCA studies. Studies in the European or North American context can provide indicative results, but given the variability and uncertainty around input parameter values in LCA analysis (see Section 5), country or at least region-specific studies are important for providing quantitatively more meaningful results. The Brazil sugarcane ethanol study [21] is an excellent model that other biofuel LCA studies might emulate.<sup>d</sup>

## 3 Striking Features of Existing LCA Studies

The most striking feature when comparing LCAs reported by different authors for the same biofuel and originating biomass source is the wide range of results in terms of net energy balances and net greenhouse gas emissions. For example, Figure 1, which shows results generated from LCAs carried out as part of a major European Study [5], shows a range in reductions of GHG emissions per vehicle-km (v-km) for RME (rape methyl ester) compared to conventional diesel fuel (for which RME can substitute) ranging from 15% to 65%. A similar variation is indicated for SME (soy methyl ester). The range for ethanol from sugar beets is

<sup>c</sup> There may, in fact, have been some studies done, but these did not turn up in my literature search.

<sup>d</sup> The Brazil study is good in part because of excellent availability of data, which may not be the case for other crops/biofuels.

somewhat smaller (but complicated by 3 alternative sets of assumptions about how credits are assigned to the residual pulp co-product of the ethanol production process – more discussion on co-product allocation issues is provided in Section 5). The range for ethanol from wheat shows anywhere from a 38% GHG emissions reduction per v-km up to a 10% penalty relative to gasoline.

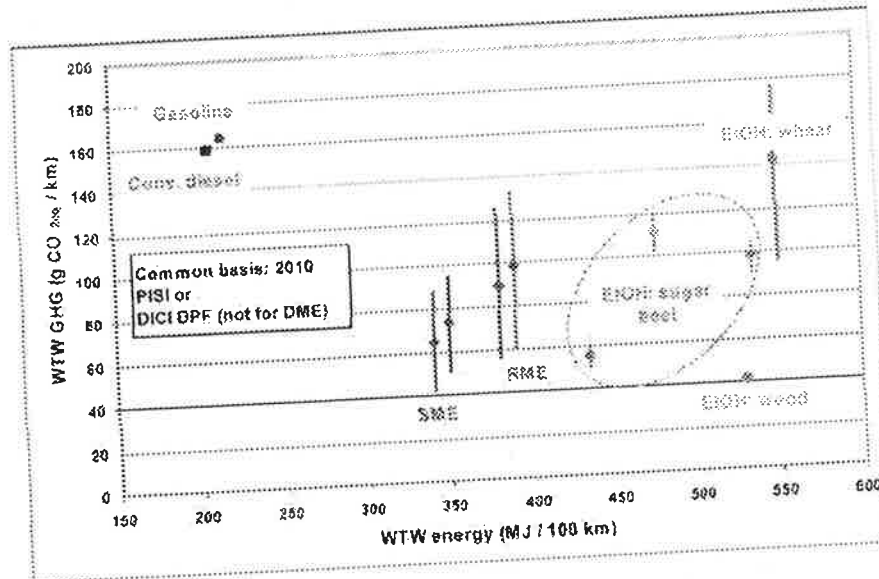


Figure 1. Well-to-wheel energy requirements and greenhouse gas emissions for conventional biofuel pathways compared with gasoline and diesel pathways, assuming 2010 vehicle technology [5].

Another example, Figure 2, is from Quirin, et al. [3], who reviewed and attempted to bring consistency to a large number of LCA studies.<sup>e</sup> Again, results for any single biofuel pathway span a large range in per-km savings relative to the use of fossil fuels. Energy and GHG savings on a per-hectare basis from the same review are shown in Figure 3. Interestingly, the range in energy and GHG savings for some pathways on a per-hectare basis is much tighter than the range on a per-km basis, e.g. for RME. For other cases, e.g., ETBE from sugar beets, the opposite is the case.

To understand the type of behavior in LCA results discussed above requires digging into details of numerical input assumptions and calculation methodologies that were used to generate the results. Different LCA analysts often use very different input parameter values for an LCA of the same biofuel pathways. For example, Quirin, et al. [3] cite application of nitrogen fertilizer for wheat production in different studies as varying from 53 to 195 kgN/ha, and assumed primary energy inputs to make fertilizer varying from 42 to 70 MJ/kgN, depending on the fertilizer production process. Wheat yields range from 2.7 to 9.0 t/ha/yr.

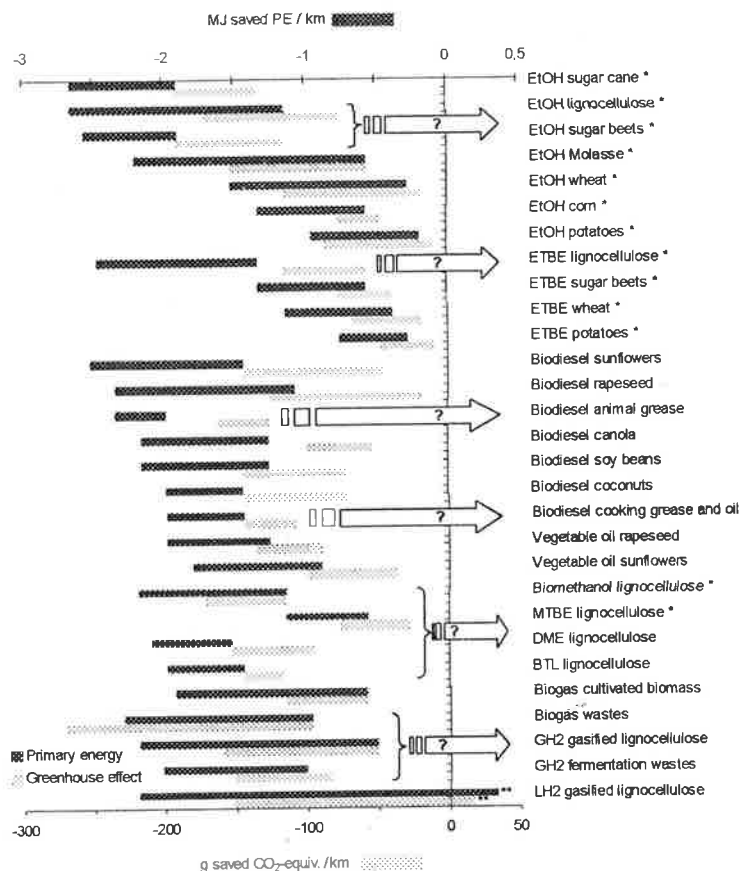
Without delving into further details, one may conclude that there can be a number "right" answers to the questions of how much GHGs and fossil energy can be saved through use of biofuels. It would appear to be difficult to make unequivocal conclusions regarding the precise

<sup>e</sup> The authors of the study reviewed some 800 documents in the course of their study.



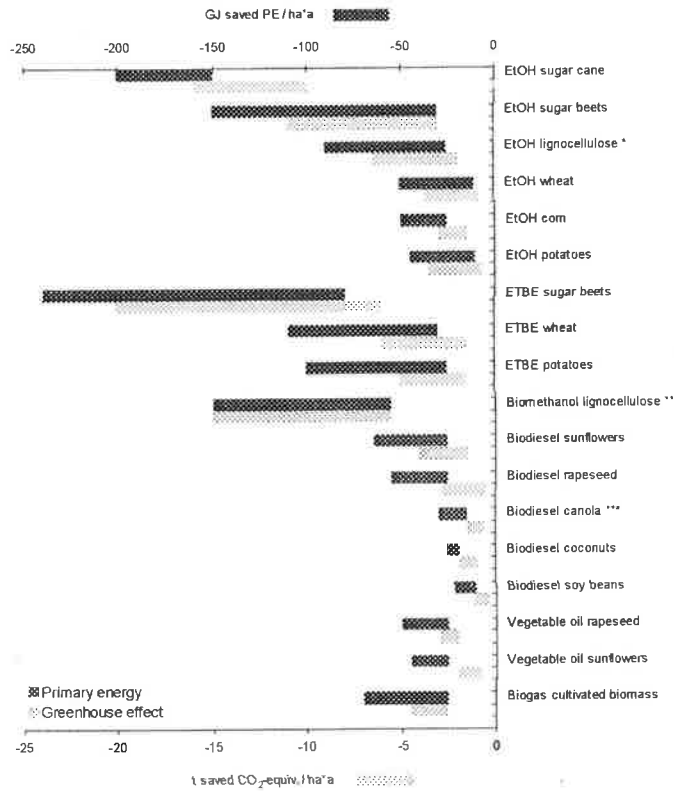
quantitative energy and environmental benefits (or costs) of any particular biofuels pathway without detailed case-specific information.

**Figure 2. Per-km savings in primary fossil energy saved and in greenhouse gas emissions saved for a range of biofuel pathways [3].** The savings are relative to gasoline (for bioethanol pathways), MTBE (for bioETBE pathways), and diesel [for biodeisel, BTL (Fischer-Tropsch), and DME pathways]. The ranges shown reflect the range of results given in the large number of LCA studies that were reviewed by the authors who prepared the chart. The cases marked with broad arrows pointing right are for biomass residue feedstocks. Other cases are for dedicated energy crops.



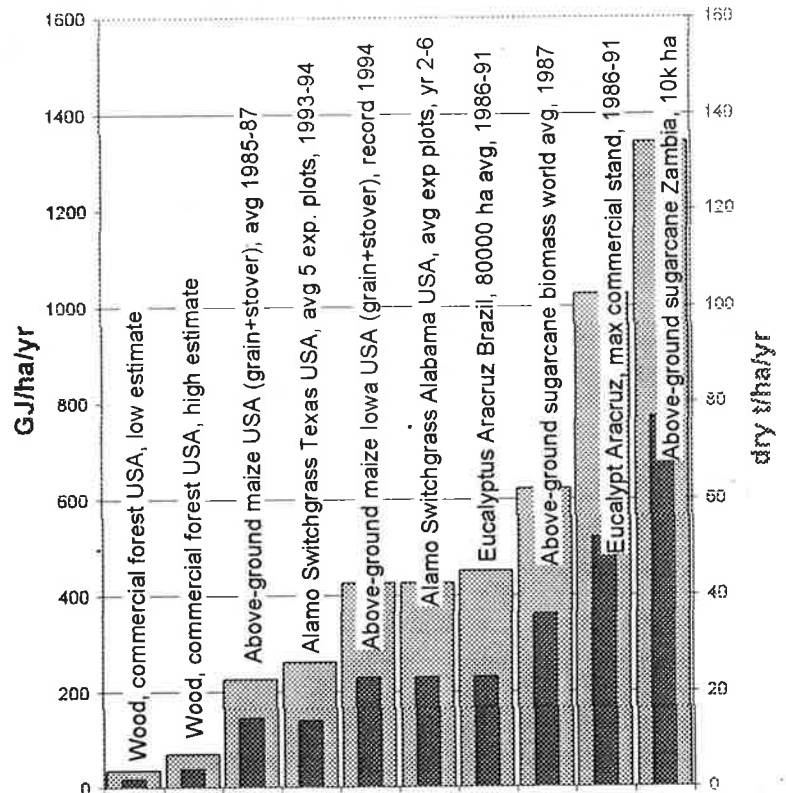
Another striking feature of LCA studies is their apparent lack of focus on evaluating GHG impacts on a per-hectare basis, which is somewhat surprising, since land is the basic primary resource for biofuel production. Nearly all LCA studies carry the analysis through to the production of the biofuel, expressing results on a per-GJ of biofuel produced basis. A number of studies carry the analysis further and express results on a per vehicle-km basis. However, relatively few studies focus on the question of relative land-use efficiency for different biofuel pathways. In an LCA study done in the mid-1990s, Kaltschmidt et al., [9] report findings on a per-hectare basis, but state that GHG savings per GJ of biofuel is the “preferred comparative value.” Quirin, et al. [3] expressed results on a per-hectare basis (Figure 3), but by comparing a wide range of studies that may not have had consistent and comparable input assumptions, the resulting comparison provides uncertain guidance as to the relative land-use efficiency of different biofuel pathways.

A chapter in the IPCC Second Assessment Report [39] was one of the earlier published studies that examined biofuels as a GHG mitigation option. In that report, the large variability in demonstrated yields from different biomass production systems was highlighted (Figure 4), and land-use efficiency of biofuels was expressed on a GJ biofuel/ha/yr and v-km/ha/yr basis (Figure 5). The report suggested (but did not explicitly state) that GHG emissions reductions per hectare would follow similar trajectories. However, such an extrapolation may not always be accurate.



**Figure 3. Per-hectare savings in primary fossil energy saved and in greenhouse gas emissions saved for a range of biofuel pathways [3].** The savings are relative to gasoline (for bioethanol pathways), MTBE (for bioETBE pathways), and diesel (for biodeisel, BTL, and DME pathways). The ranges shown reflect the range of results given in the large number of LCA studies that were reviewed by the authors who prepared the chart.

**Figure 4. Dry tonnage and energy yields per hectare for different biomass production systems [39].**





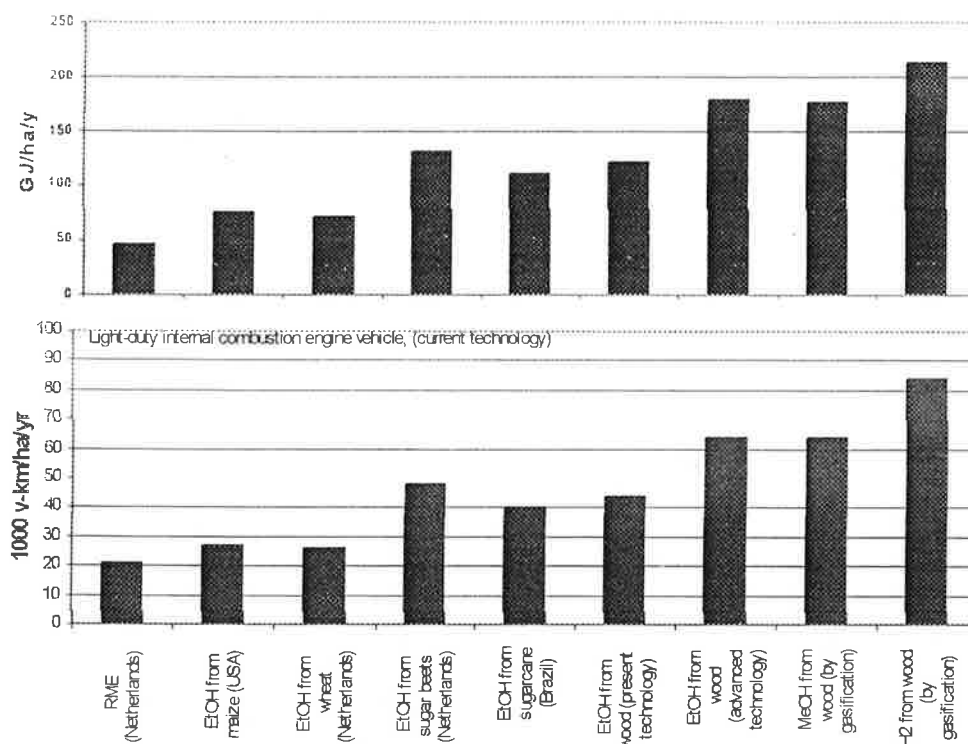


Figure 5. Land-use efficiency measures for alternative biofuels reported in the IPCC SAR [39].

Consider, for example, land requirements for several different biofuels (under UK conditions) as generated in LCAs by Elsayed, *et al.* [12]. There is a clear and easily understood correlation between GJ of biofuel produced per hectare/yr and v-km traveled per hectare/yr (Figure 6). However, emissions avoided per hectare do not necessarily correlate with emissions avoided per v-km (Figure 7). In this particular comparison, ethanol made from sugar beets avoids nearly the least GHG emissions per hectare, yet it delivers the highest level of transportation services (v-km) per hectare.

The lack of focus on land-use efficiency in the studies reviewed may be due in part to a focus on biofuels derived from presently-cultivated biomass sources. Yields are generally well known for rape, corn, wheat, and other grain and seed crops, and these values tend to be used as fixed inputs for LCA analyses. In the case of lignocellulosic energy crops, field trials have been done for a variety of lignocellulosic energy crops such as willow, poplar, and switchgrass, so some yield data are available for these. LCA studies tend to take all such yields as “given” and unvariable.

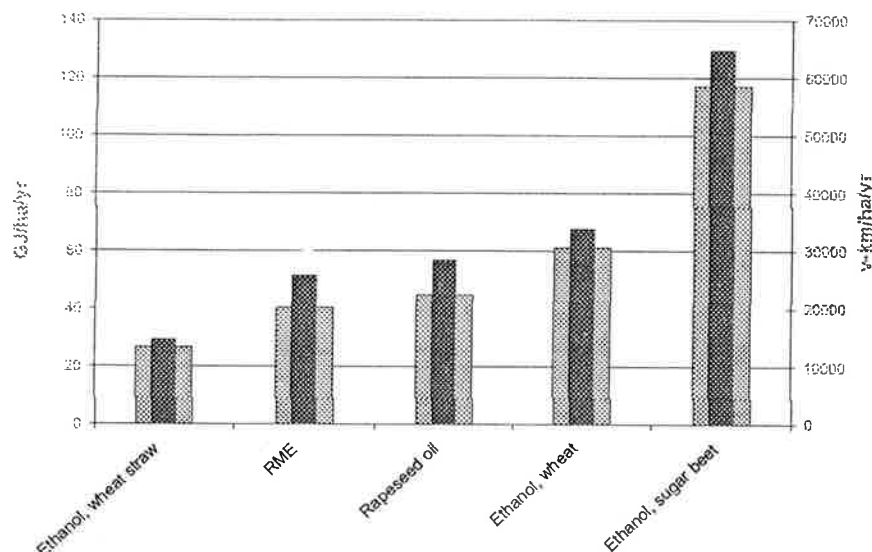


Figure 6. Biofuel use and v-km traveled per hectare of land used to grow biomass to produce different biofuels under UK conditions. This graph was developed from LCA results of Elsayed, et al. [12], together with assumed gasoline and diesel engine vehicle performance from Weiss, et al. [36].

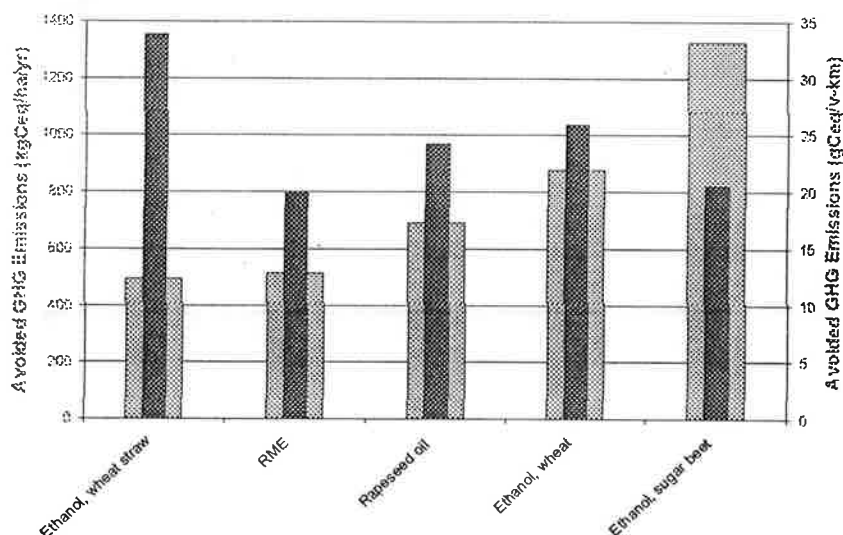


Figure 7. Avoided GHG emissions per hectare per year and per v-km of transportation services delivered with different biofuels under UK conditions, based on LCA studies by Elsayed, et al. [12]. See Figure 6.

Little analysis has been reported of the impact on LCA results of different yield levels for a given biofuel pathway, e.g., ethanol from switchgrass assuming different switchgrass yields. The impacts may be substantial. For example, Figure 8 is a simplified analysis showing avoided GHG emissions per unit land area for different approaches to bioethanol production. Greene [10] shows switchgrass yields that are expected to be achievable by 2025 and 2050 with concerted development effort (Figure 9) – an effort akin to the corn-yield development efforts

that have led to record-high yields achieved today (Figure 10). Figure 8 shows that when only already-achieved yields for cellulosic biomass are considered, the GHG benefits per ha, while still considerably better than for corn ethanol and approximately as large as for sugarcane ethanol in Brazil, are only half to one-third the potential benefits of cellulosic biomass when yields such as those projected in Figure 9 are assumed in the analysis.

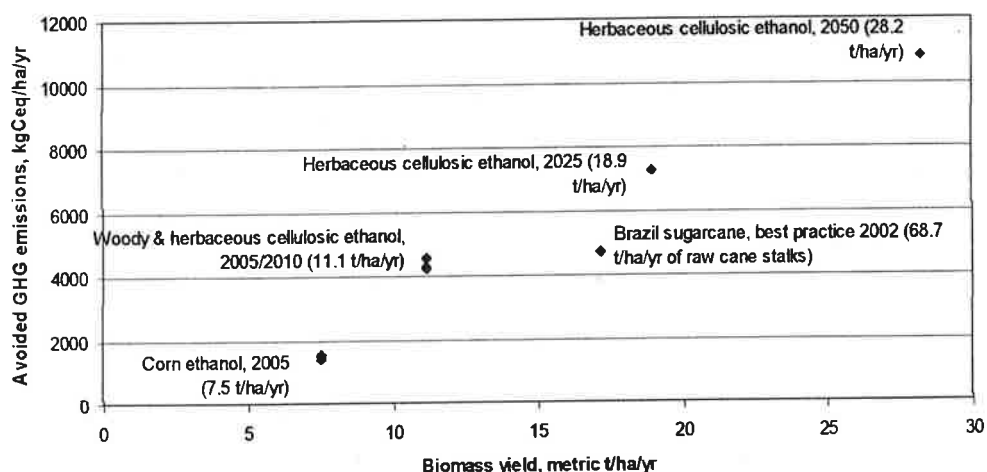


Figure 8. Avoided GHG emissions per hectare per year as a function of biomass yield for different routes to bioethanol production. The corn and cellulosic ethanol numbers are based on GHG balances for near-future (2005) and future (2010) cases developed by Wang, *et al.* [24]. The cellulosic ethanol estimates for 2025 use Wang, *et al.*'s GHG reduction estimates per GJ of ethanol produced, together with projections of future switchgrass yields given by Greene [10]. The sugarcane results are from Macedo [21]. Biomass yields (dry basis, except for sugarcane) are given in parentheses.

#### Switchgrass Yields

Region	2004 Yield (dt/ac/yr)	Breeding Gains Per Year (dt/ac/yr)	PROJECTED FUTURE YIELDS (DT/AC/YR)	
			2025	2050
Northeast	4.87	0.073	6.40	8.33
Appalachia	5.84	0.292	11.97	19.27
Corn Belt	5.95	0.179	9.75	14.23
Lake States	4.8	0.072	6.31	8.11
Southeast	5.45	0.275	11.25	18.12
Southern Plains	4.3	0.215	8.82	14.19
Northern Plains	3.47	0.052	4.56	5.86

Figure 9. Currently-achieved and projected switchgrass yields in regions of the United States [10].

The analysis using projected yields in Figure 8 is only approximate, because differences in inputs needed to achieve the higher yields have not been taken into account. Measurements of how yields change with different inputs are needed to generate more accurate results. Generating such measurements at any single geographic site (as characterized by its soil type, climate, topography, etc.) requires considerable time and effort. A less satisfactory, but easier approach could be to look for different sites where similar crops have already been grown under well-

monitored conditions and to correlate yield levels against inputs for sites having similar soil types and climate. For example, in the United States research and scaleup plots for developing switchgrass as an energy crop have been established and monitored for over a decade in each major switchgrass-growing region of the country, generating yield data for a variety of growing conditions [40].

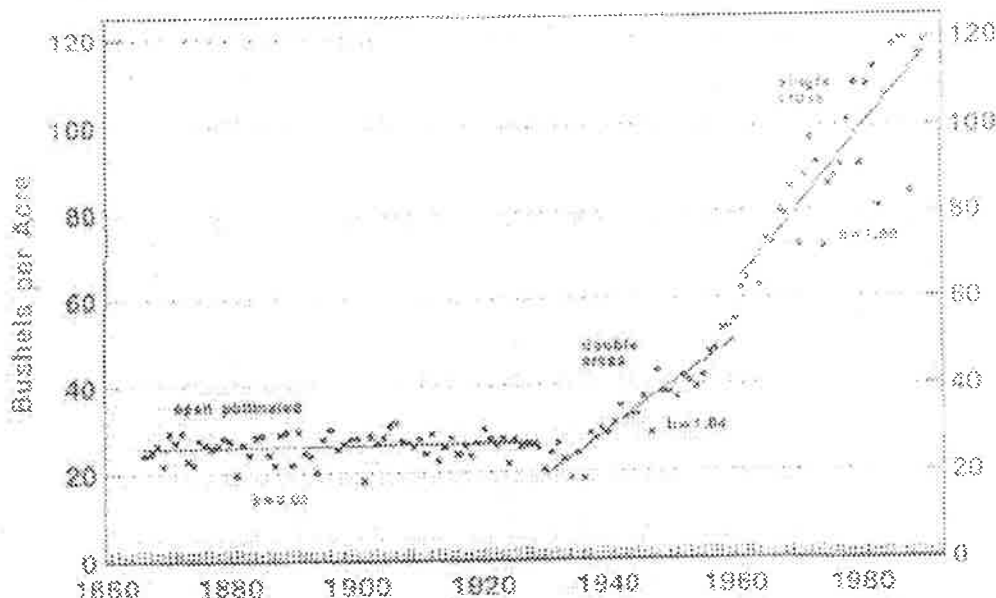


Figure 10. Historical average grain yields of corn in the United States from the 1860s to the 1990s (original figure from Tollenaar as cited by [41]).

#### 4 Comparisons of Biofuels with Stationary Biomass Energy Uses

Four of the reviewed LCA studies included comparisons of GHG mitigation effectiveness of biofuels with alternative (stationary) uses of the biomass [5, 9, 10, 12]. One of the studies [5] concludes that electricity generation from biomass may achieve larger GHG reductions per hectare devoted to biomass production, particularly compared to some conventional (near-term) biofuels (Figure 11), but the study notes that the details must be considered on a case-by-case basis to draw definitive conclusions for any site-specific comparison. Kaltschmitt et al. [9] come to similar conclusions when comparing conventional biofuels against primarily biomass heat applications (Figure 12). Elsayed, et al. [12] include GHG mitigation results for a large number of biofuel and biopower pathways, but only show results in terms of avoided CO<sub>2</sub> emissions per MJ of fuel or electricity produced, making comparisons on the basis of land-use efficiency or biomass use efficiency difficult.

Figure 13 shows my estimates (using GHG emission factors for stationary applications from the well-regarded GREET model<sup>f</sup>) for GHG reductions using biomass for power generation and displacing various types of fossil fuel generated power. This figure communicates (i) the importance of high biomass yield in achieving high GHG emissions savings, (ii) the importance of biomass conversion efficiency for maximizing carbon emission savings, (iii) the lower degree

<sup>f</sup> The GREET model is available via the Argonne National Laboratory website for public download free of charge.

of savings achieved when power from natural gas or cogeneration sources are displaced, and (iv) the high emissions savings rate when coal-generated power is displaced. By comparing the results in Figure 13 against those in Figure 7 and Figure 8, one may conclude that under some conditions biofuels will provide the more effective land use for GHG mitigation and under other conditions, biomass power will be favored. One may further conclude, as several other authors have noted, that it is difficult to make unequivocal statements regarding the relative GHG mitigating merits of different biomass applications without specific case comparisons.

Figure 11. Avoided lifecycle  $\text{CO}_2$  emissions for alternative land uses for production of various biofuels and bioelectricity, from [5].

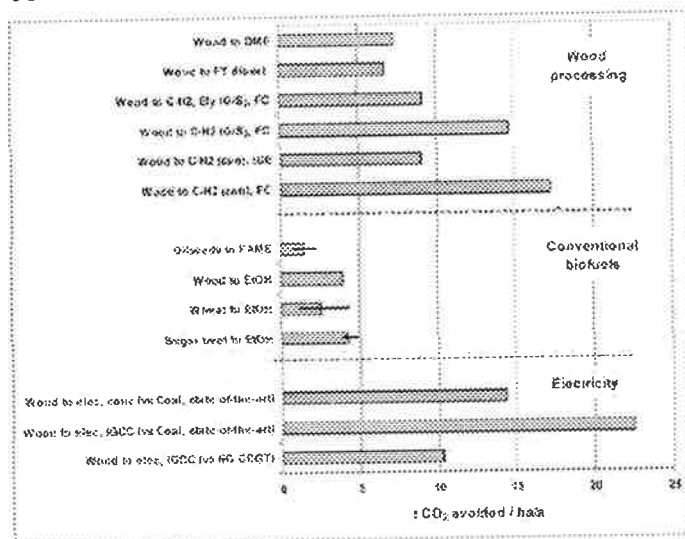


Figure 12. Comparison of lifecycle  $\text{CO}_2$  emissions saved per unit of land ( $\text{kgCO}_2/\text{ha}/\text{year}$ ) for alternative applications of biomass displacing fossil fuels [9].

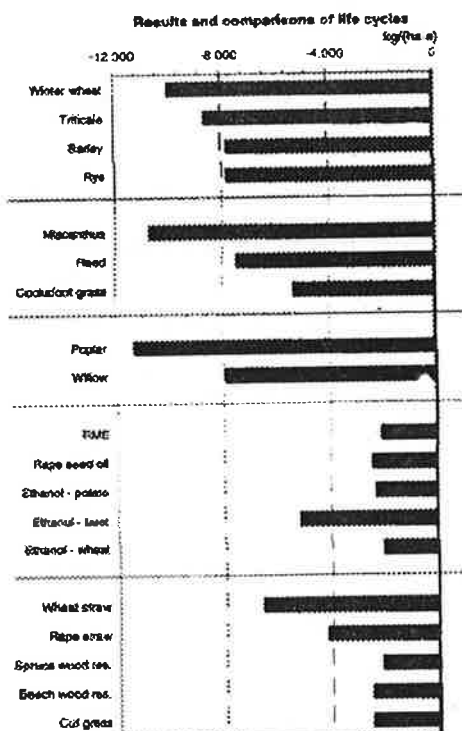


Table 3. Standard life cycle comparisons

Bioenergy carrier	Substituted energy carrier
Winter wheat	Light oil (heating plant)
Triticale	Light oil (heating plant)
Barley	Light oil (heating plant)
Rye	Light oil (heating plant)
Miscanthus	Light oil (CHP)
Reed	Light oil (CHP)
Cocksfoot grass	Light oil (heating plant)
Poplar	Light oil (heating plant)
Willow	Light oil (heating plant)
RME	Diesel fuel (tractor)
Rape seed oil	Diesel fuel (tractor)
Ethanol - potato	Gasoline (car)
Ethanol - sugar beet	Gasoline (car)
Ethanol - wheat	Gasoline (car)
Wheat straw	Light oil (heating plant)
Rape straw	Light oil (heating plant)
Spruce wood residues	Light oil (heating plant)
Beech wood residues	Light oil (heating plant)
Cut grass	Light oil (CHP)

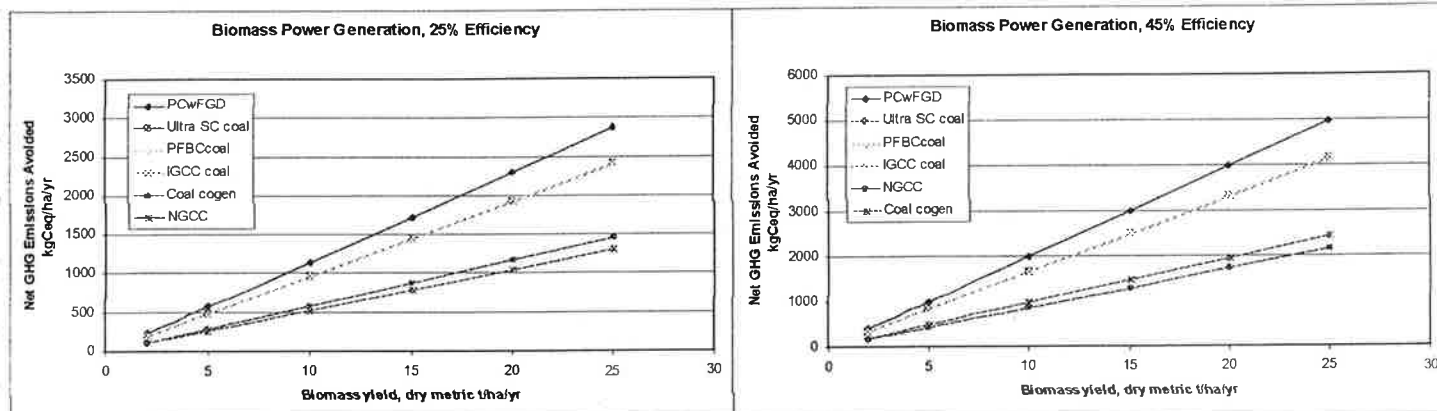


Figure 13. Estimated GHG emissions reductions for biomass power generation assuming 25% HHV efficiency (conventional steam cycle power) or 45% HHV efficiency (advanced biomass-IGCC cycle) displacing different fossil-fuel generated power. Estimated GHG emissions for these stationary sources are taken from the GREET model, and fossil-fuel power plant efficiencies are from Williams [42]. In the case of biomass, the GREET estimates for emissions per tonne of dry biomass are assumed (for purposes of generating these graphs) to be independent of the biomass yield.

## 5 Key Variables and Uncertainties in Biofuel LCA Results

The wide variation in results from LCA studies noted in Section 3 is due in part to the wide range of plausible values for key input parameters, with values often dependent on local conditions. While many numbers go into a biofuel LCA analysis, there appear to be three key input parameters that introduce the greatest variations and uncertainties into the results: allocation method for co-product credits,  $N_2O$  emissions, and soil carbon dynamics. Additionally, the choice of vehicle technology to include in an LCA is a factor that introduces not so much uncertainty as complication in comparing results of different LCA studies

### 5.1 Allocation of Co-Product Credits

Processes for making biofuels will typically involve making some co-products. For example, in the production of RME, glycerin is produced as a byproduct at a rate of about 10% by weight of the final biodiesel product. In the wet milling process for making ethanol from corn, there are multiple co-products including animal feed, corn oil, and others. In the conversion of lingo-cellulosic biomass into ethanol or Fischer-Tropsch diesel, electricity will often be co-produced.

In such cases some of the GHG emissions and energy consumption associated with the biomass conversion process should be charged against the co-products, but what allocation method and numerical values should be used? The choice significantly affects the biofuel LCA results. For example, Quirin, *et al.* [3] note that the co-product allocation assumptions in LCAs in the literature for making bioethanol from wheat grain use values from 15% to as high as 95%, which gives a range of results for the GHG advantage of bioethanol relative to petroleum ranging from nearly no advantage to as much as a four-fold advantage!

Six approaches to allocating co-product credits are mentioned in the LCA literature. One is no allocation. Woods and Bauen [6] are nearly unique in using this approach, arguing that there is too much uncertainty about which is the "correct" allocation method and that there is too much uncertainty regarding the co-product information needed to use any of the allocation methods.



The five other allocation methods include charging GHG emissions and energy use against co-products according to (i) their weight, (ii) their intrinsic energy content, (iii) how much of the total process energy their co-production is deemed to consume, (iv) the market value of co-products, or (v) the energy displaced when the co-products substitute for products that would have been made by conventional routes and would have been used had the bio-based co-product not displaced them. One can imagine cases where one or another of these approaches would be more or less viable.

Energy content	52%	57%
Energy displaced	43%	50%
Protonic energy	36%	41%
Market value	36%	24%
Expenditure	-18%	-20%

Figure 14. Impact of co-product allocation method on the energy use and emissions results for bioethanol production from corn by wet milling and dry milling processes [25].

Wang [25], using his GREET model, has shown the significant impact that alternative allocation methods can have on overall energy and emission results from LCAs for corn ethanol, ranging from benefits relative to petroleum of 16% up to 52% in the case when the ethanol is made by a wet milling process (Figure 14). Figure 15, taken from another study [2], shows a somewhat smaller (but nevertheless significant) range in GHG results for biofuels when different co-product allocation methods are used.

Biofuel	2005 GREET Energy (GJ)	2005 GREET Emissions (kg)	Net reduction Source (GJ)	Net Total GREET Emissions (kg)
Biodiesel from 100% Rape - with allocation by mass - with allocation by price - without any allocation	70 ± 1 71 ± 1 53 ± 1	32 ± 4 32 ± 4 48 ± 12	-394 ± 13 -392 ± 10 -1,188 ± 147	72 ± 1 69 ± 1 25 ± 1
Biodiesel from 100% Rape - with allocation by mass - with allocation by price - without any allocation	63 ± 1 64 ± 1 56 ± 1	32 ± 4 31 ± 1 36 ± 1	-370 ± 10 -342 ± 11 -820 ± 121	66 ± 1 63 ± 1 48 ± 1
Biodiesel from 100% Rape - with allocation by mass - with allocation by price - without any allocation	61 ± 1 70 ± 1 58 ± 1	32 ± 1 27 ± 14 28 ± 18	-313 ± 16 -429 ± 36 -442 ± 71	73 ± 1 67 ± 1 52 ± 1

Figure 15. Impact of co-product allocation method on LCA of GHG emissions for alternative biofuels [2]. This table shows a comparison of results from three different studies that used three different allocation methods [5, 6, 12].

As an best example, the results for the 100% rape seed oil are shown.

The “correct” allocation method depends to a great extent on the questions one is seeking to answer with the LCA. Wu, *et al.* [11], in a GREET-based LCA of technologically advanced pathways for biofuels from switchgrass involving co-production of electricity, choose to allocate co-product credits in proportion to the energy content of co-products (fuels and electricity in this case), because using the displacement method (which is preferred by many LCA analysts) would skew comparisons between pathways for which electricity is a large co-product and those for which it is only a minor co-product. Wu, *et al.*, report their GHG mitigation results on a per-vkm basis using this energy-content allocation method (Figure 16 and Figure 17). Instead, they use the displacement approach when calculating total GHG mitigation per tonne of biomass converted to biofuel and co-products (Figure 18).<sup>8</sup> The latter calculation is especially relevant when comparing alternative uses for biomass.

<sup>8</sup> Mitigation per-hectare could be calculated similarly, but Wu, *et al.* do not report per-hectare results.

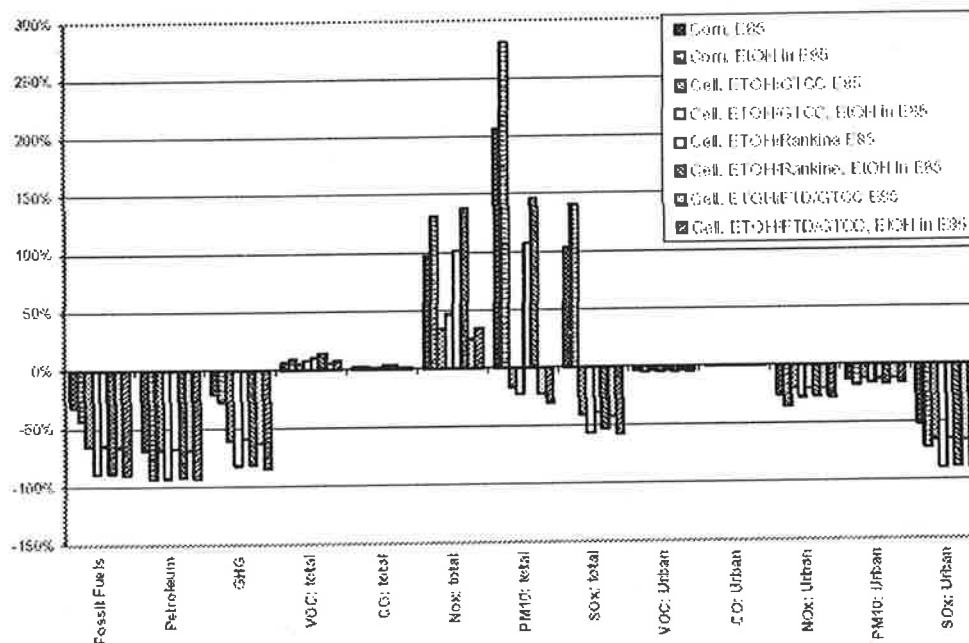


Figure 16. Lifecycle percent change in fossil energy use, GHG emissions, and criteria pollutants per vehicle-km in a hybrid electric vehicle for corn-ethanol and alternative advanced-technology options for bioethanol production from switchgrass (with co-production of electricity and/or Fischer-Tropsch diesel) in the United States relative to gasoline in the same vehicles [11], based on the GREET model. Negative values mean net displacement.

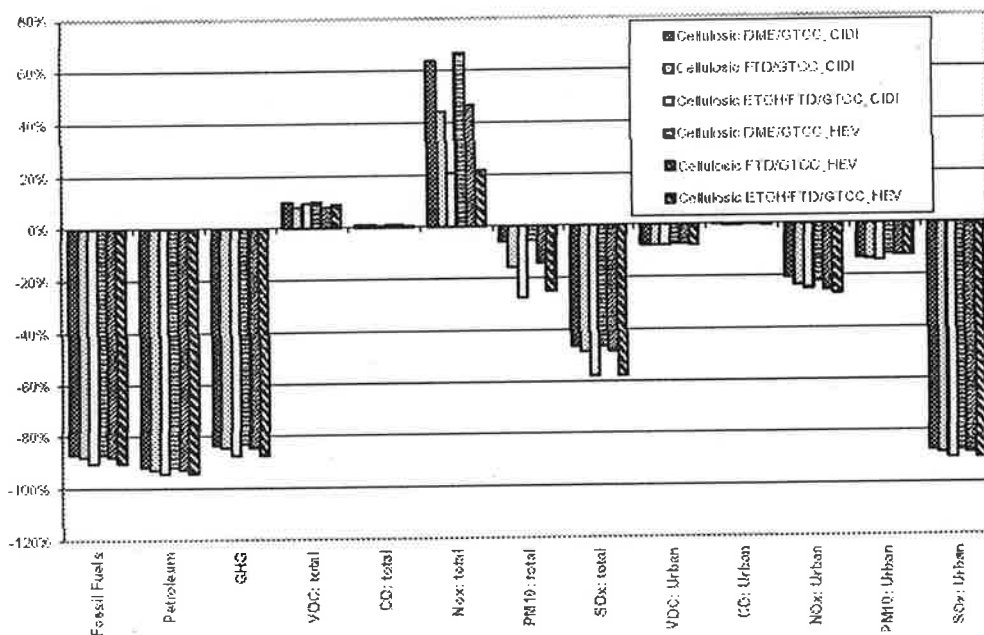


Figure 17. Lifecycle percent change in fossil energy use, GHG emissions, and criteria pollutants per vehicle-km in a compression-ignition direct-injection (CIDI) engine vehicle and a hybrid diesel/electric vehicle for advanced-technology options for Fischer-Tropsch diesel and dimethyl ether production from switchgrass (with co-production of electricity and/or ethanol) in the United States relative to diesel fuel in the same vehicles [11], based on the GREET model. Negative values mean net displacement.

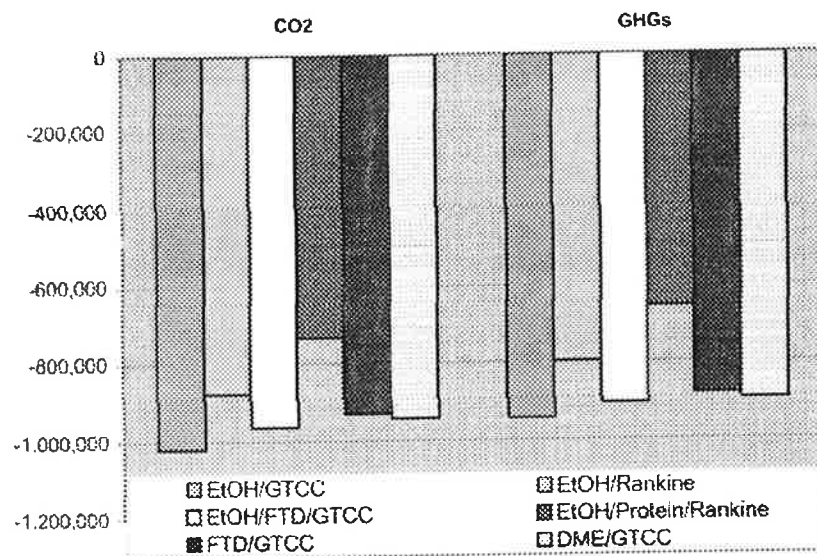


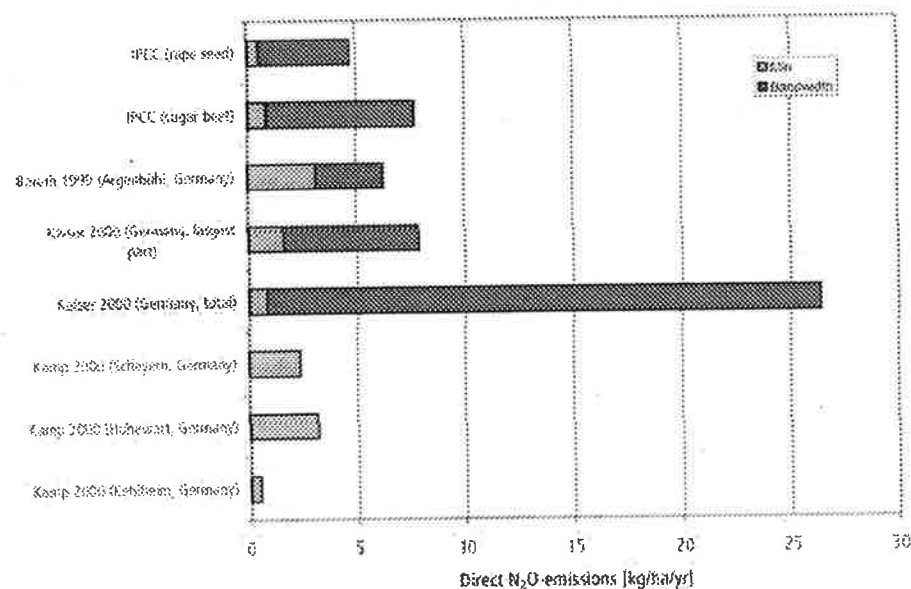
Figure 18. Well-to-wheel CO<sub>2</sub> and total GHG emissions displaced (gCO<sub>2</sub> and gCO<sub>2equiv</sub>, respectively) per ton of switchgrass fed to conversion facilities co-producing biofuels and electricity (and animal-feed protein in one case) [11]. Negative values mean net displacement.

## 5.2 Nitrous Oxide (N<sub>2</sub>O) Emissions

Another important variable, and one with perhaps the most uncertainty due to the number of parameters that can affect its value is the contribution to net GHG emissions of N<sub>2</sub>O, which evolves from nitrogen fertilizer application and leaf litter decomposition. Actual emissions from fields vary depending on soil type, climate, crop, tillage method, and fertilizer and manure application rates. The uncertainties in actual emissions are magnified by the high global warming potential of N<sub>2</sub>O.<sup>b</sup> The impacts of N<sub>2</sub>O emissions are especially significant for grain or seed-based biofuels (Figure 19, and see also [9]), since average annual fertilization rates are larger for these than for perennial energy crops, but the N<sub>2</sub>O emissions for perennial crops nevertheless can be a significant contributor to overall GHG emissions in their production (

Figure 20).

Figure 19. Range of measured N<sub>2</sub>O emissions for rapeseed and sugar beet production in Germany, with comparisons against calculated values using IPCC guidelines [7].



<sup>b</sup> The IPCC Third Assessment Report gives direct GWP values (relative to CO<sub>2</sub> value of 1) for 20-year, 100-year, and 200-year time horizons of 62, 23, and 7, respectively for CH<sub>4</sub> (in kgCO<sub>2eq</sub>/kgCH<sub>4</sub>) and 275, 296, and 156, respectively, for N<sub>2</sub>O (in kgCO<sub>2eq</sub>/kgN<sub>2</sub>O).

	CO <sub>2</sub>	Other GHG Mg CO <sub>2</sub> eq. ha <sup>-1</sup>	Total
<b>Emissions</b>			
Diesel fuel	+3.12	+0.06	+3.18
Ag. inputs <sup>b</sup>	+2.97	+0.40	+3.37
N <sub>2</sub> O from applied N	+3.97 (±1.17) <sup>c</sup>		+3.97
N <sub>2</sub> O from leaf litter	+7.28 (±5.83) <sup>c</sup>		+7.28
<b>C sequestration</b>			
Below ground biomass	-14.10		-14.10
Soil carbon	0		0
<b>Net total</b>	-8.01	+11.70 (±9.0) <sup>c</sup>	+3.7
Harvested biomass	-199.2		-199.2

<sup>a</sup>Positive values indicate additions (releases) to the atmosphere.

<sup>b</sup>Includes fertilizer and herbicide manufacturing and transport, machinery manufacturing, and nursery operations.

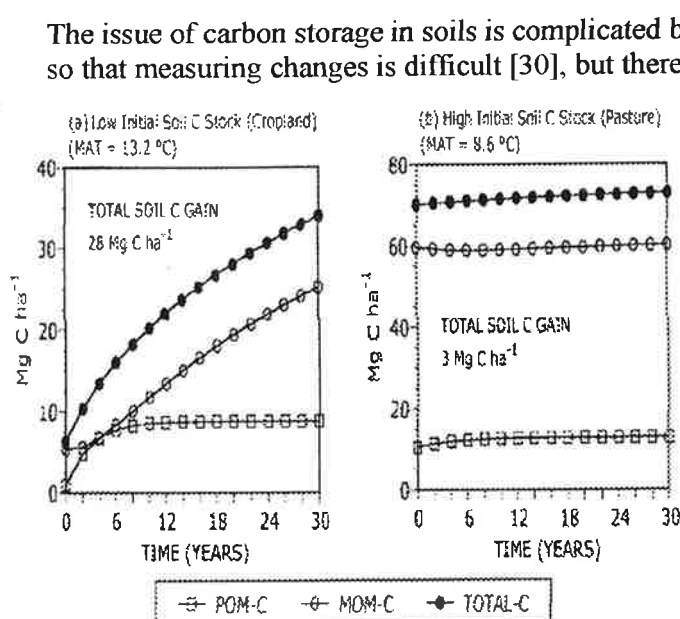
<sup>c</sup>Bracketed numbers represent the N<sub>2</sub>O emission range presented by the IPCC estimate [42].

**Figure 20. Greenhouse gas emissions from cultivation of short-rotation willow hardwood in New York state, United States [30].** N<sub>2</sub>O emissions account for about two-thirds of total emissions associated with cultivation. The total period of cultivation is 23 years (7 rotations before replanting), which gives an annual average N<sub>2</sub>O emissions of 489 kgCO<sub>2</sub>eq/ha/yr. Considering a GWP for N<sub>2</sub>O of 396, this gives an emissions rate of 1.24 kgN<sub>2</sub>O/ha/yr. This latter value can be compared against the data in Figure 19 for N<sub>2</sub>O emissions from annual grain crops, which gives an indication of the relative magnitude of emissions for perennial and annual crops.

### 5.3 Soil Carbon Sequestration

A variable that many biofuel LCA studies choose to leave entirely out of the analysis is the extent of soil carbon buildup (or degradation) associated with growing biomass.

The potential to sequester carbon in a soil is very site-specific and highly dependent on former and current agronomic practices, climate, and soil characteristics. Heavy tillage (used conventionally for annual crops) tends to liberate soil organic matter. Thus, converting previously heavily-tilled land to production of, say, a perennial energy crop like switchgrass (for which tillage requirements are much lower, and soil carbon inputs are increased due to greater incorporation of leaf litter and fine root material) could result in substantial buildup of carbon in the soil. On the other hand, if woodlands or grasslands are converted to bioenergy crop production, there could be a decrease (or little change) in soil organic carbon. Figure 21 shows results of detailed modeling of the evolution of soil carbon under switchgrass, assuming in one case that the switchgrass is established on soil that is carbon-poor (converted cropland) and in the other case on soil that is carbon-rich (converted pasture).



The issue of carbon storage in soils is complicated by the fact that the process is relatively slow, so that measuring changes is difficult [30], but there are some data that demonstrate soil carbon buildup under switchgrass [43]. It should also be noted that once the carbon in a soil reaches a saturation level, there can be no further net accumulation.

**Figure 21. Comparison of modeling results (using ALMANAC model) for soil carbon gain over time under a newly established switchgrass field on soil with either a low initial carbon stock (e.g., converted cropland) or with a high initial carbon stock (e.g., converted grassland) [29].**

## 5.4 Vehicle Assumptions

In considering transport use of biofuels, an obviously important element in determining environmental impacts (both GHG and local emissions) of any given biofuel pathway is the type of vehicle in which the fuel is used. Carrying the LCA analysis through to the transportation services delivered is particularly important if comparisons are being made among fuels for compression ignition and for spark-ignition engines. CI engines will have an intrinsic thermodynamic advantage of at least 15% or more over SI engines with comparable performance (Figure 22), and this difference would be missed if the LCA analysis were to end with the biofuel production process. That said, comparisons among different studies that carry the analysis through to v-km are complicated by different vehicle characteristics used in different studies. For example, the well-to-wheels study led by GM in the United States [8] used as its base vehicle a projected 2010-model year full-sized Silverado pick-up truck (both with and without mild hybridization of the engine), whilst studies focusing on Europe, e.g., [5,7] have used much smaller reference vehicles.<sup>1</sup>

	Gasoline				Diesel	
	2001 Reference	2020 Baseline	2020 Advanced	2020 Hybrid	2020 Advanced	2020 Hybrid
<b>Mass (kg)</b>						
Body & Chassis	830	845	746	730	757	738
Propulsion System (3)	392	284	252	289	293	297
Total (incl. 136 kg payload)	1458	1245	1134	1155	1188	1191
<b>Vehicle Characteristics</b>						
Rolling Res. Coeff	0.008	0.008	0.008	0.008	0.008	0.008
Drag Coeff	0.33	0.27	0.22	0.23	0.22	0.22
Frontal Area (m <sup>2</sup> )	2.0	1.8	1.8	1.8	1.8	1.8
Power for Accessories (kW)	700	1000	1000	1000	1000	1000
<b>Engine</b>						
Displacement (L)	2.50	1.79	1.65	1.11	1.75	1.15
Indicated Eff. (%)	38	41	43	43	51	51
Protonic ME Pressure (kPa)	190	124	124	124	163	163
Max. Engine Power (kW)	110	93	85	58	88	88
Max. Motor Power (kW)				29		30
<b>Use of On-Board Fuel</b>						
Driving Cycle						
US Urban (MJ/km)	2.82	2.00	1.79	1.20	1.53	1.03
US Highway (MJ/km)	2.16	1.45	1.25	0.91	1.04	0.78
US06 (MJ/km)	2.51	1.54	1.57	1.45	1.38	1.29
Combined (MJ/km) (4)	2.48	1.75	1.54	1.07	1.30	0.92
Combined (mpg) (5)	30.6	43.2	49.2	70.7	68.1	82.5
Combined as % Baseline	131	100	88	61	74	80
<b>Life-Cycle Combined Energy</b>						
Vehicle Operation (MJ/km)	2.47	1.75	1.55	1.07	1.31	0.92
Fuel Cycle (MJ/km) (6)	0.52	0.37	0.32	0.22	0.18	0.13
Vehicle Manufacturing (MJ/km)	0.23	0.25	0.23	0.26	0.28	0.28
Total (MJ/km)	3.28	2.37	2.12	1.55	1.75	1.31
Total as % Baseline	138	100	89	61	74	85
<b>Life-Cycle Combined GHG Emissions</b>						
Vehicle Operation (gC/km) (7)	48.5	35.4	30.2	21.0	27.1	18.1
Fuel Cycle (gC/km) (8)	12.1	8.6	7.6	5.2	4.3	3.0
Vehicle Manufacturing (gC/km)	5.5	4.8	4.8	5.0	5.0	5.1
Total (gC/km) (9)	66.1	47.8	42.6	31.2	36.4	27.2
Total as % of Baseline	138	100	89	61	76	57

Notes: (1) 1 Bar (0.737 kg) gasoline = 32.2 MJ (LHV)  
(2) 1 Bar (0.956 kg) diesel = 35.8 MJ (LHV)  
(3) Propulsion system mass includes ICE, drive train, motors, battery, fuel (2/3 full), and tank  
(4) Combined cycle is 55% urban/45% highway  
(5) Fuel cycle energy, MJ per MJ fuel in tank: gasoline 0.21, diesel 0.14  
(6) Fuel cycle gC per MJ fuel in tank: gasoline 4.9, diesel 3.3  
(7) Vehicle operation (gC per MJ burned): gasoline 13.6, diesel 20.8  
(8) Gasoline equivalent mass per gallon calculated as equal fuel LHV  
(9) gC of GHG calculated as C in CO<sub>2</sub> released plus carbon in CO<sub>2</sub> equal to 24 times mass of methane leaked

Figure 22. Characteristics of different internal combustion engine vehicles with comparable performance, as simulated by researchers at the Massachusetts Institute of Technology's Laboratory for Energy and the Environment [36].

<sup>1</sup> The European GM study [7] used an Opel Zafira minivan with an engine displacement of 1.8 L for its baseline vehicle. The Concawe study [5] used a typical European compact car similar to the Volkswagen Golf.

## 6 Final Comments

Despite the large variation in LCA results for GHG savings with alternative biofuel systems in the literature, it is possible to draw a few robust conclusions. Obviously, maximizing GHG savings with biofuels benefits from high (and ecologically sustainable) biomass yields, efficient conversion of biomass to fuel, and efficient use of the produced fuel. As well, an understanding of the relative GHG benefits of alternative biomass applications is needed to help rank biofuels relative to other uses for the biomass.

Crop	Residue	Residue ratio <sup>a</sup>	Residue energy (MJ/dry kg) <sup>b</sup>	Typical current residue uses <sup>c</sup>
Barley <sup>d</sup>	straw	2.3	17.0	
Coconut	shell	0.1 kg/nut	20.56	household fuel
Coconut	fibre	0.2 kg/nut	19.24	mattress making, carpets, etc.
Coconut	pith	0.2 kg/nut		
Cotton	stalks	3.0	18.26	household fuel
Cotton	gin waste	0.1	16.42	fuel in small industry
Groundnut	shells	0.3		fuel in industry
Groundnut	haulms	2.0		household fuel
Maize	cobs	0.3	18.77	cattle feed
Maize	stalks	1.5	17.65	cattle feed, household fuel
Millet	straw	1.2		household fuel
Mustard seed	stalks	1.8		household fuel
Other seeds	straws	2.0		household fuel
Pulses	straws	1.3		household fuel
Rapeseed	stalks	1.8		household fuel
Rice	straw	1.5	16.26	cattle feed, roof thatching, field burned
Rice	husk	0.25	16.14	fuel in small industry, ash used for cement production
Soybeans <sup>e</sup>	stalks	1.5	15.91	
Sugarcane	bagasse	0.15	17.33	fuel at sugar factories, feedstock for paper production
Sugarcane	tops/leaves	0.15		cattle feed, field burned
Tobacco	stalks	5.0		heat supply for tobacco processing, household fuel
Tubers <sup>f</sup>	straw	0.5	14.24	
Wheat	straw	1.5	17.51	cattle feed
Wood products <sup>g</sup>	waste wood	0.5	20.0	

- (a) Unless otherwise noted, the residue ratio is expressed as kilograms of dry residue per kg of crop produced, where the crop production is given in conventional units, e.g. kg of rice grain or kg of clean fresh sugarcane stalks. The ratios given here are illustrative only: for a given residue, the residue ratio will vary with the agricultural practice (species selected, cultivation practices, etc.). Unless otherwise noted, the ratios given here are from Biomass Power Division (1998).
- (b) Unless otherwise noted, these are higher heating values as reported by Jenkins (1989). The lower heating values are about 5% lower. The higher and lower heating values differ by the latent heat of evaporation of water formed during complete combustion of the residue.
- (c) The use to which residues are put varies greatly from one region of a country to another and from country to country. The uses listed here are illustrative only. They are typical uses in parts of India.
- (d) Source: Taylor, *et al.* (1982).
- (e) Estimate for China as given by Li, Bai, and Overend [1998]. Tubers includes crops such as cassava, yams, and potatoes.
- (f) Wood products refers to lumber or finished wood products such as furniture. The residue ratio is given as a broad average by Hall, *et al.* (1993). The ratio will vary considerably depending on the specific product.

**Figure 23. Typical “residue ratios” (kg of dry residues per kg of grain or seed) for a variety of crops [44].**  
Note that in most cases, the mass of the residues exceeds half of the total above-ground biomass.

It is fair to conclude that conventional grain- and seed-based biofuels can provide only modest GHG mitigation benefits by any measure (per GJ fossil fuel displaced, per-vkm driven, or per-hectare land use) and will be able to provide only modest levels of fuel displacement in the long term in any case due to high land requirements.<sup>1</sup> The fundamental reason for the relatively poor performance of grains and seeds is that they represent only a portion (typically ≤50% of the dry mass) of the above-ground biomass (as indicated by the residue ratios shown in Figure 23), so they are disadvantaged from the yield point of view. Higher conversion to fuel compensates the lower biomass yield to some extent. For example, some 380 liters of ethanol can be produced

<sup>1</sup> Consider the following numbers for ethanol production from corn in the United States – the largest grain-to-ethanol program in the world today. The U.S. produced 3.4 billion gallons of ethanol in 2004, consuming 12% of all corn grown that year in the U.S. This ethanol accounted for less than 1.5% of US motor vehicle fuel use (on an energy basis).



from a dry tonne of corn grain using current technology [18].<sup>k</sup> This compares to today's commercially-ready technology for cellulosic biomass conversion to ethanol which can only yield some 255 liters/dry tonne [26]. Future improvements in lignocellulosic conversion to ethanol are projected: 340 liters/tonne (2010 time frame) [26] and 437 liters/tonne (2030 time frame) [10]. Technology for production of Fischer-Tropsch fuels from lignocellulose (which could become commercially ready in the 2010/2015 time frame) yields some 280 liters of diesel and high-octane gasoline blendstocks per dry tonne,<sup>l</sup> or 471 liters of ethanol equivalent/tonne.<sup>m</sup>

More efficient land use in mitigating GHG impacts can be expected with dedicated high-yielding lignocellulosic energy crops in the longer term. Decades of experience with development of food crop yields, together with recent experience with developing lignocellulosic energy crops [10] suggests that major yield gains can be expected (probably with lower inputs per tonne of biomass produced) with a concerted development efforts.

Very broadly, grain or seed-based biofuels (e.g., corn ethanol or RME) might give 20-30% GHG reductions per v-km relative to petroleum fuels, sugar beets might give 40-50% reductions, sugarcane (average SE Brazil) gives 90% reductions, future advanced cellulosic conversion (to ethanol, FT, or DME) from perennial energy crops might give 80-90+% reductions. Biofuels production with carbon capture and storage (a longer-term option) will give >100% reductions [45].

While GHG mitigation per-vkm is an important measure, land use efficiency in achieving GHG reductions may be the most important consideration. The ranges of GHG reductions per v-km noted in the previous paragraph do not necessarily reflect relative land-use efficiencies, as was pointed out in Section 3. Tradeoffs between biofuel output per ha, GHG emissions reduced per hectare, and GHG emissions reduced per v-km need more careful examination.

Comparing results from different LCA studies is useful for general guidance – and some broad issues can be resolved. However, thinking in terms of potential GEF-sponsored projects, site-specific analysis is needed to determine actual GHG savings that can be expected from any specific project. (There is also the question of how to measure GHG mitigation achievements after a project has been implemented.) Very few LCA studies have been carried out in the context of developing countries.

Site-specific issues that need to be considered in estimating potential lifecycle GHG benefits of a biofuel include the biomass crop to be used and its yield, competing uses for the biomass, competing uses for the land (what would have been GHG impact if land were used for a “business as usual” purpose), agronomic practices (fertilizers, herbicides, etc., including their

<sup>k</sup> The use of cellulosic residues of grain or seed production to fuel the conversion process (substituting for fossil fuels) could improve the GHG performance of biofuels from grains or seeds to some extent, but residue use is not practiced today. Residues are used routinely to fuel the processing of sugarcane into ethanol, and the quite favorable GHG impacts of this biofuel pathway (Figure 8) can be attributed in part to this fact.

<sup>l</sup> This result is based on work in progress by the author and colleagues. Detailed energy balances developed to date give the result that a facility consuming 4545 dry metric ton/day switchgrass (893 MW LHV) can produce a mix of FT diesel, FT gasoline (305 MW LHV in total), and electricity (207 MW). Charging 2420 t/day of the input biomass against FT production (taking a credit for electricity assuming it could have been produced in a stand-alone biomass IGCC power plant consuming 2125 t/day – an efficiency of 49.5%), gives the value of 280 liters/tonne.

<sup>m</sup> Considering that one liter of ethanol contains 21.1 MJ (LHV), and one liter of diesel contains 35.7 MJ (LHV).

method of production), climate, soil type, prior use of the land (which affects soil carbon dynamics, among other factors), what products co-products will substitute for, performance of specific technologies for biomass conversion to fuel and fuel use in vehicles, what fuel will be replaced by the biofuel, etc.

Economics are also critical, of course, and biofuel pathways that both save significant amounts of GHGs and are economically competitive, or have potential for economic competitiveness in the longer term, are most desirable. The Brazilian sugarcane ethanol program appears to be a textbook example of the type of biofuel project that might be attractive to GEF. The positive GHG benefits were discussed earlier (Figure 8). Costs of bioethanol in Brazil were high in the early years of the program (1970's), but sustained commitment from the government led to continuous technology innovation and "learning by doing" that brought production costs steadily down to the point where (unsubsidized) ethanol became competitive with gasoline with a \$25/bbl world oil price – far below today's \$60/bbl price [46] (Figure 24).

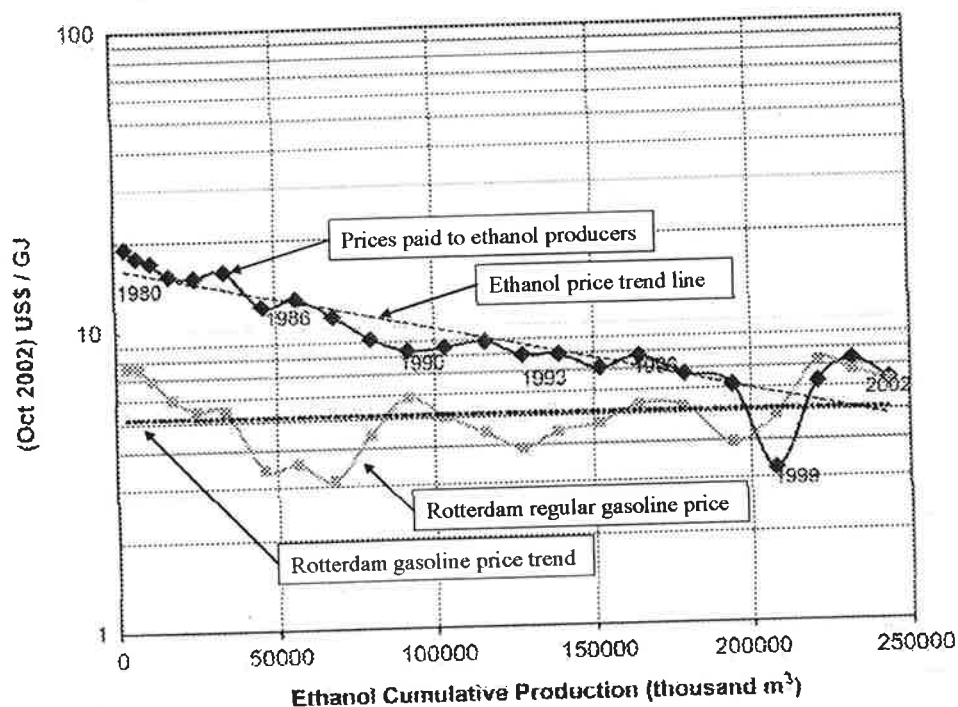


Figure 24. History of ethanol selling price (reflecting production cost) in Brazil, with comparison to Rotterdam gasoline prices [46]. Government subsidies on anhydrous ethanol (used in gasohol) were eliminated in 1997 and subsidies on hydrous ethanol (for neat ethanol vehicles) were eliminated in 1999. The indicated Rotterdam gasoline price trend line corresponds to a world crude oil price of about \$25/bbl.

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- <sup>36</sup> Weiss, M.A., Heywood, Schafer, A., and Natarajan, V.K., 2003. "Comparative Assessment of Fuel Cell Cars," MIT LFEE 2003-110 RP, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Cambridge, February, 29 pages.
- <sup>37</sup> Mann, M.M. and Spath, P.L., 1997. "Life Cycle Assessment of a Biomass Gasification Combined-Cycle System," NREL/TP-430-23076, National Renewable Energy Laboratory, Golden, CO, December, 163 pages.
- <sup>38</sup> Heller, M.C., Keoleian, G.A., Mann, M.K., and Volk, T.A., 2004. "Life cycle energy and environmental benefits of generating electricity from willow biomass," *Renewable Energy*, **29**: 1023-1042.
- <sup>39</sup> Watson, R.T., Zinyowera, M.C., Moss, R.H., and Dokken, D.J. (eds), 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, Cambridge University Press, Cambridge, UK.
- <sup>40</sup> McLaughlin, S.B. and Kxzos, L.A., 2005. "Development of Switchgrass (*Panicum virgatum*) as a Bioenergy Feedstock in the United States," *Biomass and Bioenergy*, **28**(6): 515-535.
- <sup>41</sup> McLaughlin, S.B., 2004. Univ. of Tennessee (Oak Ridge National Laboratory, retired), personal communication.
- <sup>42</sup> Williams, R.H., 2000. "Advanced Energy Supply Technologies," *World Energy Assessment*, World Energy Council and United Nations Development Program, New York, pp. 274-329.
- <sup>43</sup> Ma, Z., Wood, C.W., and Bransby, D.I., 2000. "Soil Management Impacts on Soil Carbon Sequestration by Switchgrass," *Biomass and Bioenergy*, **18**: 469-477.
- <sup>44</sup> Kartha, S. and Larson, E.D., 2000. *Bioenergy Primer: Modernized Biomass Energy for Sustainable Development*, United Nations Development Program, New York, 133 pages.
- <sup>45</sup> Larson, E.D., Jin, H., Williams, R.H., and Celik, F.E., 2005. "Gasification-Based Liquid Fuels and Electricity from Biomass with Carbon Capture and Storage," presentation at the 4<sup>th</sup> Annual Conference on Carbon Capture and Sequestration, National Energy Technology Laboratory, US Dept. of Energy, Washington, DC.
- <sup>46</sup> Goldemberg, J., Coelho, S.T., Nastari, P.M., and Lucon, O., 2003. "Ethanol Learning Curve—the Brazilian Experience," *Biomass and Bioenergy*, **26**: 301-304.

## Appendix: Literature Summaries

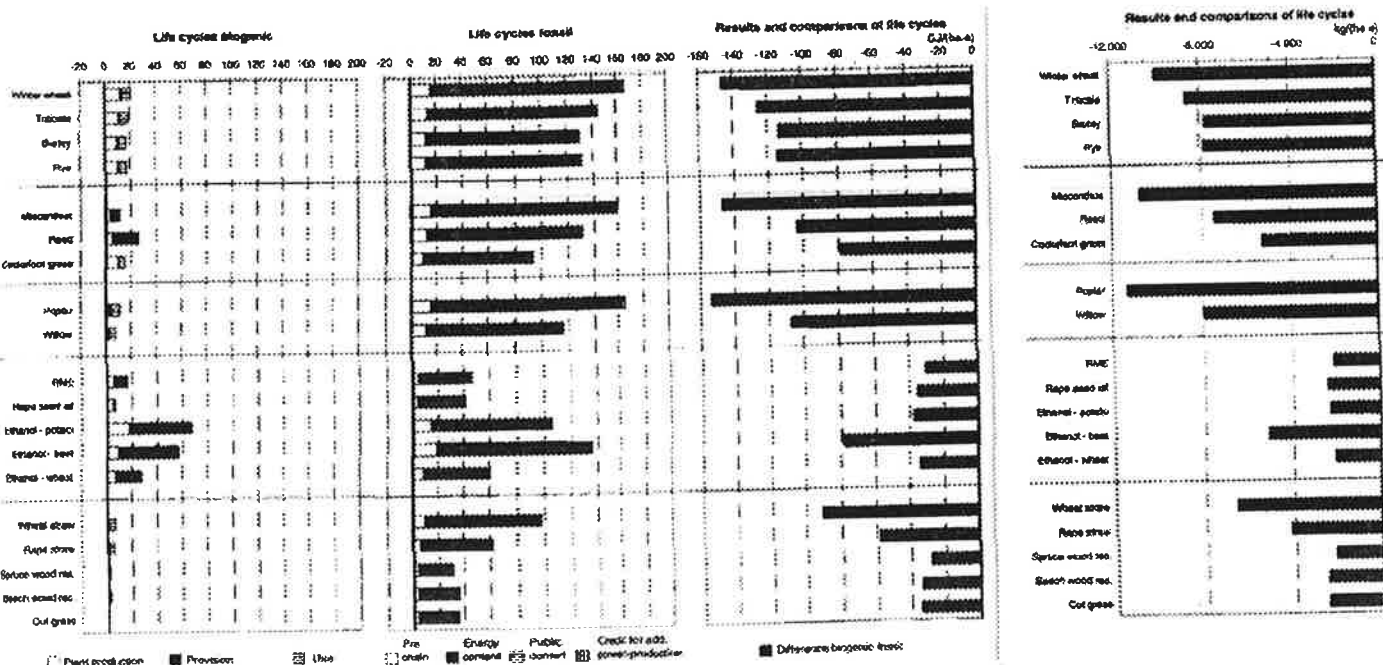
Notes are provided here briefly summarizing key points from studies that included comprehensive original LCA work on multiple biofuels or included extensive synthesis of other LCA literature. The main text cites additional literature, e.g., reporting lifecycle analyses of particular biofuels or components of biofuel pathways.

### Kaltschmitt, M., Reingardt, G.A., and Stelzer, T., 1997. "Life Cycle Analysis of Biofuels Under Different Environmental Aspects," *Biomass and Bioenergy*, 12(2):121-134.

- This is one of the earliest of the comprehensive biofuel LCAs found in the literature. For a variety of biomass to heat or combined heat and power, it evaluates net energy balances, net greenhouse gas emissions (considering CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), and net emissions of SO<sub>2</sub>, NO<sub>x</sub>, NH<sub>3</sub>, and HCl.
- The cases included in the analysis are given in the table shown to the right. For biofuels, no analysis of energy or emission impacts is provided on a per-km basis.
- The paper explicitly avoids giving energy input/output figures, stating instead that per-hectare measures are most important. Indeed, results are presented on a per-hectare basis, but the statement is also made that for GHG mitigation evaluations, GHG savings per GJ of biofuel is the "preferred comparative value". The authors go on to show that bioenergy applications show similar values for avoided GHG emissions per GJ of primary fossil energy substituted.
- The authors also show that net energy gains per hectare (left graph below) and net avoided emissions of CO<sub>2eq</sub> per hectare (right graph) vary considerably from one case.

Table 3. Standard life cycle comparisons

Bioenergy carries	Substituted energy carrier
Winter wheat	Light oil (heating plant)
Triticale	Light oil (heating plant)
Barley	Light oil (heating plant)
Rye	Light oil (heating plant)
Miscanthus	Light oil (CHP)
Reed	Light oil (CHP)
Cocksfoot grass	Light oil (heating plant)
Poplar	Light oil (heating plant)
Willow	Light oil (heating plant)
RME	Diesel fuel (car)
Rape seed oil	Diesel fuel (tractor)
Ethanol - potato	Gasoline (car)
Ethanol - sugar beet	Gasoline (car)
Ethanol - wheat	Gasoline (car)
Wheat straw	Light oil (heating plant)
Rape straw	Light oil (heating plant)
Spruce wood residues	Light oil (heating plant)
Beech wood residues	Light oil (heating plant)
Cut grass	Light oil (CHP)



- N<sub>2</sub>O emissions for biomass cases arise from both nitrification/denitrification of soil/water (all cases) and from combustion (in heating applications). The combustion contributions are considerably more significant than the soil/water-related emissions.



- In general impacts on ozone-depletion and acidification are worse for the biomass options than for their fossil fuel counterparts.
- Sensitivity analysis suggests that land cultivation methods with high external inputs (e.g., fertilizer), give significantly better energy balances than lower use of inputs (presumably because of higher biomass yields that are achieved), but significantly more N<sub>2</sub>O emissions.
- N<sub>2</sub>O emissions are very uncertain (by up to factor of 2.5), and given the high GWP of N<sub>2</sub>O, overall GHG impact may be very different than baseline results presented in the paper.

**Elsayed, M.A., Matthews, R., and Mortimer, N.D., 2003. "Carbon and Energy Balances for a Range of Biofuel Options," Resources Research Unit, Sheffield Hallam University, UK, March, 71 pages.**

- This study examines a wide body of work to assess on as consistent a basis as possible the LCA for a variety of biomass pathways in the UK context (see table). For biofuel options, no analysis is provided on a per-km basis.
- The ISO 14041 standard is followed for reporting LCA results.
- The analysis of each pathway is supported by a detailed appendix giving overall mass balance for the process (see example for RME below) and all numerical inputs used to generate results.
- Multiple studies were reviewed by the authors for each fuel, and those judged to be the "best" were synthesized and put on as common a basis as possible to develop results. The analysis is well documented regarding assumptions and sources.
- Results are presented essentially without commentary or comparisons. Typical values and ranges are given per unit of biofuel or biopower produced for fossil energy input, carbon emissions (excluding those absorbed from atmosphere by plant growth), methane emissions, N<sub>2</sub>O emissions, and total GHG emissions in terms of equivalent CO<sub>2</sub> (table next page). These same emissions for fossil fuels are also given for comparison (table below).
- The authors' preferred co-product allocation method is by displacement, but in many cases, the authors claim this is not an appropriate approach, and market values are used instead for allocations.

Biodiesel from oilseed rape
Biodiesel from recycled vegetable oil
Combined Heat and Power (large scale with industrial loads) by combustion of wood chip from forestry residues (large scale)
Combined Heat and Power (small scale) by gasification of wood chip from short rotation coppice
Electricity (large scale) by combustion of miscanthus
Electricity (large scale) by combustion of straw
Electricity by combustion of wood chip from forestry residues (large scale)
Electricity by combustion of wood chip from short rotation coppice
Electricity by gasification of wood chip from forestry residues (large scale)
Electricity by gasification of wood chip from short rotation coppice
Electricity by pyrolysis of wood chip from forestry residues (large scale)
Electricity by pyrolysis of wood chip from short rotation coppice
Ethanol from lignocellulose
Ethanol from sugar beet
Ethanol from wheat
Heat (small scale) by combustion of wood chip from forestry residues (large scale)
Heat (small scale) by combustion of wood chip from woodland management
Rapeseed Oil from oilseed rape

Flow Chart for the Production of Biodiesel from Oilseed Rape

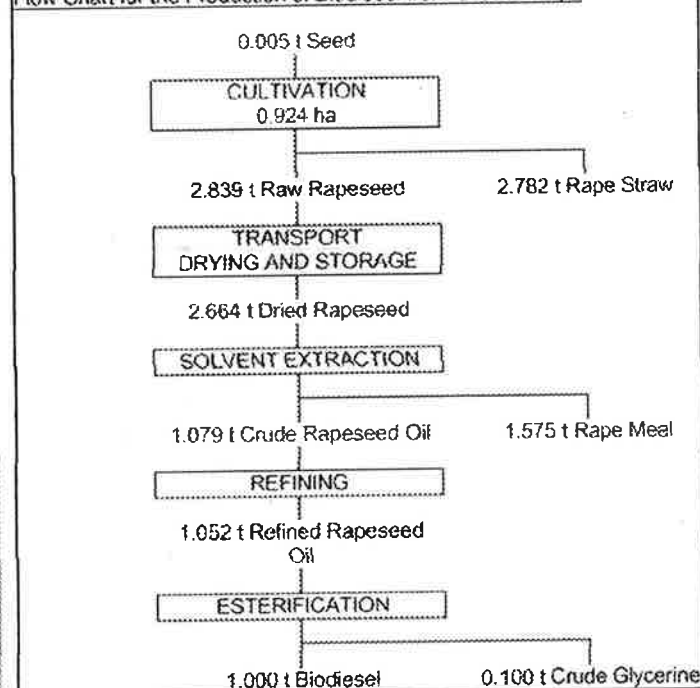


Table 8 Reference Results for a Fairly Good Sample of Conventional Sources of Energy

Source	Energy density (MJ/kg)	CO <sub>2</sub> emissions (kg/kg)	CH <sub>4</sub> emissions (kg/kg)	N <sub>2</sub> O emissions (kg/kg)	Other emissions (kg/kg)
Coal (lignite)	15.5	2.5	0.05	0.005	0.005
Coal (bituminous)	25.5	2.5	0.05	0.005	0.005
Coal (anthracite)	30.5	2.5	0.05	0.005	0.005
Oil (crude)	42.5	0.05	0.005	0.005	0.005
Oil (refined)	42.5	0.05	0.005	0.005	0.005
Gas (natural)	50.5	0.05	0.005	0.005	0.005
Gas (biogas)	20.5	0.05	0.005	0.005	0.005
Wood (logs)	15.5	0.05	0.005	0.005	0.005
Wood (chips)	15.5	0.05	0.005	0.005	0.005
Wood (pellets)	15.5	0.05	0.005	0.005	0.005

Notes:

1. Based on the average of the two sources.
2. Based on the average of the two sources.
3. Based on the average of the two sources.
4. Based on the average of the two sources.

• Jones

Guest on the national radio series of the British

Fig. 3. Correlation of airtightness and cost.

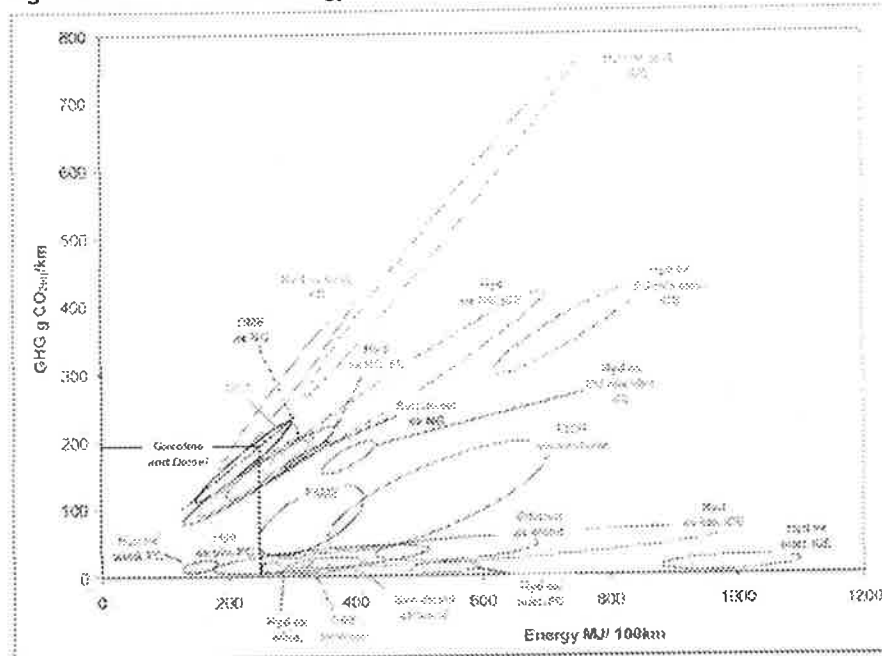
- This major report (hundreds of pages across multiple reports and appendices) examines a variety of well-to-wheel pathways for automotive fuels and powertrains considered to be relevant for Europe in 2010 and beyond. The following tables show the fuels and powertrains that were included in the study.

- This major report (hundreds of pages across multiple reports and appendices) examines a variety of well-to-wheel pathways for automotive fuels and powertrains considered to be relevant for Europe in 2010 and beyond. The following tables show the fuels and powertrains that were included in the study.
- The study draws heavily on the European GM study (see below), with some updates to numbers and some new pathways added.
- Cost analyses are included in the study, along with LCA analyses.
- A standard 5-seat compact European sedan (e.g., VW Golf) is the type of vehicle considered in all cases. Detailed simulations of drive cycles and powertrain performance were used to establish fuel economy figures.
- Co-product credits were allocated using the displacement method.
- The authors recognize the uncertainties in LCA analysis and present results in terms of ranges (see next page)

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Figure 4.1-2 WTW energy and GHG emissions (clusters)

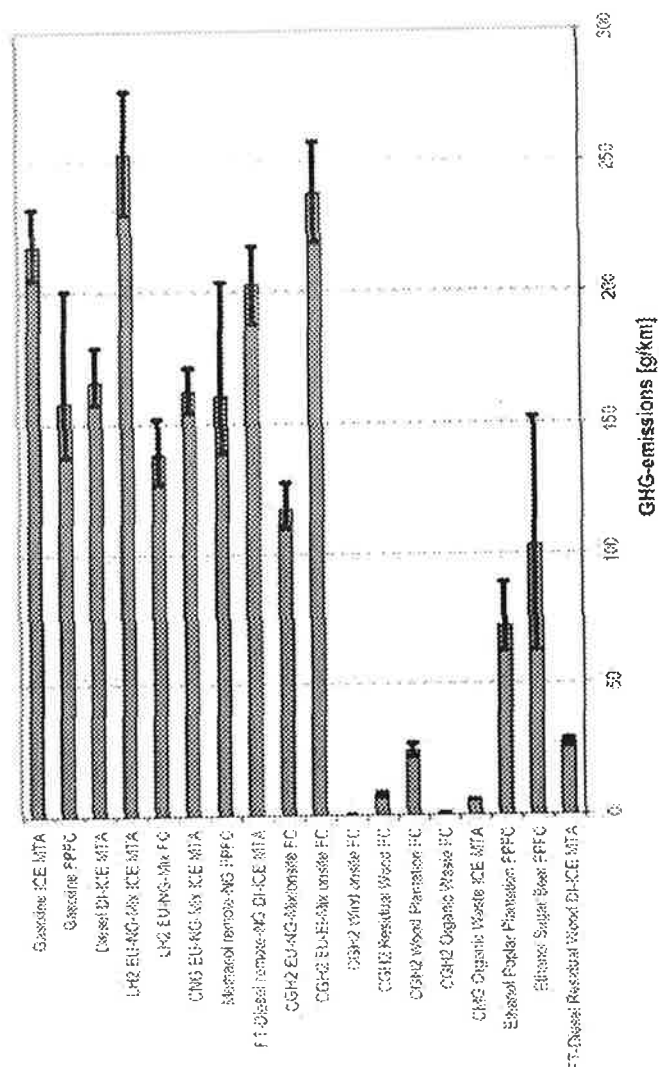


- The authors draw the following broad conclusions (supported in most cases by detailed numerical results):
  - Shifting to renewable/low carbon routes may significantly reduce GHG emissions, but will generally require more total energy use (counting fossil and renewable energies).
  - Shifting to renewable/low carbon routes will always entail costs, but high costs do not always result in large GHG reductions.
  - Transport applications may not maximize the GHG reduction potential of renewables.
  - Optimum renewables use requires considering overall energy demand, including stationary applications.
  - For conventional biofuels (FAME and starch-based ethanol), GHG balance is particularly uncertain due to  $N_2O$  emissions from agriculture. In any case, such fuels offer limited volume potential.
  - BTL (biomass gasification-based liquids) have potential for much greater GHG emissions savings than conventional biofuels at comparable cost.

GM, BP, ExxonMobil, Shell, and Totalfinaelf, 2002. "GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study," L-B-Systemtechnik GmbH, Ottobrunn, Germany, September 27, 138 pages.

- This large study (over 500 pages of text and supporting material) developed detailed well-to-wheels LCA for a number of fossil and renewable pathways (see below). Opel Zafira (2010 technology) and European Drive Cycle used to characterize vehicles. IC engine, hybrid, and fuel cell powertrains considered.
- Biomass-derived pathways showed the highest complexity and widest range of results depending on cultivation method, fertilizer use, soil type, climate, and other factors. The report concluded that selecting appropriate pathways for widespread implementation requires careful consideration of the various factors.
- Biofuels offer reduced GHGs, but magnitude of reduction depends on assumptions about  $N_2O$  from crops, which are uncertain. Processing of lignocellulosic biomass by gasification or enzymatic hydrolysis gives lower GHG emissions than conventional biofuels. See below.
- Carbon emission due to land use change not considered, but may have significant impact on results.

		Selected Fuel Pathways	
Crude Oil Based	Gasol		
Normal Gasol	(1)	Gasoline, Reformulated with 10 ppb	
	(2)	Gasol, Reformulated with 10 ppb	
	(3)	Gasoline, Reformulated with 0.4 ppb	
	(4)	ETBE, 100% conc	
	(5)	ETBE, 100% conc	
	(6)	ETBE, 100% conc	
	(7)	ETBE, 100% conc	
	(8)	ETBE, 100% conc	
	(9)	ETBE, 100% conc	
	(10)	ETBE, 100% conc	
Crude Oil Based	(11)	Gasoline, Reformulated with 10 ppb	
	(12)	Gasoline, Reformulated with 10 ppb	
	(13)	Gasoline, Reformulated with 0.4 ppb	
	(14)	ETBE, 100% conc	
	(15)	ETBE, 100% conc	
	(16)	ETBE, 100% conc	
	(17)	ETBE, 100% conc	
	(18)	ETBE, 100% conc	
	(19)	ETBE, 100% conc	
	(20)	ETBE, 100% conc	
Crude Oil Based	(21)	Gasoline, Reformulated with 10 ppb	
	(22)	Gasoline, Reformulated with 10 ppb	
	(23)	Gasoline, Reformulated with 0.4 ppb	
	(24)	ETBE, 100% conc	
	(25)	ETBE, 100% conc	
	(26)	ETBE, 100% conc	
	(27)	ETBE, 100% conc	
	(28)	ETBE, 100% conc	
	(29)	ETBE, 100% conc	
	(30)	ETBE, 100% conc	
Crude Oil Based	(31)	Gasoline, Reformulated with 10 ppb	
	(32)	Gasoline, Reformulated with 10 ppb	
	(33)	Gasoline, Reformulated with 0.4 ppb	
	(34)	ETBE, 100% conc	
	(35)	ETBE, 100% conc	
	(36)	ETBE, 100% conc	
	(37)	ETBE, 100% conc	
	(38)	ETBE, 100% conc	
	(39)	ETBE, 100% conc	
	(40)	ETBE, 100% conc	
Crude Oil Based	(41)	Gasoline, Reformulated with 10 ppb	
	(42)	Gasoline, Reformulated with 10 ppb	
	(43)	Gasoline, Reformulated with 0.4 ppb	
	(44)	ETBE, 100% conc	
	(45)	ETBE, 100% conc	
	(46)	ETBE, 100% conc	
	(47)	ETBE, 100% conc	
	(48)	ETBE, 100% conc	
	(49)	ETBE, 100% conc	
	(50)	ETBE, 100% conc	



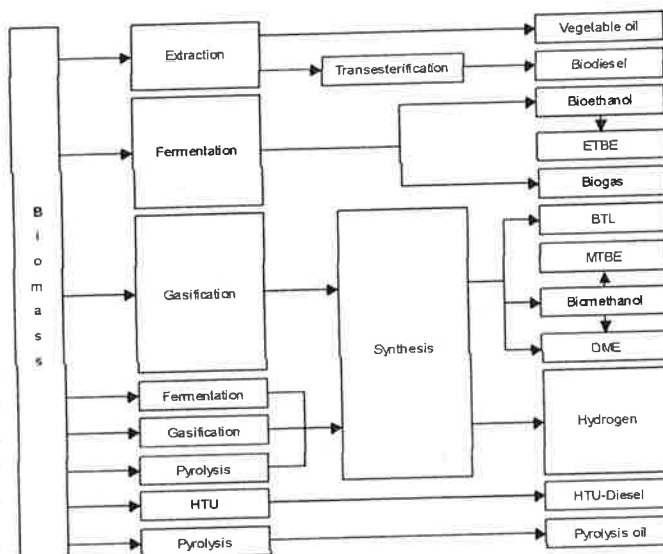
- Study sponsored by Research Association for Combustion Engines FVV to analyze/compare all international, publicly available studies on biofuels for transportation. 800 candidate studies, of which 63 met criteria for detailed analyses, leading to evaluation of 109 energy / CO<sub>2</sub> pathways – complete lifecycles in most cases – with comparisons to conventional fuels or to other biofuels.
- WTT results from other studies collected. TTW conversion done using a consistent set of values developed in this study.
- CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> considered with IPCC's 100-year GWPs (23 for CH<sub>4</sub> and 296 for N<sub>2</sub>O).
- Wide ranges in results for same pathways. Differences among cases mainly result from differences in assumptions about cultivation and handling of co-product credits. Displacement method used for co-product allocations.
- Main results:

- ETBE shows best energy and GHG performance relative to other biofuels “regarding area-related consideration” (I am unsure what that means). ETBE substituting MTBE shows best overall result for a biofuel – better than ethanol substituting for gasoline because MTBE is more energy intensive than gasoline production.
  - Bioethanol is better or worse than biodiesel depending on raw material used.
  - Bioethanol from sugarcane is most favorable among all ethanol forms.
  - Biodiesel shows advantages over vegetable oil.
  - Disadvantages of biofuels from energy crops are (typically) higher eutrophication, acidification, and ozone depletion due to nitrogen emissions from agricultural phase.
  - Range and uncertainty of cost estimates (including subsidy and local cost effects) is so large that “no serious or reliable ranking among biofuels can be made based on the available literature”.
- Qualitative result is consistent: biofuels from cultivated biomass (energy crops) advantageous in energy and GHG balances. (A few studies contradict this conclusion, e.g., Pimentel, but the vast majority support it.)

Table 5 Biofuels considered in this study and their fossil fuel counterparts

Biofuels	Fossil fuel counterparts
<b>Bioethanol</b>	
– Bioethanol from sugar-cane	– Gasoline
– Bioethanol from corn	– Gasoline
– Bioethanol from wheat	– Gasoline
– Bioethanol from sugar-beets	– Gasoline
– Bioethanol from lignocellulose	– Gasoline
– Bioethanol from potatoes	– Gasoline
– Bioethanol from molasses	– Gasoline
<b>ETBE</b>	
– ETBE from wheat	– Fossil MTBE
– ETBE from sugar-beets	– Fossil MTBE
– ETBE from lignocellulose	– Fossil MTBE
– ETBE from potatoes	– Fossil MTBE
<b>Biodiesel</b>	
– Biodiesel from rapeseed	– Fossil diesel fuel
– Biodiesel from sunflowers	– Fossil diesel fuel
– Biodiesel from soybeans	– Fossil diesel fuel
– Biodiesel from canola	– Fossil diesel fuel
– Biodiesel from coconut oil	– Fossil diesel fuel
– Biodiesel from recycled vegetable oil	– Fossil diesel fuel
– Biodiesel from animal grease	– Fossil diesel fuel
– Biodiesel from used cooking grease	– Fossil diesel fuel
<b>Vegetable oil</b>	
– Vegetable oil from rapeseed	– Fossil diesel fuel
– Vegetable oil from sunflowers	– Fossil diesel fuel
<b>Biomethanol</b>	
– Biomethanol from lignocellulose	– Gasoline * / Methanol from natural gas
<b>MTBE</b>	
– MTBE from lignocellulose	– Fossil MTBE
<b>DME</b>	
– DME from lignocellulose	– Fossil diesel fuel
<b>BTL</b>	
– BTL from lignocellulose	– Fossil diesel fuel
<b>Biogas</b>	
– Biogas from organic residues	– Gasoline * / Natural gas
– Biogas from cultivated biomass	– Gasoline * / Natural gas
<b>Hydrogen</b>	
– Hydrogen from lignocellulose	– Gasoline * / Hydrogen from natural gas
– Hydrogen from organic residues	– Gasoline * / Hydrogen from natural gas

\* fuel counterparts used in figure 4 and 5



Brinkman, N. (General Motors), Wang, M. (Argonne National Lab), Weber, T. (General Motors), and Darlington, T. (Air Improvement Resource, Inc.), 2005. “Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions,” May, 238 pages.

- Large study that uses the GREET model to generate results, including stochastic modeling feature of GREET to develop probability functions for most input parameters, on the basis of which minimum, maximum, and “most likely” LCA results are developed (see tables below for inputs for ethanol pathway and for vehicle fuel economies).
- Standard vehicle characteristics for 2010 full-size GM pick-up truck (Silverado).
- Bioethanol is only renewable pathway considered: corn ethanol (made 70% by dry mills and 30% by wet mills) and cellulosic ethanol (50% from herbaceous crops and 50% from woody). E85 is used in IC and IC/HEV powertrains; neat ethanol in FCV and FCV/HEV.
- N<sub>2</sub>O uncertainties highlighted (see figure below).
- Favorable GHG mitigation potential for cellulosic ethanol relative to corn ethanol noted (see figure below). Results all given on per-vkm basis (no per-hectare analysis)

19. **Major:** P50 values mean that there is a probability of 50% that actual values would be equal to or below the P50 values; P90 values mean that there is a probability of 90% that actual values would be equal to or below the P90 values; and P10 values mean that there is a probability of 10% that actual values would be equal to or below the P10 values.

Propulsion System	Fuel Economy, mpg gasoline-equivalent		
	Worst Case	Best Estimate	Best Case
Gasoline DOD SI CD Baseline	20.2 <sup>a</sup>	21.3	22.4
Gasoline DI SI CD	23.2	24.2	25.4
Gasol DI CI CD	25.2	25.8	27.1
Eng DOD SI CD	20.2 <sup>a</sup>	21.3	22.4
Eng DOD SI GD	19.5 <sup>a</sup>	21.4	22.1
H <sub>2</sub> DOD SI CD	24.3 <sup>a</sup>	25.4	26.9
Gasoline DOD SI HEV	24.5	26.5	24.8
Gasoline DI SI HEV	27.0	29.2	32.6
Gasol DI CI HEV	28.5	30.8	33.4
Eng DOD SI HEV	24.5	28.5	34.0
Eng DOD SI HEV	23.5	25.4	32.5
H <sub>2</sub> DOD SI HEV	29.2	31.5	40.5
Gasoline/methanol FF FCV	25.7	32.2	38.3
Gasoline/methanol FF FC HEV	29.5	37.5	42.2
Meth FF FCV	28.1	36.2	35.6
Meth FF FC HEV	32.7	40.9	45.9
EtOH FF FCV	25.7	32.2	36.3
EtOH FF FC HEV	29.5	37.5	42.2
H <sub>2</sub> FCV	47.6	56.8	54.5
H <sub>2</sub> FC HEV	52.6	56.3	59.5

\* Exports excluded without EXO for two worst-case scenarios

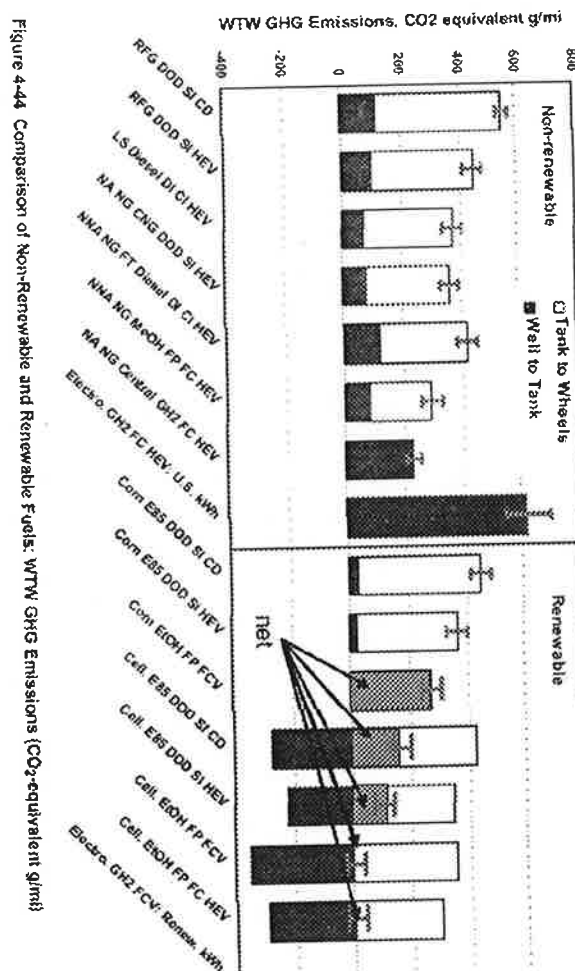
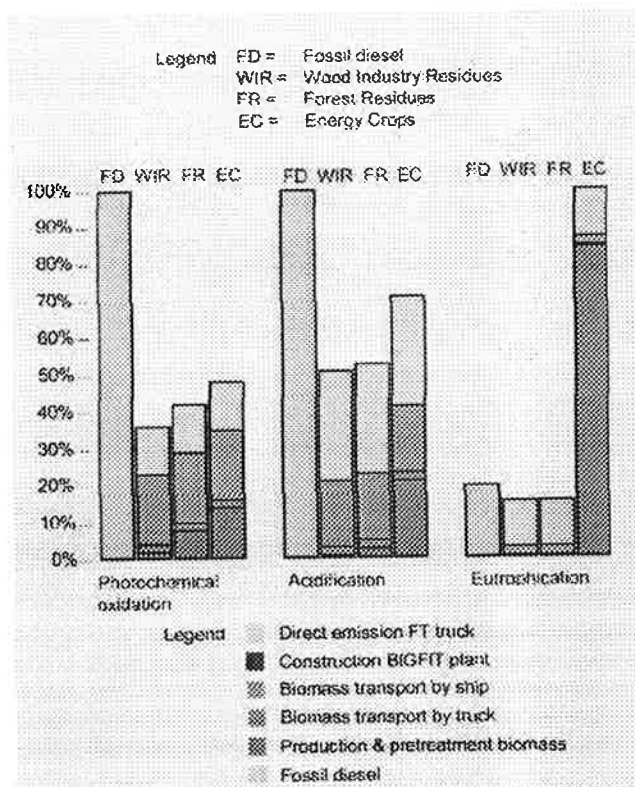
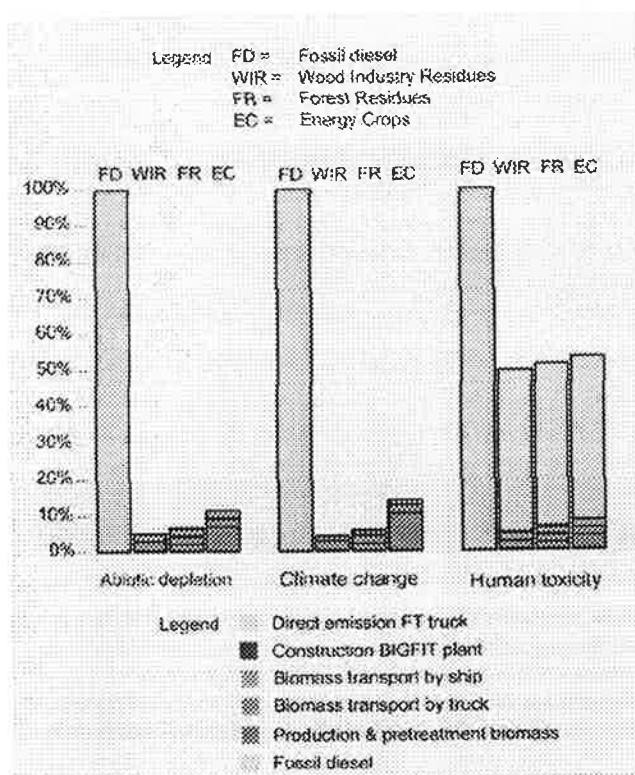


Figure 4-44 Comparison of Non-Renewable and Renewable Fuels: WTW GHG Emissions (CO<sub>2</sub>-equivalent g/mi)



**Project Team, 2002. "Climate Neutral Transport Fuels from Biomass: The BIG-FiT Concept,"  
Netherlands Organization for Energy and Environment (NOVEM), Utrecht, the Netherlands,  
September, 41 pages.**

- Prefeasibility analysis for FT fuels from biomass in Rotterdam using imported biomass.
- 100 km truck transport at origin, 1000 km shipping to Rotterdam.
- Feedstocks
  - Willow (10 dry metric t/ha/yr for 2020 assumed). Cultivation and other inputs included.
  - Forest thinnings – included collection, transport to road side, pre-treatment and road and sea transport.
  - Wood industry residues – included pre-treatment (chipping) and road and truck transport to plant (no sea transport?)
  - Vehicle emissions assume Euro 5 standard for 2008.
- Conclusions (see graphs below)
  - On climate change and resource depletion measures, the score is roughly a factor 10 better than fossil fuels. Energy output/input ratios vary between a factor 20 and 9. Even when the wood is imported from much further distances (e.g. 5,000 km) than the ones considered in the study (1,000 km) energy output/input ratio will still be between a factor 5 and 10.
  - The BIG-FiT diesel scores about a factor 2 better with acidification and photochemical oxidation and human toxicity.
  - For eutrophication impact, the score of BIG-FiT-diesel is about 10% better than fossil diesel in the case of biomass from wood industry residues and forest residues, but about a factor 2 worse than fossil diesel in the case of energy crops (due to leaching of nitrate and phosphate). These emissions can be lowered with lower fertilization levels.

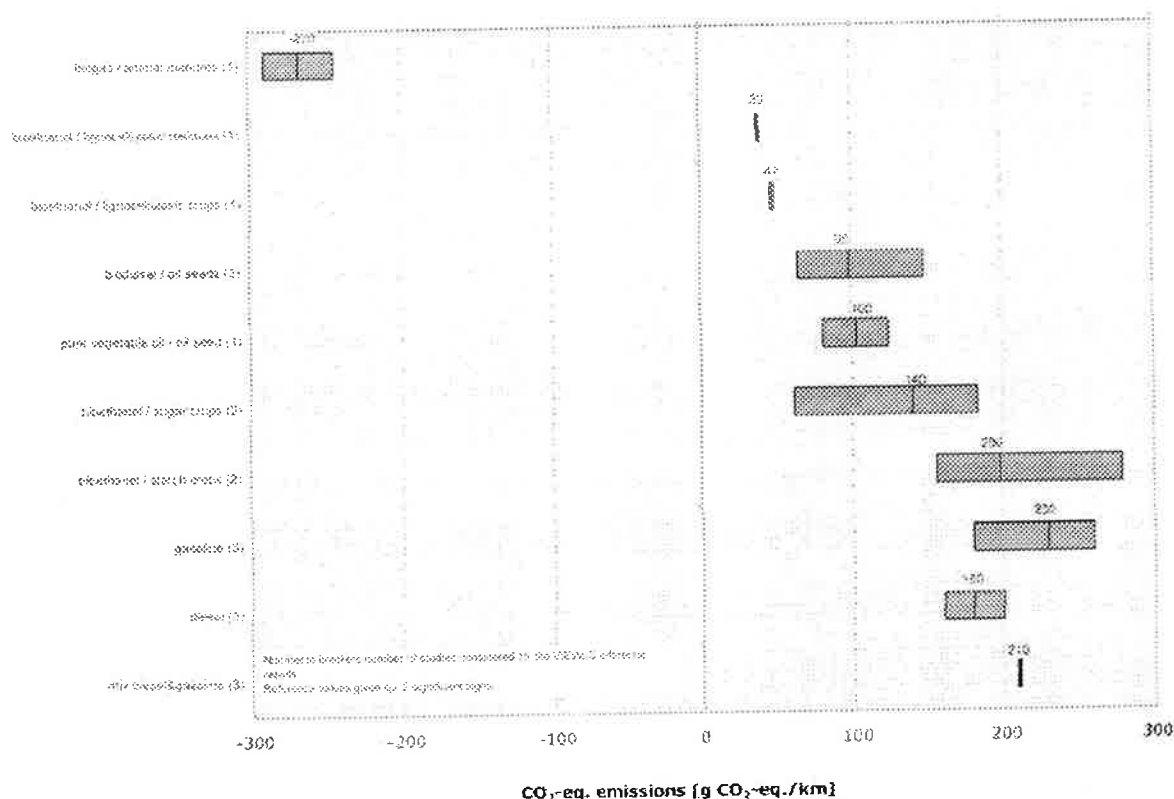


**VIEWLS (Clear Views on Clean Fuels), 2005a. "Environmental and Economic Performance of Biofuels – Volume I, Main Report," SenterNovem, Utrecht, the Netherlands, April, 242 pages.**

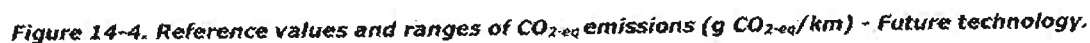
- This major study (> 400 pages with appendices) was carried out as a collaborative project among a number of analysts at different institutions around Europe. The project (VIEWLS) maintains a website with an extensive library (downloadable) of LCA-related documents.
- Approach similar to Quirin et al. in that goal is to analyze the life cycle based environmental and economic performance of different biofuels by reviewing existing international studies and attempting to synthesize their results to be able to make consistent comparisons among different biofuel pathways.
- Pathways considered in the analysis are shown at right.
- Results given in terms of reference (mid-range) values and range of values observed in different studies (see figures and table below).

Considered Resources	Considered Biofuels									
	bioethanol and bio-ETBE	bio-diesel	bio-methyl-ether (bio-DME)	bio-methanol and bio-MBE	FT-Diesel	synthetic natural gas (SNG)	bio-hydrogen	pure vegetable oil	biogas	
energy crops										
oilseed crops (oilseed rape)	+	+	+	+	+	+	+	+		
starch crops	+									+
residues										
foresty residues	+		+	+	+	+	+			
liquid manure										+
waste										
other organic waste		+								+
Considered propulsion systems										
current technology ICE	+	+	+	+	+	+	+	+	+	+
future technology ICE	+	+	+	+	+	+	+	+	+	+
future technology FCE				+			+			

ICE... internal combustion engine; FCE... fuel cell with electric engine



**Figure 14-3. Reference values and ranges of CO<sub>2</sub>-eq emissions (g CO<sub>2</sub>-eq./km) - Current technology.**



SUMMARY OF RESULTS	Current Technology	Future Technology	Compared to Fossil Fuels
<b>Environmental performance</b>			
CO <sub>2</sub> -eq [g/km] *)	-270 to +200	-170 to +110	significantly lower
CO <sub>2</sub> [g/km] *)	36 to 120	- 57 to 57	significantly lower
<b>Economic performance</b>			
biofuel cost at filling station [€/GJ]	17 to 47	15 to 35	higher (7 – 9)
total driving costs [€/100 km]	25 to 46	25 to 35	higher (24 -26)
mitigation costs [€/t CO <sub>2</sub> -eq avoided]	210 to 1,800	40 to 2,300	-
*) Negative values when avoided emission of substituting conventional material with by-products and/or of avoided reference use of the biomass are higher than emissions from the biofuel chain.			

- LCA analysis as part of a 10-institution collaboration over the course of more than 2 years to assess the long-term potential for biomass energy in the United States.
- LCA results developed using the GREET model for bioethanol, bio-DME, and bio-FT fuels from switchgrass. Four bioethanol process configurations and one DME and one FT are considered (see below). Performance of advanced processes for conversion of switchgrass to fuels (from detailed process modeling by other researchers in the collaboration) are used as inputs to the GREET calculations. Assumed switchgrass yield is ~5 t/acre/yr

(12 t/ha/yr), but inputs (fertilizer, etc.) are not linked directly to yield. Corn ethanol results are included for comparison.

- GHG and energy balance results are given on a per-vm basis and on per-tonne biomass basis.
- Co-product credits are figured based on fraction of output energy in the co-product, since in some cases co-products are very large and displacement approach would give unrepresentative results.
- Vehicle characteristics for cars and light trucks are from a study by the Union of Concerned Scientists (one of the collaboration institutions) for both ICE and hybrid electric vehicles (right).
- Ethanol results given for both E85 and "EtOH in E85". The latter is more relevant for policy analysis. The former is from driver's perspective.
- Criteria pollutants also included in analysis. NO<sub>x</sub> emissions are high in cases where residue-fired steam turbine cogen plant onsite is generating co-product electricity (because some of its emissions are allocated to the biofuel produced).
- GHG results: ~30% GHG reduction for corn ethanol relative to petroleum fuels, ~80% GHG reductions for cellulosic ethanol, ~90% GHG reductions for cellulose to DME or FT. See right.

TABLE 6 Fuel Production Options from Biological and Thermochemical Processes

Option	Power Export	Fuel Product	Co-Product (fuel)	Co-Product (others)
1. Bio-EtOH/GTCC	Yes	Ethanol	None	None
2. Bio-EtOH/Rankine	Yes	Ethanol	None	None
3. Bio-EtOH Bio-FTD/GTCC	Yes	Ethanol	FTD FTG	None
4. Bio-EtOH Bio-FTD/Rankine	Yes	Ethanol	None	Propan
5. Bio-FTD/GTCC	Yes	FTD	FTG	None
6. Bio-DME/GTCC	Yes	DME	None	None

TABLE 13 Combined Baseline Fuel Economies by In-Use Fleet Vehicle/Fuel System for 2030 (mpg/gal)<sup>a</sup>

	RFG	Bio-E85	LSD	Bio-FTD	Bio-DME
Conventional	19.6	19.6	25.7	25.7	25.7
Hybrid	27.9	27.9	30.3	30.3	30.3

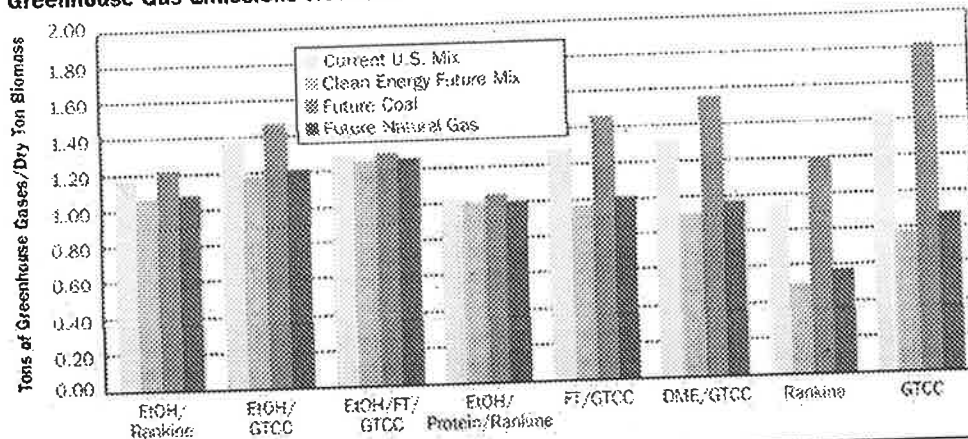
<sup>a</sup> Data presented in this table are fleet-averaged fuel economies of LDVs: data for passenger cars and LDVs were combined according to the VMT shares of gasoline vehicle types. See Section 3.2.

Reductions in Grams Relative to Conventional Fuels (%)			
Fuel: Fuel Production Scenarios		CO <sub>2</sub>	GHGs
Bio-DME: DME/GTCC	} relative to diesel	94.9	83.3
Bio-FTD: FTD/GTCC		95.8	84.7
Bio-FTD: Multifuel		96.4	87.4
Corn E85	} relative to gasoline	33.3	20.1
Bio-E85: EtOH/ GTCC		70.9	60.9
Bio-E85: EtOH/ Rankine		69.7	60.2
Bio-E85: Multifuel		70.1	62.9
Per gallon of gasoline equivalent basis			

Greene, N. (principal author), 2004. "Growing Energy: How Biofuels Can Help End America's Oil Dependence," Natural Resources Defense Council, New York, December, 78 pages.

- This is a high-level summary of a large body of analysis undertaken by researchers in a 10-institution collaboration over the course of more than 2 years. The project, "Role of Biomass in America's Energy Future (RBAEF)" aimed to assess the long-term potential for biomass energy in the United States, taking as a given that resources to support concerted research, development, and demonstration efforts (which are significant in many cases) needed to commercialize energy crops and bioenergy conversion technologies would be available.
- Focus is on biofuels for transportation. (LCA analysis by Wu, Wu, and Wang [above] was part of this project.)
- GHG results for biofuels vs bioelectricity: Bioelectricity is better option than the biofuels analyzed, if existing (US) electricity mix or coal-intensive electricity mix are displaced. If clean mix or natural gas electricity are displaced, then biofuels gives larger GHG mitigation. See below. (Technologies are described above under Wu, Wu, and Wang 2005.)

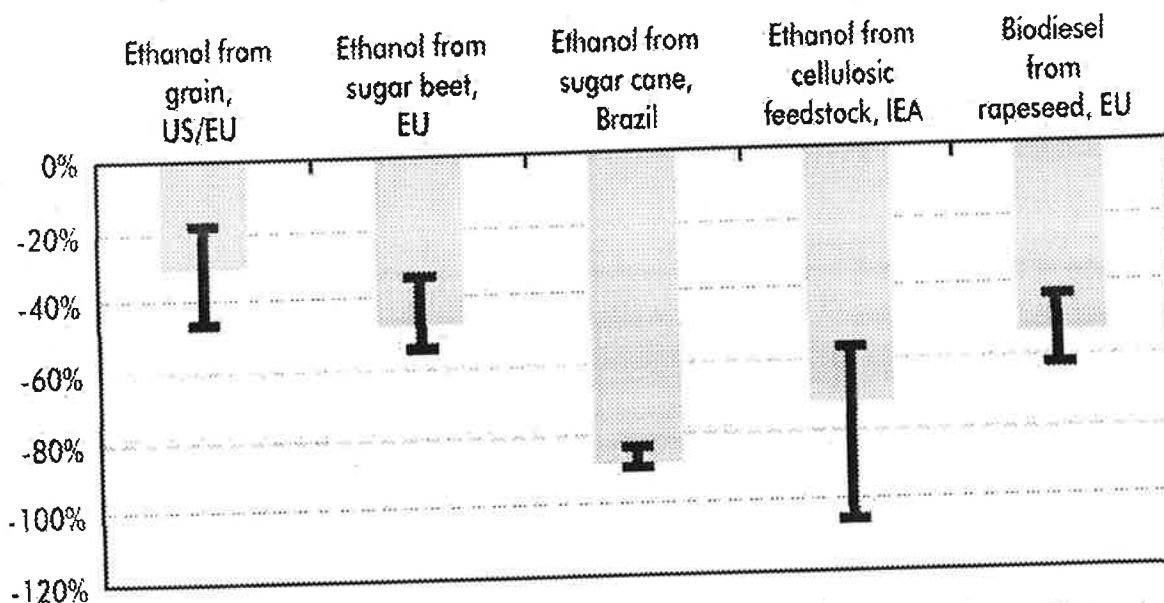
**FIGURE 7**  
**Greenhouse Gas Emissions Reductions**



International Energy Agency, 2005. "Biofuels for Transport: An International Perspective," OECD, Paris, 215 pages.

- Comprehensive assessment of biofuels technology, economics, and policy, including one chapter that reviews LCA studies. Concludes that GHG savings are significant, but vary by feedstock and technology (see below).

### Range of Estimated Greenhouse Gas Reductions from Biofuels



Note: This figure shows reductions in well-to-wheels CO<sub>2</sub>-equivalent GHG emissions per kilometre from various biofuel/feedstock combinations, compared to conventional-fuelled vehicles. Ethanol is compared to gasoline vehicles and biodiesel to diesel vehicles. Blends provide proportional reductions; e.g. a 10% ethanol blend would provide reductions one-tenth those shown here. Vertical black lines indicate range of estimates; see Chapter 3 for discussion.

Wang, M., C. Saricks, and D. Santini. 1999. "Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions," ANL/ESD-38, Argonne National Laboratory, Argonne, IL, 39 pages.

- Using the GREET model, the authors estimate GHG emissions, fuel-cycle petroleum use, and total primary energy used by a mid-size passenger car per vehicle-mile running on gasoline or on bioethanol blended as E10, E85, or E95 and made from corn or from cellulosic feedstocks (woody and herbaceous).

- Some key input assumptions are at right.

- For corn-based ethanol, key factors determining energy and emissions impacts include energy and chemical usage intensity of corn farming, energy intensity of the ethanol plant, and method used to estimate co-product credits.
- For cellulosic biomass, key determining factors are energy and chemical usage intensity of biomass farming, ethanol yield per dry ton of biomass, and electricity co-product credits.

- Results in terms of % GHG reductions per v-mile and per gallon of ethanol are below.

Table 5 Parametric Assumptions for Current Case, Near-Future Case, and Future Case

	Current Case	Near-Future Case (2005)	Future Case (2010)
<b>Vehicle fuel economy</b>			
City mpg	20	25	27
E85 EFP (city mpg corrected)	5%	7%	7%
E95 dedicated (city mpg corrected)	10%	13%	12%
<b>Corn ethanol plant yield</b>			
Dry milling (gallons)	2.8	2.7	NN <sup>a</sup>
Wet milling (gallons)	2.3	2.8	NN <sup>a</sup>
<b>Corn ethanol plant energy use</b>			
Dry milling (Btu/gal)	41,400	36,600	NN <sup>a</sup>
Wet milling (Btu/gal)	69,300	34,800	NN <sup>a</sup>
<b>Cellulosic ethanol plant yield</b>			
Woody biomass (gallons/dry ton)	NN <sup>a</sup>	76	98
Herbaceous biomass (gallons/dry ton)	NN <sup>a</sup>	85	103
<b>Cellulosic ethanol plant electricity credit</b>			
Woody biomass (kWh/gal)	NN <sup>a</sup>	1.73	0.59
Herbaceous biomass (kWh/gal)	NN <sup>a</sup>	0.893	0.28

<sup>a</sup> Not included; these cases were not evaluated.

Table 6 Reductions in per-Vehicle-Mile GHG Emissions and Energy Use by Ethanol Blends (percentage relative to emissions and energy use of gasoline)

	E10	E85	E95	E10	E85	E95
<b>Corn-Based Ethanol: Current Case</b>						
		Dry Milling			Wet Milling	
Petroleum	6.4%	74.9%	87.7%	6.1%	72.5%	83.0%
GHG emissions	1.3%	16.9%	24.5%	0.8%	13.7%	19.1%
Fossil energy	2.7%	35.0%	44.3%	2.7%	34.4%	42.3%
<b>Corn-Based Ethanol: Near-Future Case</b>						
		Dry Milling			Wet Milling	
Petroleum	6.4%	75.6%	88.1%	6.2%	71.7%	86.1%
GHG emissions	1.0%	25.5%	32.9%	1.6%	23.8%	30.3%
Fossil energy	3.2%	43.7%	49.1%	3.1%	42.5%	51.0%
<b>Cellulosic Ethanol: Near-Future Case</b>						
		Woody Biomass			Herbaceous Biomass	
Petroleum	5.0%	89.6%	91.4%	6.0%	71.4%	83.0%
GHG emissions	6.9%	162.7%	146.2%	6.7%	67.8%	79.3%
Fossil energy	6.7%	79.9%	92.0%	5.9%	70.4%	82.3%
<b>Cellulosic Ethanol: Future Case</b>						
		Woody Biomass			Herbaceous Biomass	
Petroleum	7.0%	71.3%	82.1%	7.4%	70.7%	84.7%
GHG emissions	9.8%	61.3%	105.1%	7.6%	67.5%	79.6%
Fossil energy	8.5%	71.5%	86.6%	8.0%	70.6%	82.1%

Table 8 Reductions in GHG Emissions and Energy Use per Gallon of Ethanol in Ethanol Blends (percentage relative to emissions and energy use of gasoline)

	E10	E85	E95	E10	E85	E95
<b>Corn-Based Ethanol: Current Case</b>						
		Dry Milling			Wet Milling	
Petroleum	93.3%	94.9%	94.7%	90.2%	91.0%	91.8%
GHG emissions	19.2%	23.8%	25.9%	10.4%	17.3%	20.7%
Fossil energy	40.3%	44.4%	46.5%	39.5%	43.8%	45.7%
<b>Corn-Based Ethanol: Near-Future Case</b>						
		Dry Milling			Wet Milling	
Petroleum	93.7%	95.8%	95.2%	91.2%	93.3%	93.0%
GHG emissions	26.4%	32.3%	34.6%	24.1%	30.1%	32.5%
Fossil energy	46.4%	51.7%	53.0%	45.7%	51.0%	55.1%
<b>Cellulosic Ethanol: Near-Future Case</b>						
		Woody Biomass			Herbaceous Biomass	
Petroleum	85.9%	88.2%	87.4%	88.0%	90.5%	90.1%
GHG emissions	136.5%	129.7%	127.8%	85.6%	86.7%	85.8%
Fossil energy	98.3%	102.2%	99.4%	89.6%	89.2%	88.3%
<b>Cellulosic Ethanol: Future Case</b>						
		Woody Biomass			Herbaceous Biomass	
Petroleum	106.3%	95.4%	89.8%	108.5%	92.2%	91.5%
GHG emissions	143.8%	118.4%	113.5%	112.0%	88.8%	88.1%
Fossil energy	125.0%	94.5%	91.9%	120.1%	89.5%	88.7%

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**Woods, J. and Bauen, A., 2003. "Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK," B/U20/00785/REP, URN 03/982, New and Renewable Energy Program, Department of Trade and Industry, London, UK, 88 pages.**

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- Similar approach to some of the other studies (e.g., Elsayed, et al., Quirin et al., VIEWLS) -- literature-review based detailed analysis of 13 renewable transport fuel chains of potential relevance to UK.
- Cases include four for H<sub>2</sub> from offshore wind and nine biofuels: ethanol from sugarbeet, from wheat grain, from wheat straw, and from wood; RME and VME (vegetable methyl ester from waste oils), FT from short-rotation coppice (SRC) wood, methanol from SRC wood, and hydrogen from SRC wood.
- Results given on per GJ of biofuel basis (no vehicle analysis).
  - No allocation of co-product credits because 1) uncertainty about appropriate methodology to use and uncertainty in data about co-products
  - Low to high range given for estimates.
  - Results similar to other studies:
    - o A wide range of results are possible, depending on yields achieved, input needed for given yield, technologies chosen at each stage of fuel chain and type of direct fossil-fuel used.
    - o Conventional biodiesel and bioethanol routes are relatively inefficient and require large land areas to achieve significant GHG reductions. SRC-based conversion, e.g., to FT, MeOH, or H<sub>2</sub>, provides much greater GHG reductions, but these technologies are not yet commercially ready.

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**Fergusson, M. (editing author), 2003. "Expert Paper on the Global Impacts of Road Transport Biofuels: a Contribution to the Government's Analysis," NSCA, Cleaner Transport Forum, and the Institute for European Environmental Policy, 25 pages.**

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- Biofuels policy analysis with focus on UK.
- LCA analysis compares/contrasts results from three prior studies (Elsayed et al., Woods and Bauen, and Concawe, et al.).
- Contains good pedagogy on LCA, including good discussion of methodological issues.

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**Weiss, M.A., Heywood, Schafer, A., and Natarajan, V.K., 2003. "Comparative Assessment of Fuel Cell Cars," MIT LFEE 2003-110 RP, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Cambridge, February, 29 pages..**

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- Authoritative analysis of future vehicle drive trains, including fuel cell vehicles and conventional ICE and ICE/Hybrid vehicles.
- LCA analysis included, but WTT focus is entirely on fossil fuel pathways.



# **Technology State-of-the-art**

**Philippe Girard, Abigail Fallot, Fabien Dauriac  
Forest Department of CIRAD**

## Technology state-of-the-art

Review of existing and emerging technologies for the large scale production of biofuels  
and identification of promising innovations for developing countries

Philippe Girard, Abigail Fallot, Fabien Dauriac  
Forest Department of CIRAD

### 1. Introduction

World energy supply is largely dependent on oil production and the figure 1 below shows that most of the expected increases in oil demand on the medium term will come from the transport sector, with the largest growth from non OECD countries among which developing countries. Consequently the transport sector may become be responsible for almost one third of the world Green House Gas (GHG) emissions growth (see figure 2).

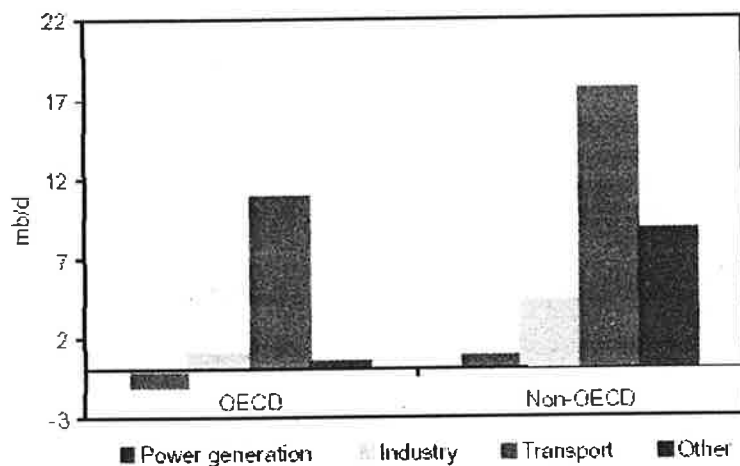


Figure 1: Increase in world Oil demand, 2002 – 2030 <sup>1</sup>

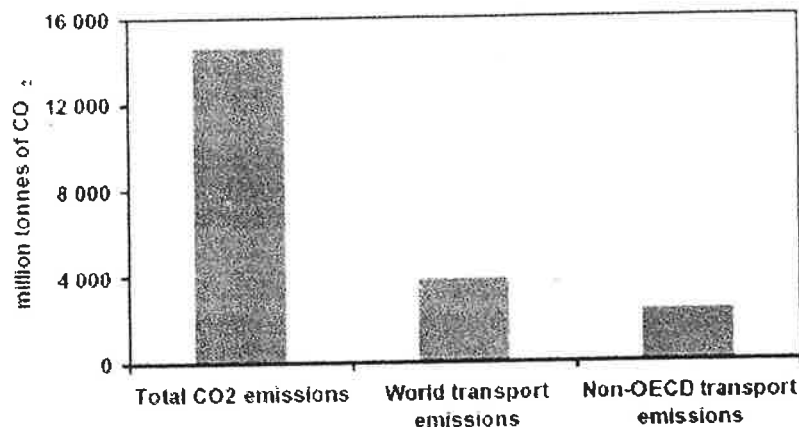


Figure 2: incremental CO<sub>2</sub> emissions in the transport sector, 2002-2030 (IEA 2004)

### 1.1. Alternative fuels, possible conversion routes

A number of alternative fuels for transport are potentially available and presently used or investigated at different stages of development worldwide (see figure 3):

- Liquefied petroleum gas (LPG), usually composed of propane from refineries and oil process ;
- Compressed or liquefied natural gas (CNG) ;
- Methanol which can be produced from natural gas or from biomass ;
- Esterified vegetable oil from seed and fruits generally called bio diesel ;
- Ethanol from different sources of biomass ; sugar rich crops (sugar cane) ; starch-rich crops or cellulosic biomass ;
- Hydrogen obtained from the electrolysis of water or the reforming of a variety of other fuels;
- Dimethylether (DME) from natural gas or lignocellulosic biomass;
- Synthetic gasoline and diesel from natural gas or biomass using the Fischer-Tropsch (FT) process.

The term 'biofuels' stands for ethanol and diester products (first-generation biofuels). New products, called second-generation biofuels, are in development; at first based on fossil resources, there are now produced from biomass such as methanol, dimethylether, FT diesel and ethanol from lignocellulosic feedstock. Future laboratory investigation deals with third-generation biofuels as hydrogen and fuelcells. We won't consider them here.



## **1.2. Demand for and production of biofuels: developing countries' specificities**

Biomass is a local resource which can contribute to the diversification of energy supply and maintain see create employment for cultivation, harvesting, transport and fuel preparation. Well-managed, biomass allows for carbon neutral fuels when substituted to fossil fuels. Amongst renewable energy sources, biomass appears to be the most important in terms of technical and economic feasibility. It is therefore considered today as a major future energy source for development and industry, raising a growing interest worldwide not only for transport.

Actually, improving energy security, reducing CO<sub>2</sub> emissions are primarily goals for the development of alternative fuel policies. In developing countries, oil saving and independency may often take precedence as petroleum products imports are a major source of foreign currency expenditure. Therefore large natural gas reserves or the availability of land for energy crops in a given region may orientate fuel and therefore technology choices. Different lobbies among which engine manufacturers and oil companies do play a significant role when in favour of minimal or no modification of the existing types of engine or refuelling infrastructure. Government willingness to support local industry and agriculture will also orientate these choices. The complexity of often non technical drivers for the development of alternatives to conventional petroleum transport fuel makes it difficult to assess beforehand technology development trends with regards to their sole technical advantages.

The purpose of the paper is to give an overview of feedstock and process technologies for biofuels production with a focus on emerging technologies of interest to developing countries.

The developing world gathers countries of very heterogeneous characteristics, particularly when biofuel production opportunities are concerned. Indeed, population density and dynamics, climatic conditions, available infrastructure and capital, land ownerships..., widely vary from one developing country to another.

However, some common characteristics might base the relevance of biofuel production and technology choices in developing countries:

- The resource: tropical countries with high levels of biomass productivity are mostly developing countries. In most developing countries, agriculture is the sector from which depends the major part of the population.
- The energy sector: energy consumption levels are comparatively low, see very low, increasing with standards of living and industrialization. Therefore the lock-in effect in favour of fossil fuel may be easier to overcome for alternative energy technologies such as biofuels'. For that matter, the technology review should not be limited to first generation biofuels such as ethanol from sugarcane or biodiesel from soybeans. It'll also consider more innovative second generation biofuels offering wider prospects in the short to medium term (within ten years) and possibly leapfrogging instead of following step by step paths taken by industrialised countries.
- Poverty challenge: given their specific priorities and levels of unsatisfied basic needs, developing countries are probably not to invest in very forward-looking Research & Development (R&D) for which results cannot be expected before decades even if some third generation biofuel technologies consider offering more definitive solutions to energy problems.

Accounting for these specificities, the paper will successively consider resources, technologies and the performance criteria.

## **2. Biomass feedstock for Biofuel processes**

Biomass that can be converted in biofuels is of two different origins:

- conventional agricultural products like oily seeds and sugar or starch rich crops or,
- lignocellulosic products and residues.

Cellulose is more abundant and cheaper because in less direct competition with food crops than conventional agricultural products. In principle, there are numerous potential benefits to develop and improve biofuels production from cellulose:

- limit conflicts with land use for food production;
- improve incomes for farmers through a better use of by-products;
- increase potential in terms of toe/ha (ton of oil equivalent biofuels per hectare of land required) and net GHG emission reduction;
- provide an opportunity to use set aside land or poorer soil for energy plantation like short rotation crop and fast growing tree species (willow, poplar, eucalyptus);
- possibly use residues and waste from municipal solid waste (MSW).

Lignocellulosic biomasses are diverse and versatile energy sources widely available from agro-based industry. They consist in different kinds of residues such as bagasse from sugar cane mills, cotton stalks, rice husks, and wood industries residues, short rotation energy crops and forest plantations. Beside these uncontaminated biomass resources, there are large amounts of waste, demolition woods, etc, which can add up to the potential available for energy generation at a competitive price.

A brief description of the most important feedstock potentially available in tropical countries is given in the following sections. It should be noted that when taking into account these resources some may have alternative uses and their real availability for energy uses may be limited.

### **2.1. Conventional agricultural products**

#### **2.1.1. Sugar rich crops**

Ethanol is traditionally produced from the fermentation of glucose (sugar) by yeast, therefore sugar cane and sugar beets which contain a substantial amount of sugar constitute the main biomass source of ethanol production worldwide, even if the US production from maize (13.9 Mm<sup>3</sup>, 90% of the US ethanol production)<sup>4</sup> is nowadays almost as important in volume as from sugar cane in the world. Other suitable sources of sugar are molasses (a by product of sugar industry and sweet sorghum). According to IEA<sup>5</sup> about 60 % of the world ethanol production is from sugar crop and molasses, mainly from sugar cane as Brazil is by far the largest producer. Its Centre-South region with good soils and adequate rainfall is one of the cheapest regions of sugar cane and ethanol production (80 to 85% of the total Brazilian production)<sup>6</sup>.

Almost half of the sugar cane production is transformed into ethanol. One of the advantages of sugar cane consists in a well establish crop in terms of cultivation, breeding, harvesting and processing. When operated at high efficiency, sugar cane mills and distillery can be a source of extra electricity to be sold to the grid or contributing to rural electrification. As access to electricity is also a major challenge for developing country, sugar cane offers this opportunity of poly-generation (see below).

Many developing countries are already producing sugar cane, therefore making the Brazilian scheme potentially interesting for replication. However, crop requirements (water and soil) limit the surface available for sugar cane and land availability will certainly constitute the main limiting factor. Nevertheless, world market greatly influences the price of the main agricultural crops and consequently the biofuel. The total "liberalisation" of the sugar price in 2007 would certainly modify the situation due to the concordant increasing price of crude oil (present and foreseen). Sugar cane plantation might be economically converted into biofuel plant.

Sugar beet is used in Europe, namely France<sup>7</sup>, with a feedstock cost much higher than of sugar cane. The uses of other sources of biomass like fruits and to certain extent to sweet sorghum (with present varieties) is limited due to cost effectiveness.

### **2.1.2. Starch rich crops**

Because starch, largely present in many agricultural products, is easily converted into glucose, the largest part of ethanol produced in OECD (northern countries) is made from cereals. Yeast and enzymes for starch conversion and glucose fermentation are commercially available. The potential feedstock includes maize, wheat, potato, cassava, sweet potato. Maize, used for biofuels in the USA is by far the largest used for ethanol production worldwide with 81.51 Mhl produced in 2002<sup>17</sup>.

In the conversion of grain to ethanol process, only the starchy part of the feedstock is used, which represents a relatively small percentage of the total plant mass, in particular to compare to the cellulosic part (husk and straw for wheat). Even on the grain itself, starchy ethanol production results in numerous co and by products like animal feed from corn in the dry mill processing and gluten, high fructose maize syrups ... in the wet processing plant.

Cassava could be an interesting feedstock for developing countries as its cultivation is relatively easy and do not require rich soil as sugar cane.

### **2.1.3. Oily seeds**

If we consider that approximately one litre of biomass oil plus 10% of methanol are needed to make 1 litre of biodiesel and 350 g of glycerol, the biofuel production from crops is high. However oil yields per hectare greatly vary as illustrates table 1.



Crops	Seed yield t/ha	Oil content wt %	Litres bio diesel per ha
Soybean	2.67	18	524
Cottonseed	1.05	19	216
Canola	1.54	40	665
Sunflower	1.52	40	657
Peanuts	3.40	25	920
Rapeseed	1.47	40	638
Mustard (spice)	1.04	40	452
Jatropha	2	37	701
Palm oil	20 (fresh fruit bunches)	49	3000

Table 1: Seeds and oil yields and equivalent Biodiesel per ha<sup>8 9 10</sup>

As for starchy crops, biofuel production from oil crops results in co and by products, namely animal feed from cake. This by-product is of importance for some developing countries (namely Africa) as animal food is generally a problem (in Burkina Faso cotton oil price from cotton seed extraction is equivalent and often cheaper than cotton cake sold as animal feedstock).

The vast potential of biodiesel from oily biomasses is under investigation in India or Brazil. Concrete plans are being formulated to use wastelands for tree-borne oilseed plantations such as *Jatropha curcas* and other native or oil rich plants using the large diversity of palm trees in Brazil as example. *Jatropha* and other native oil rich plant are interesting as they do not compete with food crops and, concerning *Jatropha* at least, do not require much water to grow. Figures on productivity are nevertheless limited and to certain extend contradictory<sup>11</sup>. Plant selection and the improvement of agricultural practice may improve the productivity per hectare.

The amount of biomass oils potentially available for energy on a country basis is not a fixed estimate. Indeed, production, demand, exports and prices can vary greatly from year to year as a result of surface really planted, weather, oilseed crush, food and feed demand, competitions and even exchange rates.

Because oil crops and plantations are primarily large-scale, commercial monocultures, while they offer considerable economic benefits, their development present the risk of resulting in the total clearing of natural vegetation. In industrial plantations, the use of pesticides and herbicides may have additional significant impact on biodiversity in bio-diverse countries as are many developing countries. The challenge for the development of oily biomass feedstock as for other energy plantations would consist in developing pesticide resistant strains and more drought tolerant crops as well as in developing the commercialisation of higher value co-products from the raw material through biorefineries (see below, part 3.4).

Feedstock is characterized by the type and concentration of fatty acids present: generally saturated, monounsaturated, or polyunsaturated. Feedstock with similar compositions can be used interchangeably in processes designed for those compositions; depending on prices. Tallow, palm oil, sunflower oil and rape seed oil are the most common industrial feedstock. For biodiesel, the perfect feedstock is composed of 100 % mono-unsaturated fatty acid.

Fuel properties (freezing point, cetane number and viscosity), hence its use as transport fuel in conventional car without engine modification, vary with fatty acid composition and the presence of minor compounds such as sterols, antioxidants and phosphatides

Table 2 shows the relative impact of biomass oil composition on fuel properties. Several documents report specific data on these properties for various types of feedstock as well as fatty acid esters<sup>12</sup>.

	Saturated	Mono-unsaturated	Poly-unsaturated
Cetane Number	High	Medium	Low
Cloud Point	High	Medium	Low
Stability	High	Medium	Low
NOx Emissions	Reduction	Medium increase	Large increase

**Table 2: Biomass Oil Composition and Impact on Fuel Properties<sup>13</sup>**

To overcome these problems and allow the use of wider range of vegetable oil at a large scale without engine modification and with environmental impact improvements, oils (triglyceride) are transformed into smaller molecule by means of esterification with alcohol mainly methanol (see below).

The fatty chains are hydrocarbons, 6 to 26 carbons in length, with a carboxyl group attached at one end. Saturated fatty acids are structurally similar to their petroleum counter parts – paraffin. When they are not fully saturated, the degree of unsaturation (number of C=C bonds) varies from 1 (olefins) to 5 double carbon bond sites. When fatty acids are made into methyl esters, a methanol molecule is bonded to the carboxyl end of each fatty acid.

## **2.2. Lignocellulosic products and residues**

The largest part of a plant is not sugar or starch but rather cellulose, hemi cellulose and lignin (particularly for woody biomass). Cellulose and hemi cellulose can be converted into ethanol through a first step which consists in converting them into sugar. Unfortunately, it is not possible with lignin.

The cellulosic component of woody and herbaceous biomass ranges from 30 % to 70 %. The remaining organic part is lignin which can be use to generate the energy for the process or can be considered as raw material for bio synfuel routes.

### **2.2.1 Forest residues**

Woody biomass which includes wood itself, the wood forest and wood processing industry residues account for the world largest renewable energy source. It represents for the EU-25 about 83 % of the total bioenergy production in 2002, as illustrated in figure 5. It accounts also for more than 60 % of the total energy consumption for many developing countries and can reach up to 80 % for the African poorest (Mali, Niger...).

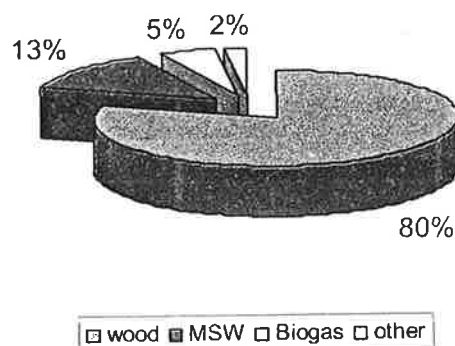


Figure 5: Breakdown of primary bioenergy production in EU 25 (Kavalov B.)

Wood is a well known product and presents interesting characteristics such as relatively high density and a low level of impurities compared to other biomasses. It therefore constitutes a perfect feedstock for biofuels production. However, partly due to these properties, it is also widely used for other purposes: paper, timber, particle and fibre boards and consequently it certainly constitutes one of the most expensive raw materials as the appearance of new applications would result in increasing prices.

Wood residues consisting in logging residues (tops, branches) and process residues (off cuts, sawdust), from the forest industries, demolition wood, constitute a large potential which might be available at lower prices compared to logs. Thinning might also be an important resource.

The availability of these resources largely depends on the efficiency of the industry it comes from. Small branches, stumps, bark, sawdust and coarse residues are the result of logging and primary production processes. Typical yield from a tropical sawmill for export is between 15 to 20 % of the total biomass: between 25 to 40 % of the total harvested wood, which only accounts for 50 to 60 % of the total tree, depending of many factors. Their characteristics vary in composition, volume and quality, particularly the moisture content (from 12 to 55 % on dry basis), depending on the step of processing and following possible soil contamination. Depending on its particle size, the bulk density may also vary significantly which requires preliminary pre-treatment in order to make it appropriate for the down stream process.

Wood industries require heat for drying or steam for board manufacturing and electricity. The trends are for the development of cogeneration facilities on conventional steam cycle. Cogeneration is penetrating this sector rapidly (common in ASEAN) resulting in limited availability of biomass for other applications such as biofuels. As a consequence of increasing diesel price, wood based power plants are rapidly replacing diesel genset. This trend would probably not change.

### 2.2.2. Energy plantations

Energy plantations are grown and harvested to specifically provide energy. Production costs are still relatively high (an example below) but may come down as plant varieties with higher yields are bred and efficient harvesting methods are developed. Energy plantations are already in development, namely in Brazil where eucalyptus plantations are supplying charcoal to the steel industry.

Plantations offer can grow on lower quality land, hence do not necessarily compete with other agricultural activities for food. They also require fewer inputs (pesticides and fertilizers). However, particular attention should be paid on species selection and large monocultures. In the long term, highest potentials will result from the use of local and mixed species preserving some biodiversity.

Productivity of plantation varies according to many factors among which species and plant selection, plantation and maintenance techniques. In addition, the location accounts for a large part. When water is not the limiting factor, tropical countries benefit from favourable climatic conditions that allow productivity two to three times higher than northern countries like in EU.

If the full tree utilisation maximises the short-term biomass yield, it also means a larger removal of nutrients. Forest growth and continuing high yields require leaving on the soil part of the nutrients. If this nutrients balance is not carefully controlled, it can affect wood yields and biodiversity, the plantation sustainability would require an increasing use of fertilisers. It is therefore important to find the appropriate balance between high biomass production yields and long-term fertility of forest soils.

Achieving such a balance is relatively easy in practice, since the largest part of the hydrocarbon content of a tree is bound in stems, while the majority of nutrients are contained in leaves and branches. Hence, after felling, the common practice in eucalyptus plantation in Brazil for example consists in leaving the all tree on the ground for a couple of weeks. During this period, allowing a significant drop in moisture, the leaves and small branches fall down and the nutrients are back to the soil<sup>14</sup>.

In Brazil<sup>15</sup>, significant gains in productivity were achieved with the adoption of more intensive forestry techniques (preparation of the soil, fertilization, breeding ...); from 15 m<sup>3</sup>/ha/year productivity in 1967 to 21 m<sup>3</sup>/ha/year today<sup>16</sup>. With the introduction of new materials and through clone selection, a 40 m<sup>3</sup>/ha/year was achieved<sup>17</sup>. This very high productivity allows Brazilian steel industry to efficiently use wood as feedstock, after its conversion to charcoal. The cost of charcoal produced from plantation is between 20 to 25 US\$/m<sup>3</sup> (15% plantation and maintenance and 20% harvesting, 25% wood transportation, 20% investment cost and manpower, 20% taxes). Charcoal produced with native wood and in the informal sector costs around 14 US\$/m<sup>3</sup>.<sup>16</sup>

Considering a 30 to 40 m<sup>3</sup>/ha/year production in a 6 year cycle, which should become the standard in Brazil, each hectare shall have a wood production volume of 180 to 240 m<sup>3</sup>. On this basis, the average production costs are within the following intervals in US dollar<sup>18</sup>:

- Implantation 337 US\$/ha = 1.4 - 1.8 US\$/m<sup>3</sup>
- Maintenance 146 US\$/ha = 0.6 - 0.8 US\$/m<sup>3</sup>
- Budding 237 US\$/ha = 1.0 - 1.3 US\$/m<sup>3</sup>

The total overall plantation cost adds up to 3 - 4 US\$/m<sup>3</sup> or 5 - 6.6 US\$/t or 0.3 - 0.5 US\$/GJ.

Looking at potential productivity increases in the longer term implies further considerations illustrated in Figure 6 where potential, achievable and real productivities are distinguished. Potential productivity is defined by factors that are intrinsic to the plant and its environment. Achievable productivity is the productivity potentially achievable under limiting factors of the environment such as availability of water, nutrients and fertility of soil. Real productivity is the achieved productivity as a consequence of reducing factors, such as diseases, fire ...

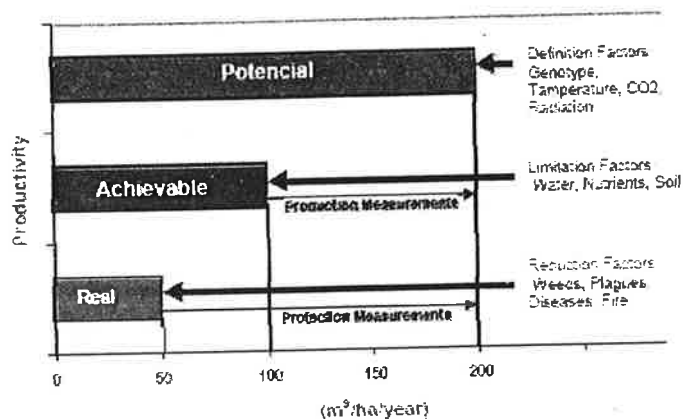


Figure 6: Definition of productivity from plantations and there limiting factors (Stape, 2004)<sup>19</sup>

Careful understanding of such differences is required to convert potential land availability into biofuel potentials.

### 2.2.3. Perennial energy crops

Growing dedicated herbaceous crops for energy purposes is also possible. However, information on various aspects of their cultivation is still limited despite intensive research, particularly in the USA and the EU. The main herbaceous species considered for energy application are miscanthus, switch grass or cane fibre. Miscanthus is an attractive option, since it requires low input while yields can reach up to 15 tons per hectare per year under optimum conditions. To compare with short rotation forest plantation, herbaceous crops have lower moisture contents but are bulkier products, increasing transportation costs. Their ash content is higher with a wider composition, including some undesirable compounds which may create catalyst rapid deactivation or poisoning, as well as create corrosion and slag problems with some type of gasifiers.

Energy crops can provide a useful energy source both for the export market (although liable to market fluctuations) but more importantly for the more stable local market. Today several tropical countries like Malaysia or Thailand are looking into establishing dedicated plantations mostly for liquid biofuel production for the transport sector.

### 2.2.4. Agri-based residues

Agriculture and agro industries are large providers of biomass resources after a fraction of the plant only has been used for food and feed. The availability of by-products depends on objectives pursued for the corresponding main crop and on world market prices. By-products do not have autonomous market behaviour.

The total world potential represents 9.5 EJ energy equivalent<sup>20</sup>. If this figure may appear important, the real availability is much less in practice, limited by a number of factors as it will be discussed later.

China and India by far present the largest agri-based residues potential. This is mainly due to the share of rice by-products: straw and husk, which represent 83 and 71 % of their respective agricultural residues potentials. Rice straw account for 56 % of the top ten global potential followed by bagasse (15%) and rice husk and cotton stalks for 10 % each.

Crops	Residue amount on dry weight basis (tons/ha)	Range of straw/grain ratio
Barley	4.3	0.82–2.50
Maize	10.1	0.55–1.50
Cotton	6.7	0.95–2.0
Rapeseed	-	1.25–2.0
Soybeans	-	0.8–2.6
Rice	6.7	0.75–2.5
Sorghum	8.4	0.85–2.0
Wheat	5.0	1.10–2.57

Table 3.: Residues and dry weight ratio of straw to grain for different crops<sup>21</sup>

#### 2.2.4.1. Herbaceous residues: Straws and stalks

Cereals straws are the main source of herbaceous material available for energy supply. The net availability of straw per hectare would be function of the crop itself and its variety with its specific biomass to crop ratio (see table 3) as well as of the climate conditions, and the alternative uses.

However agro-residues are a source of fertiliser, sometimes the only one, thus an important fraction of the biomass is reintroduced into the soil. Farmers also consume a significant fraction as bed material for livestock and animal feed.

Maize is approximately half grain and half stalks and leaves. Therefore 1 hectare of maize with a yield of 8 t/ha would also deliver 4 tons of cellulosic biomass if we consider only 50 % recovery. Wheat is approximately 55 % grain and 45 % straw, with a crop yield which amount from 6 to 9 t/ha, it would offer a potential of 2 to 4 tons of biomass with the same 50 % recovery ratio.

Straw usually has a very low moisture content (10%) which is a clear advantage to compare with woody biomass; however, it has a higher ash content, which results in a lower calorific value and constitutes a source of contaminant for several biofuel technology alternatives. In order to improve its bulk density, the straw is generally baled before transportation. These technologies are well established and options exist of very high density baling.

Some attempt were applied (particularly in Denmark) to reduce the ash content of the straw by washing it at mild temperature (60°C). The washing allows reducing significantly the alkali content of the straw. However, washing does not remove all ashes and it increases the moisture content. Further drying may be therefore necessary afterwards particularly for gasification. On the other hand washing might improve hydrolysis efficiency.

Straw is already used on large scale for energy generation (Denmark) or paper industries (China). Due to the ban of field burning and the development of more livestock practices, straw are largely available in industrialised countries. However, in tropical countries, alternative uses and the weakness of infrastructure for transport would limit their availability. The same remark applies for cotton stalks, corn cobs and other herbaceous feedstock. Nevertheless, it can be assumed that a significant share of the straw would be available particularly in countries with economy in transition.

#### **2.2.4.2. Cane Trash and Bagasse from the Sugar Cane Industry**

Cane trash and bagasse are produced during the harvesting and milling process of sugar cane which normally lasts between 5 to 7 months. Cane trash consists of sugarcane tops and leaves. Nowadays, it is mostly burnt in the field as sugar mills are already largely self-sufficient in energy as their collection would increase costs. Bagasse is the fibrous residue produced when the juice has been extracted from sugarcane.

A large portion of the bagasse produced is already used in existing sugar mills to meet their own electricity and heat demand. Low pressure boilers (below 20 bar) and low efficiency steam generators are commonly used. Upgrading or renewing existing CHP plant to highly efficient, high pressure systems with higher capacities and utilising the excess bagasse is a more commonly considered nowadays with the increasing demand for electricity worldwide.

Of the world's sugar mills, more than half have a potential for exports generating capacity greater than 5 MWe. This excess of raw materials, added to the cane trash potential can constitute an important source of biofuel feedstock. However, renewing the factories might not free a large amount of bagasse and cane trash as it exists in many countries (India, Thailand, Philippines...) real incentives to produce electricity, through IPP (independent power production) scenario.

In Brazil, the excess bagasse indirectly contributes to transport fuel economy through electricity generation which allows production cost of the Brazilian Bioethanol to be competitive. This scheme would certainly be replicated in several developing countries as the price of sugar is expected to drop in 2007 with the global liberalisation of the market.

#### **2.2.4.3. Rice Husk**

Rice husk, the main by-product from rice milling, accounts for roughly 22% of paddy weight, while rice straw to paddy ratio ranges from 1.0 to 4.3 depending on the species. In general there is a large excess of rice husk which can create additional costs to the rice millers for disposal. The type and particularly the size of the rice mill affect rice husk real availability as a potential fuel. Indeed, large producers like Indonesia and to a certain extent India, present industrial sectors characterised by a large number of very small mills disseminated all over the country. Despite a large potential of unused rice husks, collecting this feedstock is not economically viable. This aspect limits greatly the real availability of rice husk in developing countries. When the industry is well established, the growing demand for parboiling rice increase the use of rice husk to covers the heat needed by the mill. Large CHP plants up to 10 MWe are in operation in Thailand and in India.



The high silica content of rice husk means that the conversion process needs to be carried out in a carefully controlled system since heating the ash above melting point would result in bed agglomeration. Approximately 30 % of the husk ends up as ash. If a high quality can be guaranteed for this ash, it may have a retail value to metallurgy of presently up to US\$ 200 per ton (equivalent to US\$ 40 per ton of rice husk, or US\$ 8 per ton of rough rice)<sup>22</sup>. These levels of prices would rapidly make rice husk not available for conventional energy uses if the process cannot guarantee a high quality ash and it is preferred to produce silica rich ashes for metallurgy without energy consideration. On the other hand, with a well under control energy conversion process, ashes can constitute an interesting source of profit which can benefit large scale improved technology for biofuel.

#### **2.2.4.4. Coconut Husk and Shell**

Potentially available biomass residues from the coconut industry include coconut husk and shells. The residues to crop ratio is 0.12 shell and 0.42 husk. However these residues are largely utilized as fuel in the copra drying processes as well as in industrial sectors.

The two largest producers of coconuts in the world are Indonesia and the Philippines, having about 3.7 Mha and 3.1 Mha respectively resulting in 5.7 and 6.8 Mt wastes respectively. Despite and because of the very high quality of the shell, this feedstock is almost fully used as a source of raw material for activated carbon industry. Only the husk could be available. Up to now, the largest part of the husk remains in the fields as de-husking is done during harvesting.

#### **2.2.4.5. Municipal Solid Wastes**

Municipal Solid Wastes (MSW) generated in cities throughout the world, contain a high proportion of biomass that can be an interesting source of energy. The vast majority of this domestic waste is dumped in landfill sites creating environmental problems.

The best route for the use of this biomass for transport fuel is the syngas route through gasification. However, this feedstock can be heavily contaminated and might be a source of difficult problems downstream of the process. In addition, as MSW collection is still a real problem in most developing countries this feedstock is not considered as an opportunity for biofuel production on the medium term. Power generation from methane through managed land field would certainly constitute the main option.

### **2.2.5. Pre treatment of lignocellulosic biomass**

As it will be discussed in the next chapters, synthesis processes require large see very large scales to be economically viable. Major drawbacks of raw biomass are then some of its physical characteristics: low energy density, heterogeneity (particle size...) ... The production of standardised upgraded biomass will definitively constitute a prerequisite to produce biofuels rather than the use of raw biomass.

These pre-treatment can be drying and grinding, compaction through densification or pyrolysis, allowing the utilization of various residual material. The poorest quality of one of them can be in that case, partly compensated with the better quality of another. Homogenisation of feed stock constitutes an important requirement for conversion processes and particularly gasification as the spectrum of feedstock requirements is relatively narrow.

### **2.2.5.1. Drying and grinding**

Thermo chemical conversion technologies most generally require low moisture content as water limits heat transfer, requires a lot of energy to evaporation, increases the volume of flue gas, etc. Drying is generally done on raw biomass to reduce the moisture content down to 20 % at minima.

Depending on the biomass size, grinding is a prerequisite to conversion processes requiring small particles such as flash pyrolysis to liquid biofuels in fluid bed and circulating fluid bed systems. Almost as important as particle size, the size distribution may affect the performances of thermo chemical technologies. Down sizing and screening would generally apply in most processes to optimize heat and mass transfers. Reversely, other processes such as slow pyrolysis to solid biofuels facilitate the grinding of biomass. There is obviously a cost of size reduction in financial and energy terms but we lack data to define such a penalty associated with the small particle size requirements.

### **2.2.5.2. Densification**

Pellets are normally 10-30 mm long with a diameter of 8-12 mm. Pellets are produced from various residual biomasses (sawdust, herbaceous products and waste). The dry biomass, primarily grinded, is forced through a matrix under high pressure, followed by immediate cooling for durability and stability. The main advantage of pellets is the higher energy density, which reduces significantly transportation, storage and handling costs per energy unit. The drawback of pellets is the global energy efficiency drop and the increasing cost resulting from investment and operation. As drying is actually necessary, the energy costs may raise up to 30 % compared with wood chips. However, large volumes of pellets are already subject to international trade. Indeed, Scandinavian countries import large volumes of wood pellets from Canada<sup>23</sup>.

### **2.2.5.3. Pyrolysis**

To enhance the overall applicability of biomass for large scale production, pyrolysis processes offer several options for upgrading biomass. The amount and nature of end products from pyrolysis depends on temperature, heating rate and residence time and on the composition of the biomass itself. There are several types of pyrolysis processes, with different heating rates: slow pyrolysis, carbonization or torrefaction to produce a coal-like material and fast pyrolysis to produce a liquid similar to a crude-oil.

#### **2.2.5.3.1. Slow pyrolysis processes for solids**

In a slow pyrolysis process the biomass undergoes a mild thermal treatment. Depending on the final temperature and the residence time, the resulting material still contains most of the energy of the raw biomass. The working temperature of the torrefaction process is typically between 220 and 280°C. At this level only the hemicellulosic fraction and slightly the lignin fraction are modified, which confers to the final product a hydrophobic property and facilitates the grinding of the product. The moisture content of the end product is thus very stable between 4 to 6% and is not influenced by the air humidity to compare to biomass presenting moisture content varying constantly with time and storage conditions. Gasification of torrefied biomass in an entrained flow gasifier might be an interesting option.

At a rather higher temperature, typically 500°C, carbonisation results in charcoal, a very similar product than coal. However conventional processes suffer from a relatively bad energy efficiency, typically between 55 to 65% which makes this option economically non viable even it offers similarities with flash pyrolysis (energy concentrated product, easy to transport, easier to grind than coal, ...). The carbonisation under elevated pressure, on the range of eight to ten bars results in a very high efficiency with energy yields above 70%. This option which feasibility has been demonstrated at lab scale<sup>24,25</sup> is under development at pilot scale (100 kg/h) in the US<sup>26,27</sup> might offer some room for biomass conditioning and pre treatment. On principle any type of biomass can be used. However depending of the process applied and if the scope is to produce charcoal, small particles are not easy to convert into char and would result in very fine particles difficult to handle. Woody biomass looks more appropriate.

#### 2.2.5.3.2. Flash pyrolysis processes for liquid

The production of liquid fuel from biomass via fast pyrolysis processes also known as flash pyrolysis results in a liquid, "bio-oil", having the potential to be easily transported and pressurized, and with a considerable advantage downstream of the synfuel processes, to be nearly free of inorganic material, ashes being concentrated in the remaining char.

Flash pyrolysis has benefited from active research program in the last twenty years<sup>28, 29</sup>. Used as a fuel oil substitute, combustion tests have shown that bio-oil burns efficiently in standard or slightly modified boilers and engines with efficiencies similar to those for commercial fossil fuels. Using the bio-oil in existing entrained flow gasifier for syngas production is therefore a real possibility and there are ongoing tests of gasification at pilot scale in Europe<sup>30,31</sup> (see frames in the text). Today, flash pyrolysis is at the boundary between development and demonstration and several plants are operating in Europe and North America. Significant quantities (from kilograms to tons) of bio-oils are produced and transported either for research or for development purposes<sup>32, 27</sup>.

In fast pyrolysis processes, small, low-moisture biomass particles are heated rapidly to temperatures in the range of 450° to 550°C. Oil mass yield is typically around 70 to 75 percent of the original feedstock when wood is the feedstock. In flash pyrolysis processes, the residence time is below one second resulting in a very high heating rate of the particles - higher than 10,000°C per second. The vapour formed needs a rapid cooling to enhance liquids. The part of the non-condensable gases produced mainly consists of CO, CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>. They are generally recycled for the drying of the biomass or used as fluidising gas.

Figure 7 presents the general process scheme for flash pyrolysis.

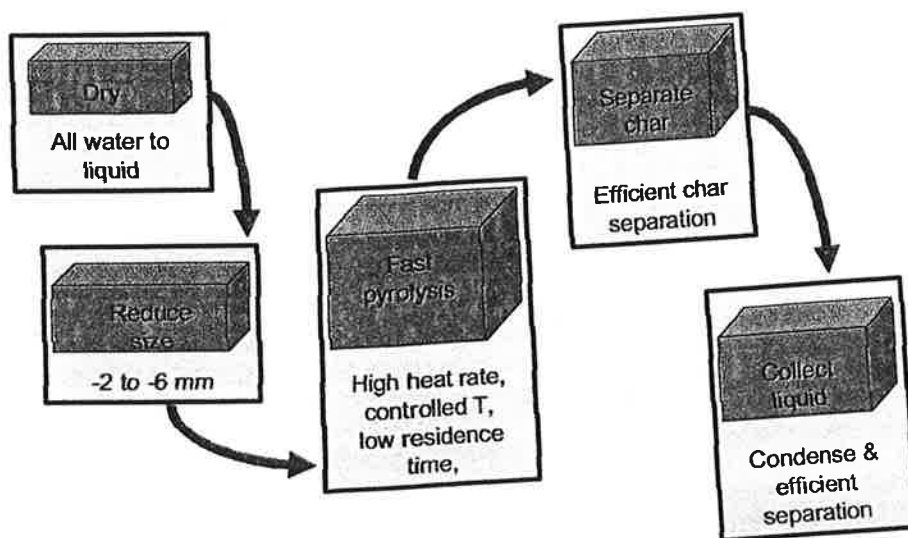


Figure 7: General process scheme of flash pyrolysis reactor<sup>33</sup>

Any type of biomass can be used for pyrolysis processes. The requirements for the feedstock for fast pyrolysis differ from a biomass to another, the reactor design and on the expected product, but feedstock requirements for fast pyrolysis are strict in terms of particles size and moisture content: a particle size smaller than 6 mm and low moisture content (below 10 % weight for a bio-oil with around 20% water content). Those requirements are heat transfer requirements. In theory, particles size should be as small as possible in order to increase liquid yields. Ablative reactors such as National Renewable Energy Laboratory's or ASTON's are less sensitive to particle size as far as heat transfer is concerned. Still, biomass must be dried and grinded prior to flash pyrolysis.

Several types of reactors can be used, such as fluid bed reactors. In this type of reactor, the fine biomass particles are fed to a reactor with a bed, made of an inert component, e.g. sand. The heating of the biomass particles is done by means of blowing hot gas through them, from the bottom to the top. Technology with no fluidisation gas (ablative<sup>34</sup>, rotating cone<sup>34</sup>) would simplify the collection of the pyrolysis products after the reaction and improve the energy efficiency. A disadvantage of these technologies is the difficulty to upscale. BTG in the Netherlands has constructed and is now commissioning a two tons per hour unit in Malaysia<sup>35</sup>, this unit would probably constitute the maximum size. The cost is actually not known, BTG claims a specific investment cost in the range of 200 to 300 €/kW<sub>th</sub>.

Pyrolysis liquids are referred to by many names: pyrolysis oil, bio-crude, bio-oil, pyrolytic liquids, tars, liquid smoke, wood distillates ... They have been well known for years as they were largely used for chemical applications, today replaced by petroleum chemistry. Biomass pyrolysis liquids are complex, dark brown, viscous, highly polar and acid products. Typically, the pyrolysis liquids are single phase liquids containing water in various in various possible amounts, keeping the bio-oil in a liquid form. Water content is around 20% on a dry feedstock (10 wt %) and higher with wet feed. Water also comes from chemical reactions during pyrolysis. Elementary analysis is close to that of the biomass it comes from. This does not represent an advantage for further upgrading as oxygen still needs to be removed.

As bio-oil properties from different sources of biomass can be relatively close to each other, fast pyrolysis would also be an interesting option for biomass homogenisation to allow economic supply of large biofuel plants under realistic economic conditions.

The bio-crude contains several hundreds different chemicals ranging from low molecular weight to complex high molecular weight phenols and anhydrosugars. It has a heating value of nearly half that of a conversion fuel oil, typically 16-22 MJ/kg. The water content of the liquid being able to vary in a wide proportion depending on the feed moisture content and to a certain extent on the process, the heating value varies accordingly. The density of the liquid is very high at around 1.2 kg/l compared to the biomass it comes from (between 0.4 and 0.8) and to light fuel oil at around 0.84 kg/l. Compared to the bulk density of some biomass resources like agri-based residues, straw, saw dust which may have bulk density as low as 150 kg/m<sup>3</sup> pyrolysis liquids offer a large reduction in the cost associated with storage and transportation. Indeed, considering the density and NCV of a raw straw and a straw bio-oil, respectively 0.15 kg/m<sup>3</sup>, 12.5 MJ/kg and 1.2 kg/m<sup>3</sup>, 20 MJ/kg; with a liquid yield of 75%, the transport cost can be reduced by almost 10, all other cost being equal.

A typical characteristic of wood derived pyrolysis liquids, compared to fuel oil, is summarised in table 4.

Physical properties	Typical range	Light diesel
Moisture	15 to 30 (%)	0.7
pH	2.5	...
Specific density	1.20 to 1.30 kg/dm <sup>3</sup>	0.84
Ultimate analysis (moisture free)		
C	56 %	85.9
H	6 %	13.3
N	0.3 %	0.25
S	-	0.3
Ash	0.1 %	-
O	37 %	0
LHV on dry basis	18-22 MJ/kg	41.9
Solids content	0.1 to 1 %	-
Viscosity at 40°C	40 to 100 cp	7.5
Viscosity at 80°C	6-24 cp	-
Pour point	-12 to 33 °C	
Flash point	50 to 70 °C	

Table 4: Typical characteristics of wood derived pyrolysis liquids

These pyrolysis technologies would certainly contribute to the development of biofuel production as they allow the supply of a large scale biorefinery (in the range of 5 to 10 million tons of biomass a year) with a wide range of lignocellulosic feedstock homogenised on the location where they are grown. Hence, transportation distances associated to large raw material requirements are reduced. In addition, the possibility to co-refine bio-oils in conventional oil refinery, not fully explored yet, might be an interesting option for existing facilities.

Initiatives to investigate flash pyrolysis technology by the implementation of larger pre industrial units such as the already mentioned Malaysian BTG rotating cone technology<sup>36</sup> or the last 3 tons an hour Dynamotive fluid bed unit commissioned early 2005<sup>37</sup>, should be reinforced and replicated in developing countries to avoid the implementation of the readily conventional biofuels solutions based on oily and sugar rich biomass (more directly competing with food than lignocellulosic feedstock).



In Africa this way, biomass energy may offer a new opportunity for agriculture development and the access to modern energy in rural area as well as the expansion and the development of infrastructure and logistics for energy plantations and biofuels production.

Indeed, developing countries should not be merely perceived as potential biofuel exporting countries but rather as countries where Lignocellulosic biomass availability should offer a chance for regional and economic development with local access to energy. This will definitively require innovative and well designed policies and the co-development of the technologies.

### 3. Biofuel conversion technologies – state of the art

The scope of this chapter is to describe main pathways for the production of bio fuel on the basis of the final product sought-after, on both technical and economic terms. For each technology, biomass required characteristics and degrees of maturity will be presented for discussion. Biofuel names of the considered routes are summarized in the table 5 here after.

	Name of bio fuel	Name by EU directive	Production process
1 <sup>st</sup>	Straight vegetable oil	Pure vegetable oil	Mechanical or chemical extraction, refining
1 <sup>st</sup>	Ethanol	Bio ethanol	Sugar fermentation, starch hydrolysis and fermentation
1 <sup>st</sup>	Fatty acids esters	Bio diesel	Triglycerides etherification and purification
2 <sup>nd</sup>	Fischer-Tropsch (FT) diesel	Synthetic bio fuel	Gasification, gas-shift, synthesis, hydrocracking
2 <sup>nd</sup>	Methanol	Bio methanol	Gasification, gas-shift, synthesis
2 <sup>nd</sup>	DME	Biodimethylether	Gasification, gas-shift, synthesis
2 <sup>nd</sup>	SNG from syngas	Biogas, synthetic bio fuel	Gasification, gas-shift, synthesis, CO <sub>2</sub> /H <sub>2</sub> O-removal
2 <sup>nd</sup>	Ethanol from celluloses	Bio ethanol	Advanced hydrolysis, fermentation, distillation
2 <sup>nd</sup>	Pyrolysis-diesel	Synthetic bio fuel	Pyrolysis, hydro de oxygenation, refining

Table 5: Considered first and second generation biofuels for transportation

#### 3.1. Fermentation for bioethanol production

Ethanol can be produced from any feedstock that contain sugar or compounds like starch or cellulose that can be converted into sugar.

##### 3.1.1. Conversion technology

##### 3.1.1.1 From sugar, fermentation and distillation

The oldest way of producing ethanol is fermentation of glucose recovered by soaking, crushing or chemical extraction, repeated for complete recovery. Glucose is fermented to alcohol using yeast and other micro organisms. The final step purifies the alcohol from water by distillation to the desired concentration and usually removes all the water to produce anhydrous ethanol that can be blended with

gasoline. In Brazil 60% of the ethanol is sold in hydrated form (93% vol ethanol 7% water). The affinity of ethanol with water is certainly one of its main drawbacks.

### 3.1.1.2. From starch, hydrolysis then fermentation and distillation

Starch consists of a long chain of glucose molecules that have to be broken down into simpler sugars by hydrolysis prior to their fermentation.

The first step of the hydrolysis process consists in milling the grain to free the starch from the raw material. This step can be dry or wet if the grain has been soaked and broken down before the starch is converted to sugar.

The starch is converted into sugar in hot dilute phase to dissolve the water soluble starch and maintain the activity of the yeast. The starchy material is converted continuously into short carbon hydrates. For the development of the yeast needed for the fermentation process, the solution must be slightly acid, pH around 5.0. Therefore, hydrolysis can be achieved by the addition of dilute mineral acid to the grain slurry prior to cooking (acid hydrolysis process). Due to the presence of water, the ethanol produced is diluted in water. Through series of distillation and dehydration steps the ethanol is purified down to the desired concentration. Figure 8 presents the dry milling process scheme.

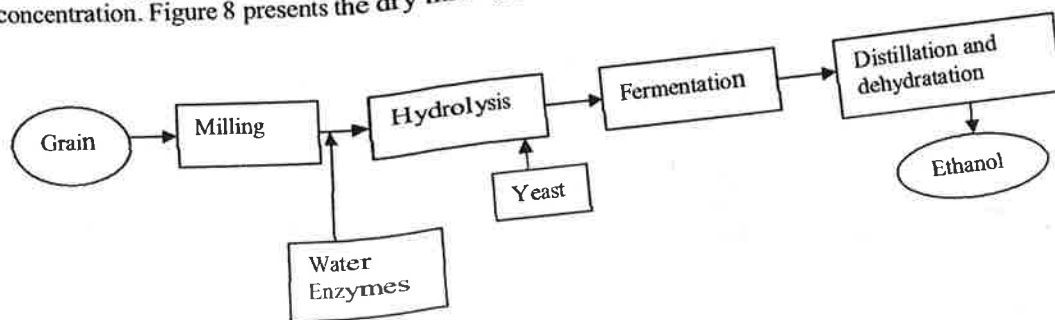


Figure 8: Ethanol production from grain dry milling<sup>38</sup>

### 3.1.1.3. From cellulose, saccharification then fermentation and distillation

For the conversion of cellulosic material to ethanol, two key steps are necessary. At first, cellulose and hemicellulose must be broken down into small hydro carbonates. This step results in a complex mixture of a wide variety of sugars making the second step quite challenging: these sugars have to be fermented into ethanol. The first step is presently subject to intense R&D worldwide and particularly in the USA as it remains the major challenge to develop this route.

A large number of thermal, chemical and biological processes are under investigation to carry out this so called saccharification step. The conversion (hydrolysis) of cellulose to sugar can be realised using diluted acid, concentrated acids or enzymes (cellulase). Enzymatic hydrolysis of cellulose is clearly preferred to acid hydrolysis from a process and environmental point of view (high concentration of sulphuric acid). There are numerous publications available on the subject<sup>39</sup>. Figure 9 illustrates the main options for pretreatment and hydrolysis processes of lignocellulosic biomass.



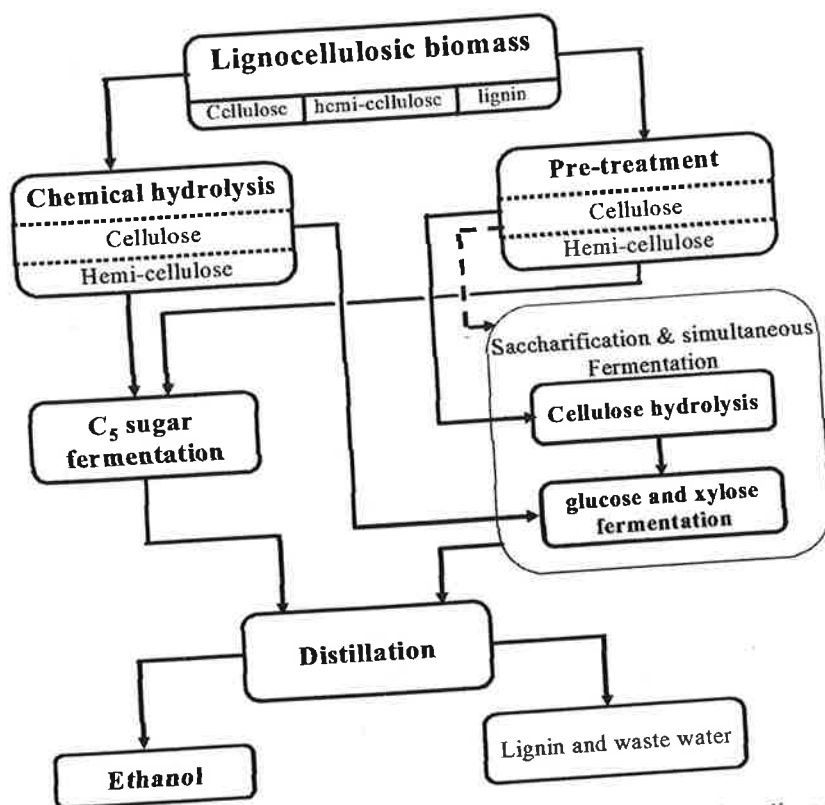


Figure 9: Simplified bloc flow diagram of ethanol production from ligno-cellulosic biomass<sup>40</sup>

The hydrolysis of hemicellulose takes place under relatively mild conditions. Because the cellulose fraction is more resistant, it requires more severe treatment. The major limits of acidic hydrolysis remain its relatively high cost associated to limited yield. That is why considerable effort is given to enzymatic hydrolysis. Present researches are looking at the possibility of including hydrolysis and co-fermentation of xylose and glucose in the same reactor (SSCF technology)<sup>41</sup>. Different types of pre-treatment are being studied, but three options look more efficient: dilute acid hydrolysis, steam explosion with catalyst addition and finally thermo hydrolysis. They could result in high hydrolysis yields, near 100 % for the cellulosic fraction and superior to 80 % for the hemicellulosic fraction with limited by product formation.

Purification of the ethanol produced follows the same principles as for the conventional routes.

#### 3.1.1.4 Conversion efficiency

Process efficiency on an overall basis is one of the most important parameters to assess the performance of options, as it will impact on the net GHG emission reduction as well as on the cost. It would also have a considerable impact on the plant capacity requirement, which most probably will constitute one of the bottlenecks of some of the options. Graboski and McClelland<sup>42</sup> discussed Pimentel's assumptions regarding the amount of energy and GHG emissions on the account of co-products, electricity for instance. For the authors, it results in a positive energy balance of about 30 % meanwhile, Pimentel reported that it takes 1.7 times more energy to produce ethanol than its energy content.

Biomass Ethanol production	Cane	beet	Maize	wheat	Cellulosic biomass		
Technology pathway	Fermentation distillation		Hydrolysis/fermentation distillation		Wood	Straw	Maize residues
Processes Efficiency (energy in/energy out) (%)	0.12 0.098	0.64 (low) 0.56 (high)	0.54 (dry mill) 0.57 (wet mill)	0.90 0.98	1.2 1.52	1.12	1.10
Ethanol production efficiency (l/ton feed stock)	73 90	54.1 101.3	387.7 372.8	348.9 346.5	na 288	330	345
Well to wheels GHG emission compare to gasoline % reduction/km travelled	na 92	50 56	32 25	29 47	51 107	57	61

Table 6: Ethanol production efficiency (adapted from <sup>5</sup>)

Regarding efficiency, a large number of studies were carried out past 15 years which show a wide range of figures because:

- the degree of maturity of the technology is not the same and it is difficult to fairly compare actual figures to expected results for “promising technologies” experimented on a pilot scale basis,
- assessment methodologies have evolve since the first work done on the subject,
- all studies do not take into account the same factors,
- the type of GHG considered and the knowledge on their respective impacts on the climate have evolve,
- the context of the study may also considerably affect the impact on the process i.e. energy used both directly and for the generation of the electricity used (whether from charcoal or nuclear) for example).

The final energy efficiency including assumptions on cars and engines efficiency can also have a significant impact (IEA 2001).

To limit distortions of the various origins listed above, information provided on table 6 comes from most recent studies. It shows that one energy unit of ethanol respectively requires between 0.6 to 0.8 and 0.9 to 1.0 units of fossil energy to produce it from maize and wheat. The production efficiency varies between 346 and 398 l ethanol / t feedstock. It represents for maize, a productivity between 2,570 and 3,113 l/ha with crop yields considered between 5.65 and 7.97 t/ha.

Ethanol from sugar cane in Brazil shows the best performance in terms of energy efficiency, as well as GHG net emissions. This is due to the high productivity of a tropical crop and the very high degree of integration of the plant where bagasse can largely covers the plant energy needs.

However, in many sugar industries worldwide and including Brazil, additional fossil energy is required as the process design or the equipment are too old. Nevertheless, it can be expected that the highest efficiency achieved in the best Brazilian mills will soon become the average values on a short term basis for entire Brazil as well as several other countries (Thailand, India ...). Indeed, increasing oil price has prompted countries to elaborate policies in favour of biofuels. In India, the government has declared the use of 5 percent ethanol blend in petrol mandatory in nine states and four Union Territories by the end of 2003.

The trends are also for a large ban of the cane trash burning practice which will increase the volume of cellulosic residues available at the mill side to be converted into electricity. However the potential alternative uses of bagasse for paper production or particle-board could affect the global energy balance in the case fossil fuel would be used instead of bagasse sold at higher prices to the paper industry.

Conventional ethanol production from glucose fermentation and starch hydrolysis and fermentation are mature and well established technologies, applied on large scale. They are limited possibilities to improve the technology which reaches a level of performance and investigation reducing opportunities for energy balance improvement or cost reduction.

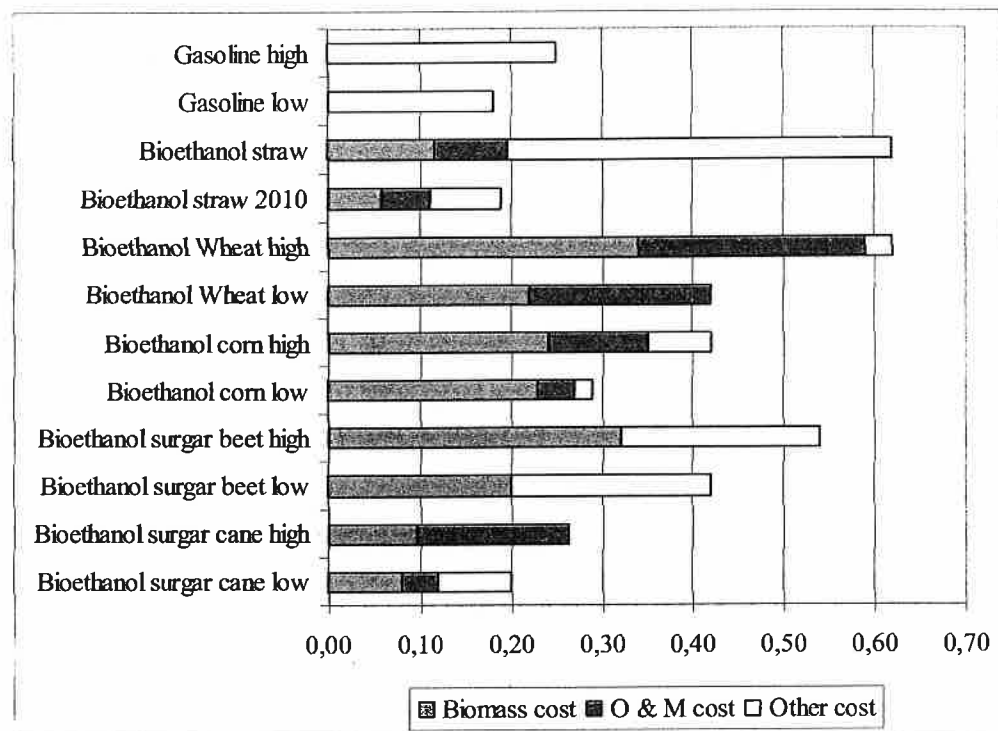
Most of the research and development nowadays focus on the lignocellulosic route where, as in sugar cane conversion, lignin and other unconverted products fuel the energy-consuming conversion process and may produce additional electricity<sup>37</sup>. The main drawback of this option may concern the type of feedstock used and the total fossil fuel energy required for collection and transport of the biomass (straw for example), or in fertilizer (for short rotation plantations) depending on the situation and the size of the plant. Results which are today available come from engineering studies and are not monitored figures. Indeed, only few large scale production facilities exist as the process improvement was more difficult than expected when research started 20 years ago.

Because of the cost related to the acid used in the acidic hydrolysis pathway, and their limited efficiency, research in this area is almost stopped. Enzymatic hydrolysis is a most interesting route to investigate and most of the efforts internationally focus on this option. Enzyme production cost and xylose fermentation remains the major obstacle to its development as yeast used in the ethanol industry are fermenting C6 sugars but they are not capable of converting C5 sugars such as xylose.

### **3.1.2. Economics of bioethanol production by fermentation**

As for other biofuels, the largest bioethanol cost component, illustrated in the figure 10 is of the feedstock, although about 50% of this cost is paid back by the sales of the co-products. The plant size has also a major impact on the cost. For instance, tripling the size of maize mills, dry or wet, would result in cost reductions, saving 0.05 to 0.06 US\$/l<sup>5</sup>: 40% on specific investment and 15 to 20% on operating costs.

The biofuel sector is heavily subsidised and prices discussed in figure 10 do not reflect these subsidies and the ensuing differences observed between EU and US. .



NB: In the case of gasoline full cost is given for comparison. Low and high prices correspond to different world market prices. These figures are only indicative as great variation occurs and the detail of the cost breakdown is not always provided. The largest part of other cost is capital cost.

Figure 10: Comparison of bioethanol low and high production costs breakdown compare to gasoline on a volume basis (figures on Europe, USA and Brazil)<sup>43 44 45 46 47</sup>.

Ethanol production from lignocellulosic material is more capital intensive than conventional sugar/starch plants due to the complexity of the process. However it can benefit from cheap feedstock explaining the expected competitiveness of bioethanol by year 2010. Investments cost estimates and cost breakdown details are given in table 7<sup>5</sup>.

	Near-term base case	Near-term "best Industry" case	Post-2010
Plant capital recovery cost	\$0.177	\$0.139	\$0.073
Raw material processing capacity (tonnes per day)	2 000	2 000	2 000
Ethanol yield (litres per tonne)	293	316	466
Ethanol production (million litres per year)	196	221	326
Total capital cost (million US\$)	\$234	\$205	\$159
Operating cost	\$0.182	\$0.152	\$0.112
Feedstock cost	\$0.097	\$0.087	\$0.059
Co-product credit	(\$0.019)	\$0.029	\$0.0
Chemicals	\$0.049	\$0.049	\$0.028
Labour	\$0.013	\$0.011	\$0.008
Maintenance	\$0.024	\$0.019	\$0.010
Insurance & taxes	\$0.018	\$0.015	\$0.007
Total cost per litre	\$0.36	\$0.29	\$0.19
Total cost per gasoline-equivalent litre	\$0.53	\$0.43	\$0.27

Table 7: Cellulosic ethanol plant cost estimates (\$/l) source NREL extracted from OECD/IEA Biofuel for transport<sup>5</sup>

### 3.2. Esterification for biodiesel production

Biomass oil can be used as fuel in a variety of ways: directly as a fuel in a boiler or a stationary genset, processed into biodiesel (fatty acid esters) or processed into "bio distillates" through refinery technology. Vegetable oils have been used as a fuel for a long time already as the process to convert biomass into vegetable oils for transport is similar to the well established food oil process. Europe has largely contributed to the development of this pathway mainly from rapeseed.

#### 3.2.1. Conversion technologies

Extraction of vegetable oil from seeds can be done mechanically or by a solvent like hexane. The latter results in a higher yield and is generally applied for biodiesel production.

Methyl ester is generally produced through catalytic trans-esterification of the oil with methanol. Oil molecules are broken down apart and reformed into esters and glycerol which are then separated from each other and purified. These processes are well known and well documented<sup>13 48</sup>. If a variety of types of esterification exists, most processes follow a similar scheme. Depending on the biomass oil, additives might be used to adjust properties and characteristics (free acid removal ...). Pre-treated oils and fats are mixed with the alcohol and the catalyst as illustrated in figure 11.

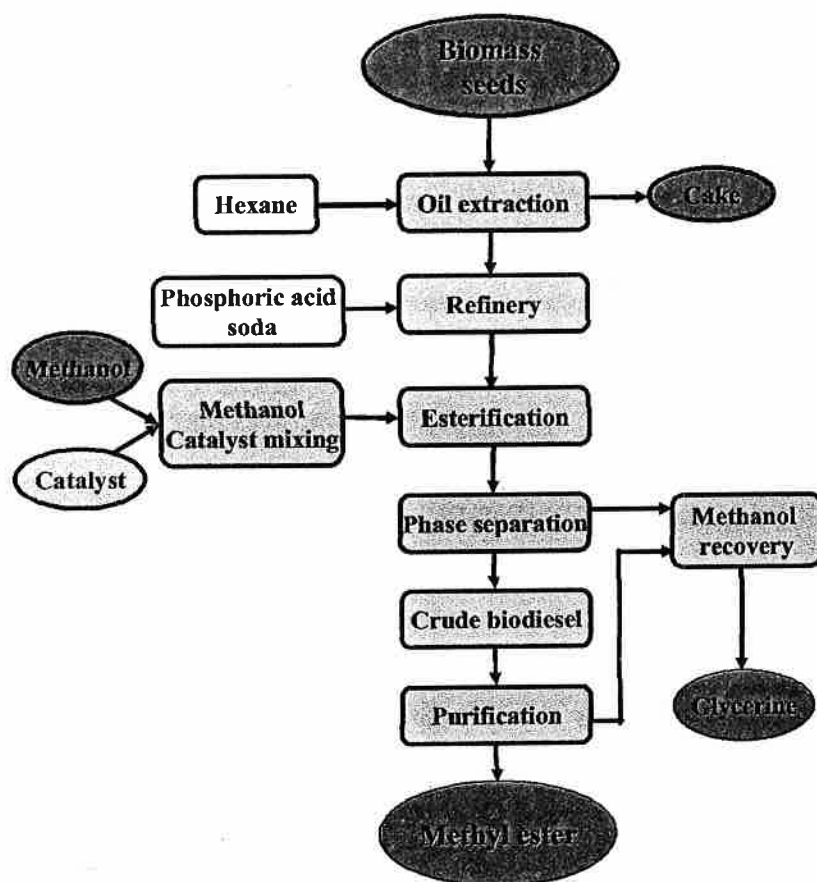


Figure 11: General conversion process for bio diesel production from vegetable oil<sup>49</sup>

Biodiesel can be used in diesel engine, either in pure form or more commonly in 5 to 20 % blend with petroleum diesel.

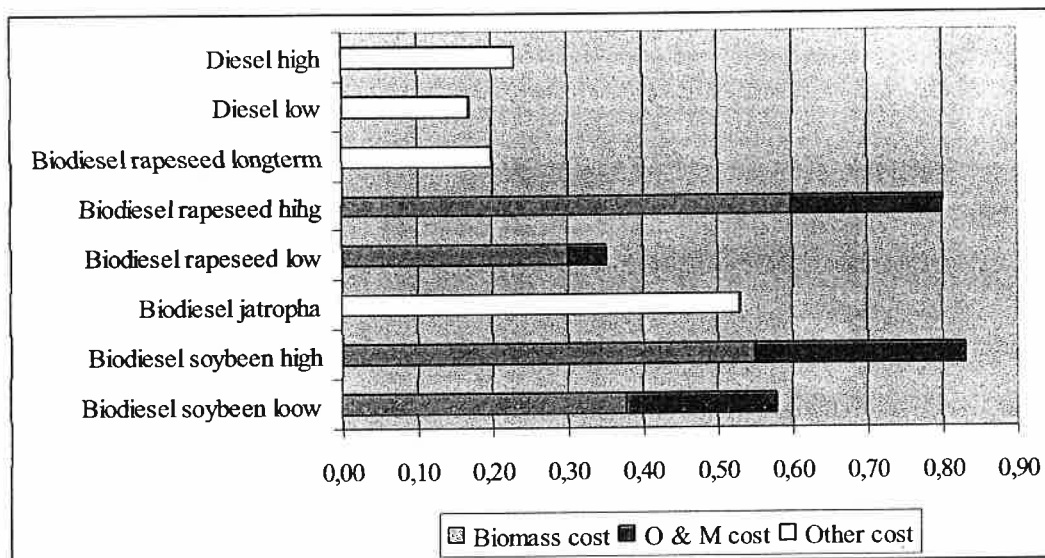
Though pure biodiesel can be used in unmodified diesel engines, technical and economic barriers restrict this practice. They include: seals material compatibility, cold weather freezing, storage stability and NOx emissions. The blending with petroleum fuel offers the best commercial potential because of better performance and lower costs up to now.

Esterification is highly efficient with yields exceeding 99% (methyl ester / oil) with total average production cost relatively little affected at this stage (not including oil production) by feedstock costs, economies of scale, or even investments in processing technology.

News routes are under investigation in Canada and US, particularly to convert biomass oil into hydrocarbon fuel, using conventional existing petroleum refinery technology with minor modification. This approach would allow significant cost reduction as existing infrastructure would be used. However, technical limits in terms of biomass oil refining volume share and the feedstock quality requirements are still unclear.

### 3.2.2. Economics of biodiesel production by esterification

Seeds cost shares the largest part of biodiesel production costs from 60 to 80 % of the total cost<sup>13</sup>. Seeds production costs vary widely depending on where the crop is grown: quality of soils and seeds, climate, quantity and prices of fertilizers and pesticides... all elements which will affect yields and production cost.



NB: Diesel oil costs are full cost fluctuation depending on the oil price. Long-term cost on biodiesel is an estimate on the basis on better use of co-products

Figure 12: Biodiesel production cost breakdown (Europe, USA and India)<sup>50 51</sup>

Glycerine is an unavoidable co-product of biodiesel. At current glycerine market prices, glycerine credit reduces biodiesel cost in the range of 0.05 to 0.1 US\$/l of biodiesel in the EU. A large biodiesel expansion would flood the international market with glycerine. Therefore the development of new applications for glycerol would allow a rapid growth of the biodiesel industry.

For a 150 to 200 million litres per year conventional plant, total non-feedstock production costs will be less than 5 c\$ per litre of biodiesel, representing only 7 to 15% of the total production cost depending on the feedstock price.

Some systems use fixed catalysts, which reduce variable costs but raise fixed costs. Some systems are catalyst free, which might save as much as 5 c\$/l in processing costs, but raise capital and energy costs because these systems tend to be high pressure and temperature<sup>16</sup>. Even if non feedstock costs could be reduced by half, the savings are generally not enough to make biodiesel competitive with diesel fuel because of feedstock costs as illustrates figure 12 above.

The amount and value of the co-products play a critical role in the seed oil prices as the price of oilseeds, cake and oil are intrinsically bound together. Producing or crushing seeds of high oil content is not



necessarily cheaper than producing or crushing seeds with a lower oil content, all other things being equal depending on the credit that co-products offer.

Costs might be lower with biodiesel produced from waste oils or fats. However, limited availability of this feedstock would limit the volume of biodiesel production and probably result in small scale implementation with higher non feedstock production costs.

Table 8 below presents investment costs as a function of plant capacity. It shows that except for small size, the economies of scale between medium and large plants are limited.

Plant size (10 <sup>6</sup> l/year)	Low		High	
	Total investment cost (10 <sup>6</sup> US\$)	Specific investment cost (10 <sup>6</sup> US\$/10 <sup>6</sup> l)	Total investment cost (10 <sup>6</sup> US\$)	Specific investment cost (10 <sup>6</sup> US\$/10 <sup>6</sup> l)
4	1.9	0.475	3.1	0.775
60	9.5	0.158	15.8	0.263
150	19.7	0.131	32.8	0.218

Table 8: Capital cost estimates as a function of scale (Kearney, 1998) cited by<sup>13</sup>

Integrated biodiesel/livestock producers will need to weight the value of local cake supplies, to determine if they are putting themselves at a disadvantage with other livestock producer's vis-à-vis production costs. In addition, any excess cake will also have to compete with other feed on the international market. Frequently, transportation cost savings can make some projects viable in specific locations which would probably be the case in many developing countries.

### 3.3. Advanced biofuel synthesis

Promising routes to convert biomass into liquid are by means of gasification associated to syngas conversion as all biomass compounds, hemi cellulose, cellulose and lignin, can be converted into a H<sub>2</sub>/CO rich gas. Among obtainable fuels are methanol, diesel and gasoline through FT synthesis and dimethylether (DME). Several comprehensive and well documented publications have been recently released on the subject by IEA<sup>5</sup>, ECN<sup>2</sup>, and the European joint research centre ISPRA<sup>52</sup>. If they do not focus on developing countries they nevertheless constitute a major source of technical information. The following review draws on these publications.

The general scheme of this process also known as biomass to liquid (BTL) route is summarized in figure 13. The thermo-chemical routes start from a biomass feedstock which is converted into a syngas by means of different steps consisting in:

1. Pretreatment/upgrading of biomass
2. Conversion of the biomass feedstock to a CO and H<sub>2</sub> rich gas
3. Gas cleaning and conditioning
4. Synthesis.

First steps of the process would remain quite similar whatever is the final product. Only the gas conditioning to adapt the  $H_2/CO$  ratio and particularly the synthesis will be specific to the targeted fuel, i.e. methanol, FT diesel or DME.

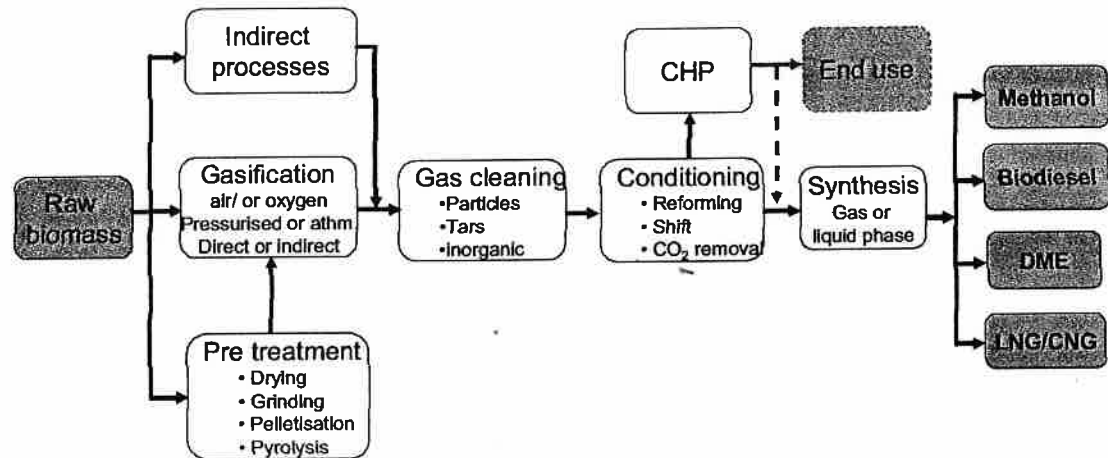


Figure 13: General biomass gasification conversion scheme to biofuels

As LNG or CNG would require adaptations of both the vehicle engine and the refuelling infrastructure, its potential interest would probably be limited to countries already equipped for LNG or CNG consumption (Italy...), where the biomass route will hardly compete with natural gas. So we won't further detail on LNG/CNG from biomass.

### 3.3.1. Biomass gasification technologies

To convert a biomass feedstock into a suitable gas for the synthesis of transport fuel, a gasification process is applied, either air/oxygen gasification, steam gasification or more advanced processes like gasification in supercritical water. The gasification process yields a  $CO/H_2$  rich gas. Depending on the oxidation agent (steam or air-oxygen), the overall maximum stoichiometry of the reaction of biomass will drive the overall gas composition based on the following reactions:

- Steam reforming:  $CH_{1.47}O_{0.67} + 1.33 H_2O \rightarrow CO_2 + 2.07 H_2$
- Air-oxygen gasification:  $CH_{1.47}O_{0.67} + 0.665 O_2 \rightarrow CO + 0.735 H_2$ , followed by the shift reaction:  
 $CO + 0.735 H_2 + H_2O \leftrightarrow CO_2 + 1.735 H_2$

Typical hydrogen yields are 170 kg  $H_2$  per ton of biomass for steam reforming and 140 kg  $H_2$  per biomass ton for oxygen gasification followed by a shift.

In the case of direct gasification processes, the heat necessary to the process is produced by the internal sub-stoichiometric combustion of part of the biomass fed into the gasifier. Both air-blown and pure oxygen biomass gasifiers are used for direct gasification. When oxygen is used, a nitrogen-free synthesis

gas is produced, but the use of oxygen leads to higher investment costs and minor global energy efficiency.

Indirect gasification processes use heat that is generated by burning part of the biomass outside the gasifier or that comes from an external source of energy. The heat is generally fed to the gasifier with steam. Using steam increases the hydrogen content in the raw gas. However, due to the low temperatures applied the tar content in the gas is still rather high.

R&D is still needed on pure biomass feedstock, and a number of process configurations are being experimented. Nevertheless, the gasification route for syngas production is already demonstrated by:

- SVZ<sup>53</sup> (Germany) producing methanol from different types of biomasses and coal,
- Sasol<sup>54</sup> (South Africa) for Fischer Tropsch synthesis from coal.

#### **Sasol (South Africa).**

*The firm has built a series of Fischer-Tropsch coal-to-oil plants, and is one of the world's most experienced synthetic fuels organisations and now marketing a natural-gas-to-oil technology. It has developed the world's largest synthetic fuel project, the Mossas complex at Mossel Bay in South Africa that was commissioned in 1993 and produces 25 000 barrels a day. To increase the proportion of higher molecular weight hydrocarbons, Sasol has modified its original reactor to operate at higher pressures. Sasol has commercialised four reactor types with the slurry phase distillate process being the most recent. Its products are more olefinic than those from the fixed bed reactors and are hydrogenated to straight chain paraffin. Its Slurry Phase Distillate converts natural gas into liquid fuels, most notably superior-quality diesel using technology developed from the conventional tubular fixed-bed reactor technology.*

*The resultant diesel is suitable as a premium blending component for standard diesel grades from conventional crude oil refineries. Blended with lower grade diesels it assists to comply with the increasingly stringent specifications being set for transport fuels in North America and Europe. The other technology uses the Sasol Advanced Synthol (SAS) reactor to produce mainly light olefins and gasoline fractions. Sasol has developed high performance cobalt-based and iron based catalysts for these processes. The company claims a single module or the Sasol Slurry Phase Distillate plant, that converts 110 Terajoules per day of natural gas into 10 000 barrels a day of liquid transport fuels, that can be built at a capital cost of about US\$250 million. This cost equates to a cost per daily barrel of capacity of about US\$25 000 including utilities, off-site facilities and infrastructure units. If priced at US\$0.50/MMBtu, the gas amounts to a feedstock cost of US\$5 per barrel of product. The fixed and variable operating costs (including labour, maintenance and catalyst) are estimated at a further US\$5 per barrel of product, thereby resulting in a direct cash cost of production of about US\$10 a barrel (excluding depreciation).*

For several decades, different types of reactors have been developed for biomass gasification, such as fixed beds, fluid beds and entrained beds. It is important to consider that many of the gasification concepts were originally developed and optimized for the production of electricity with gas quality requirement less strict than for the optimal production of syngas.

#### **3.3.1.1. Fixed bed gasification**

Fixed beds operate at temperatures between 700 and 1200°C with slagging at these temperatures. They can be either co-current or countercurrent, depending on the flow directions of the solid flow and the gas stream. Co-current reactors are able to produce a gas relatively clean of tar content, in contrast with the

counter-current gasifier type. However the latter is less critical with respect to the biomass feedstock quality. As the original Lurgi gasifier (see figure 14), fixed bed gasifier has to be considered for syngas production only at large-scale mainly for cost reasons.

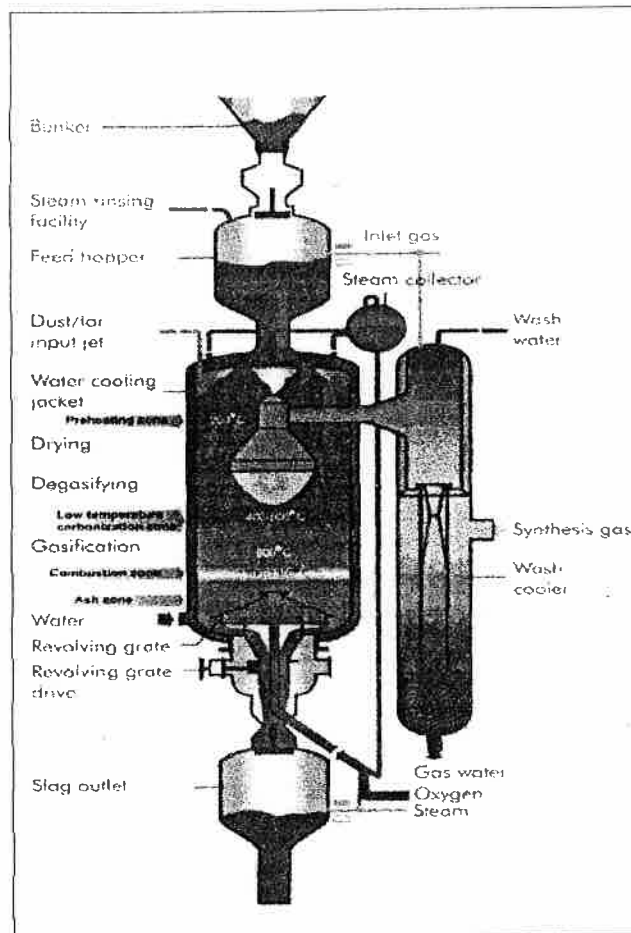


Figure 14: Pressurized Solid Bed Gasifier with Revolving Grate (original Lurgi gasifier)<sup>55</sup>

### 3.3.1.2. Fluidised beds systems

Fluid beds (FB) are used at the levels of research and demonstration not ready yet under full commercial conditions for applications requiring very high quality gas. The gasification bed contains a mixture of biomass with a hot material (sand). The reaction takes place in the whole reactor volume. The temperature, which is uniform throughout the bed, can be controlled by changing the air-biomass ratio. The reaction temperature is limited (below 1000°C) to avoid bed agglomeration, particularly with ashy biomasses. Fluidised bed reactors are more tolerant than fixed bed's regarding the biomass used as small biomass particle can be used, but due to the relatively low temperature tar and methane concentrations are rather high, compared to fixed bed. The gas cleaning step requires intense removal.

For large scale applications circulating fluidized bed (CFB) design are preferred as it is a robust and fuel-flexible technology, which can be applied for scales up to several hundreds of megawatts, whereas at a small scale (50 megawatts) a bubbling bed seems to be more suitable. In most cases, air is used as the fluidizing medium.

For syngas production dilution by nitrogen needs to be avoided and steam is preferred to air, air-oxygen gasification is appropriate for electricity production. Ongoing research on FB, catalytic steam reforming using fast pyrolysis oil, methanol or ethanol as a feedstock, devotes major attention to optimal catalyst development.

### **3.3.1.3. Entrained flow reactors**

They operate in the absence of bed material at a very high temperature (1,500°C) and produce tar-free syngas. However, the process requires very small biomass particles as input. As a result of the high temperature, hydrogen concentration in the produced gas is higher, and tar/methane concentrations become negligible.

Therefore various demo- and commercial-scale entrained flow reactors for biofuel production are developed in Europe, using solid and liquid fossil fuels. These plants are rapidly described in the frame below.

As already mentioned, biomass pre-treatment and conditioning by a pyrolysis step (torrefaction or fast pyrolysis) may improve the feasibility of the concept. FZK in Germany use coal gasification tar residues as a feedstock in a former Chemrec Process/ Babcock Borsig Power design entrained flow reactor to produce methanol.

On black liquor, gas composition achieved at low and high pressure gasification is given in the table 8 and compared to steam gasification results.

### **3.3.1.4. Two-stage gasification systems**

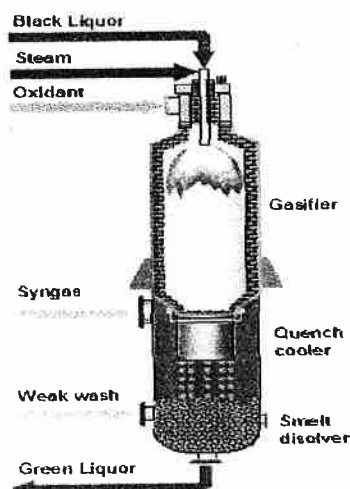
Two stage systems consist of two physically separated reactors to improve the control of the different reactions: pyrolysis, oxidation and reduction, and therefore the gas quality. This technology has been successfully demonstrated at relatively small scale for electricity generation on the fixed bed system Viking and TK Energy (Denmark), on the fluidised bed system of the Batelle Institute (USA) and on the Repotec<sup>56</sup> Forced Internal Circulation Fluidized Bed (FICFB) plant originally invented by the University of Vienna (Austria), see figure 15. For those last two concepts air is used for the oxidation step (providing process heat), and in a separate step biomass is gasified with steam. An advantage of this type of gasification process is that it produces an almost nitrogen- free gas without the use of oxygen anywhere in the process.

Main innovation in the FICFB process is its ability to produce a medium calorific value gas without the use of oxygen. The process employs a catalytically active circulating fluidized bed of solids that can reduce tar in the raw gas. The raw gas is further processed to produce syngas for tests at the laboratory scale in methane production loops and Fischer Tropsch units.

End of 2004, the gasifier had been operating for more than 14,000 hours and the total operating time with the integrated gasifier and gas engine is about 11,000 hours. Characteristics and performances of the FICFB Güssing demonstration CHP plant are widely published.

#### CHEMREC AB, SWEDEN

The Chemrec process, see figure below, was developed in Sweden in late 80s for the gasification of black liquor (a product comparable to fast pyrolysis oil). Since then various demonstrations have taken place. It can be operated at high pressure or slightly above atmospheric pressure. The reactor is similar to the Texaco gasifier. Under high pressure conditions, black liquor is injected with oxygen, into a 30 bar and 950°C reactor to gasify the cellulose and lignin components and slag the inorganic. The favourable reaction kinetics in the gasifier is maintained through a catalyst (Na and K) and results in low methane content compared to normal gasification of biomass. In the low-pressure Chemrec process, black liquor is gasified with air. The high-pressure Chemrec process is operated with oxygen. The slag is recovered from the gas stream at the bottom of the gasifier by quenching with condensate.



A few percent of sulfur, as  $H_2S$ , is in the gas with the low-pressure system while approx 60% of sulfur leaves with the produced gas in the high-pressure system. At present the booster system (based on air-blown entrained flow gasification at atmospheric pressure), which increases the black liquor recovery rate, is commercially available.

The black liquor gasification combined cycle (BLGCC) system, based on oxygen-blown entrained flow gasification at 15 bar, is at a development phase, as well as the system, for black liquor gasification for producing alternative motor fuels and hydrogen (BLGAM/ $H_2$ ), based on oxygen-blown entrained flow gasification at 30 bar. The first plant of such type for methanol, DME and hydrogen, situated at the Kappa Kraftliner mill in Pitea, Sweden, started in May 2005. The overall efficiency of biomass to methanol conversion of the plant is predicted to be 65-75%, slightly higher than the FT synthesis with the same reactor.

Source: adapted from Kavalov and Peteves

	Chemrec Low Pressure Air	Chemrec High Pressure O <sub>2</sub>	FICFB Steam
Reactor Temp, °C	950	950	900
Reactor Pressure, bar	2	30	atmospheric
Air / O <sub>2</sub> feed, t/tds	2.2	0.34	-
Gas Composition (vol. %):			
CH <sub>4</sub>	0.26	1.4	8 - 12
CO	8.0	37.9	20 - 30
CO <sub>2</sub>	16.7	18.8	15 - 25
COS	-	0.04	-
H <sub>2</sub>	11.5	40.0	30 - 45
H <sub>2</sub> S	0.26	1.9	20 - 50
NH <sub>3</sub>	0.01	0.00	500 - 1000
N <sub>2</sub>	61.8	0.23	1 5
HHV (MJ/m <sup>3</sup> , dry, 15°C)	2.6	10	-
Tars	n.a.	n.a.	0.5 - 1.5
Particles	n.a.	n.a.	10 - 20

Table 9: Gas quality as function of the feedstock and operating conditions <sup>57 58</sup>

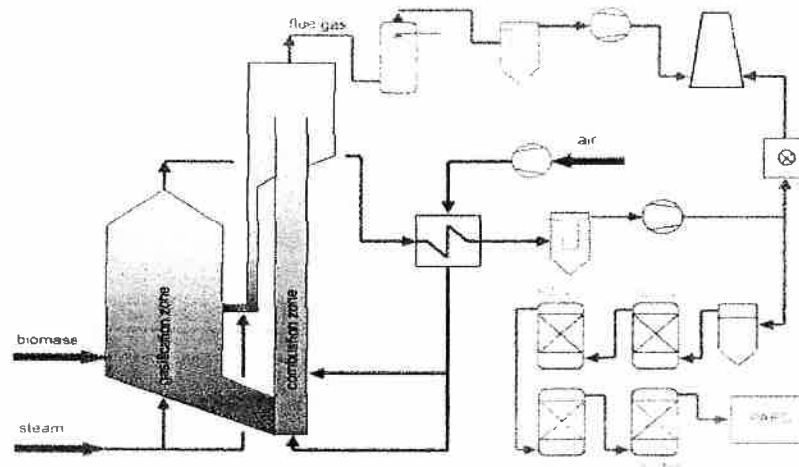


Figure 15: FICFB Gasification Process <sup>59</sup>

### 3.3.1.5. Further innovative concepts

Other advanced technologies are currently under research. The hydrogen rich gas they are expected to produce may allow biofuel synthesis with a straightforward appropriate H<sub>2</sub>/CO ratio. Because they are very advanced technology they will be only rapidly mentioned hereafter.

- Supercritical gasification is a concept that would be dedicated to the conversion of relatively wet biomass (>50% moisture) at high pressures, above 300 bars and moderate temperatures (500-700°C). Under these conditions, the biomass is dissolved in the water and is converted into a



hydrogen rich gas. The raw gas may contain about 60 v% of hydrogen and the gas would be available at a high pressure. This concept is still at an early stage of development and several weak points need to be solved like plugging, heat transfer, effect of catalysts, etc.

- Thermal cracking of bio-oil under high temperatures comparable to the thermal decomposition of methane.
- Molten salt/metal bath technologies consisting in the injection of biomass in an extremely hot bath to instantaneously and completely convert hydrocarbons to hydrogen and CO.

The number of projects aiming at producing syngas from biomass by thermo-chemical processes is limited, but they are significantly increasing since a couple of years, in a number of countries, particularly in Germany, and new advanced systems are being developed with a complete biofuel production scheme.

### **3.3.2. Indirect routes**

During the 1980s, several laboratories carried out research on the Hydro Thermal Upgrading process. The biomass reacts in liquid water at a high pressure (120 - 180 bars) and a relatively low temperature (300 - 350°C). It decomposes in water to produce a crude oil-like liquid called 'bio-crude'. As the biomass does not have to be dried, these processes were particularly adapted to wet biomass such as pulp or sludge. The main product of the reaction is a liquid with a mass yield of about 50%, it also produces 30% gases. Objectives of this process were similar to those of fast pyrolysis, aiming at concentrating the energy of the biomass into a higher energy density fuel.

This principle associated with the catalytic hydro-de-oxygenation techniques which consists in reducing the oxygen content of hydrocarbons to make them similar to conventional transport fuels, was applied with the objective of upgrading the liquids so as to use them as a regular fuel.

None of these technologies are completely technically proven. One of the main concerns is the catalyst stability and life time of the hydro cracking step. Moreover both results lead to unacceptably high costs.

### **3.3.3. Syngas cleaning and conditioning**

The synthesis gas resulting from any thermo-chemical biomass conversion system contains carbon monoxide, carbon dioxide, hydrogen, methane, water and may contain nitrogen. The composition of syngas varies depending on raw biomass composition and operating conditions as illustrated in tables 10 and 11. Typically syngas would need further cleaning as it is contaminated by impurities, and conditioning like shift reaction to adjust its composition in terms of H<sub>2</sub> and CO. Basically, these operations are similar to the existing systems for coal- or natural gas-based systems.

One aspect of special importance is the presence of tar in the raw gas, with a much higher concentration and a wider composition when biomass has been gasified rather than coal. Last two decades, enormous effort has been put into the development of tar removal/conversion technology with mitigated success.

Gas composition vol. % dry	Air blown atmospherics CFB	O <sub>2</sub> Atmospherics CFB	O <sub>2</sub> pressurized CFB-	Atmospherics H <sub>2</sub> O	O <sub>2</sub> Pressurised entrained flow
CO,	19.3	26.9	16.1	42.5	46.1
H <sub>2</sub> ,	15.6	33.1	18.3	23.1	26.6
CO <sub>2</sub> ,	15.0	29.9	35.4	12.3	26.9
CH <sub>4</sub> ,	4.2	7.0	13.5	16.6	0.0
N <sub>2</sub> ,	44.5	0.7	12.3	0.0	0.4
C <sub>2</sub> ,	1.4	2.4	4.4	5.5	0.0
NCV, (MJ/m <sup>3</sup> )	5.76	8.85	8.44	13.64	7.43
H <sub>2</sub> /CO ratio	0.81	1.23	1.14	0.54	0.58

Table 10: Main components and properties of gases obtained via different gasification concepts<sup>60</sup>.

However, in the case of large scale coal gasification plants, tars are recovered and further converted (FZK) or sold as a by-products (Sasol). That is to say that, depending on the size of the plant, the way of handling problems might be radically different: an almost dead-end tar problem in small scale power generation gasification unit is industrially solved at a large scale and may contribute to further income. Nevertheless, biomass tars are serious problems in biomass gasification systems, responsible of corrosion and soot formation as a result of partial combustion or polymerisation reaction at high temperatures. Tars are removed by cleaning devices like fabric filters or scrubbers under dry and hot or wet and cold conditions.

The gas also contains other contaminants like small char particles, chlorides, sulphur, alkali metals and nitrogen compounds as illustrated in table 10. These contaminants would decrease the catalyst activity in the gas reformer, the shift and synthesis reactor and may cause corrosion and fouling problems in heat exchangers and pipes.

Contaminants	Concentration (Wt%) <sup>61</sup>	Concentration (Wt%) <sup>62</sup>	Estimated gas cleaning spec. (ppb)
Particles		1.33	0
HCN & NH <sub>3</sub>		0.47	20
H <sub>2</sub> S & COS		0.01	10
Alkalis		0.1	10
HCl		0.1	10
Pb & Cu		trace	not known
Tars (g)		0.05 to 5	0

Table 11: Syngas impurities content and maximum concentration gas cleaning specification.

Impurities can be removed using conventional cold gas cleaning trains including cyclones and scrubbers. However, the very strict requirements of the synthesis catalysts make the gas cleaning step the major challenge for the coming years. More advanced and efficient but still not proven, hot gas cleaning devices using hot gas filters and catalyst are considered. The two basic concepts are shown in figure 16.

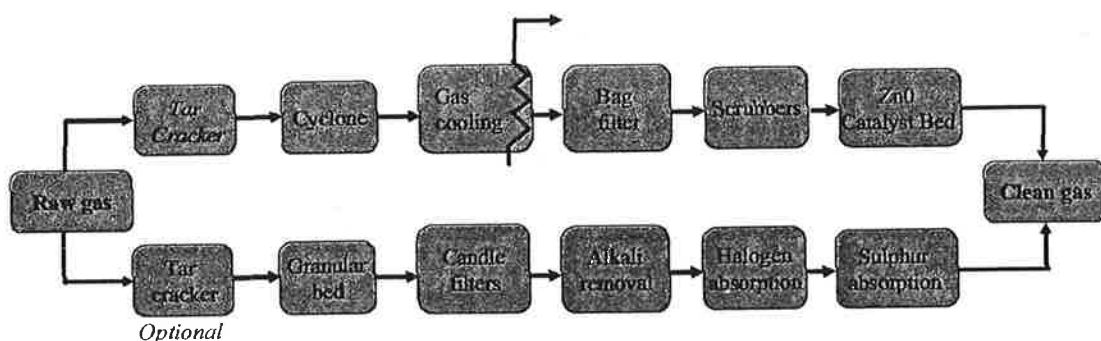


Figure 16: conventional and advanced syngas cleaning principles<sup>63</sup>.

The cold gas train feasibility has been demonstrated on Sasol coal gasification. Alkali and the largest part of the sulphur content and the nitrogenous contaminants are removed by scrubbing; the catalyst is able to reduce the gas sulphur content below downstream requirements. The hot gas treatment offers better energy efficiency with the gas conditioning high temperature step. Particulate removal is very efficient and has been proven on the Vamamo plant<sup>63</sup>.  $\text{SO}_x$  and  $\text{NO}_x$  can be removed by sorbent. However some inorganic compounds remain gaseous at this temperature and can't be removed. Different catalyst train are also experimented to efficiently remove  $\text{NH}_3$  or sulphurs.

After being cleaned, the syngas is conditioned. Further steps then include processes like  $\text{CO}_2$  removal and reforming. During the conditioning step, the gas hydrocarbons are converted by steam reforming to  $\text{H}_2$  and  $\text{CO}$ , over a nickel catalyst. Auto thermal reforming is preferred as it is cheaper to operate. However, coking may occur, the prevention of which would require higher steam consumption.

$\text{H}_2$  and  $\text{CO}$  must be available in the ratios of 3/1 for methanol production, and 2/1 for FT synthesis. As illustrated in table 13, the proportion of hydrogen in the raw gas is usually lower than required. Therefore, the proportions of these two components must be adjusted via a water-gas shift reaction.

The  $\text{CO}$  reacts with water to produce  $\text{CO}_2$  and  $\text{H}_2$ . The  $\text{CO}_2$  is removed afterwards by means of chemical or physical absorption. The synthesis gas is compressed and transported to the final synthesis reactor. The synthesis reaction will be developed hereafter. Biofuels produced by gasification and synthesis processes would be very clean fuels as the syngas cleaning and conditioning steps are very demanding.

### 3.3.4 - Methanol production from biomass

Conventional methanol reactors use fixed beds of catalyst and operate in the gas phase. Processes under development are mainly slurry technologies which have a higher efficiency and eliminate the need for a gas recycling loop, in contrast to conventional fixed bed reactors. In liquid phase processes a mix of  $\text{H}_2$  and  $\text{CO}$ , the produced methanol and the catalyst is suspended in a liquid allowing a very efficient heat transfer between the solid catalyst and the liquid. These processes are able to reach conversion of up to 95% methanol. Several reactor types are available as the process is well known from petroleum companies. From biomass however, the main concern will be the gas quality. Indeed, in order to protect the copper catalyst, the syngas must be cleaned thoroughly to meet the very stringent process

- requirements. The process is generally implemented with a combined cycle gas turbine where the purge gas is utilised for electricity generation.

Methanol can be used as such; however it also can be converted to produce hydrocarbons. The better known methanol-based route is the Mobil process. Mobil's methanol to gasoline (MTG) process was commercialised in 1985 in New Zealand. In the conversion, a number of reactions take place. Methanol reacts on the ZSM-5 zeolite catalyst to produce first DME, which then gives hydrocarbons with up to ten carbon atoms. The Mobil fluid bed process demonstrated in Germany was able to produce 15.9 m<sup>3</sup>/day of gasoline. Methanol was converted to 88% gasoline, 6.4% LPG and 5.6% fuel gas when operating at 413°C and 2.75 bar. The feed was raw methanol with 27% mol. water. The heat evolved was 1.74 MJ/kg of methanol, recovered through heating oil tubes immersed within the bed<sup>64</sup>. Methanol cost contributed about 90 percent of the total cost of producing MTG gasoline<sup>65</sup>. This percentage can be kept to compute the price of MTG gasoline and compare it with the current price of gasoline in various countries.

One of most attractive application of methanol is related to its very high hydrogen to carbon ratio. Methanol is considered as potential hydrogen carrier for on board reformer in fuel cell technologies on the long term. If methanol might be of interest from natural gas, the Fischer Tropsch (FT) synthesis appear more appropriate considering the syngas composition and its ability to produce diesel as will discuss later.

### 3.3.5 - Fischer-Tropsch (FT) Liquids

Conversion of the syngas to liquid hydrocarbon is a chain growth reaction of carbon monoxide and hydrogen by means of a catalyst. The principle of the mechanism is:



The catalyst is either iron- or cobalt-based and the reaction is highly exothermic. The temperature, pressure and catalyst determine whether a light or heavy product is synthesized. For example at 330C mostly gasoline and olefins are produced whereas at 180 to 250C mostly diesel and waxes are produced. Indeed, the synthesis results in a wide range of products as illustrated in figure 17. Therefore the main performance of the process will be related towards its selectivity. For diesel production a high degree of selectivity is required which can be achieved with high reactant partial pressure. Any gas contamination by nitrogen (air blown gasifiers) will be therefore detrimental to high biodiesel selectivity.

There are mainly two types of FT reactors to produce biodiesel. The vertical fixed tube type reactor has the catalyst in tubes that are cooled externally by pressurised water. For a large plant, several reactors in parallel may be used presenting energy savings. The other process is a slurry phase reactor in which pre-heated synthesis gas is fed to the bottom of the reactor and distributed into the slurry consisting of liquid wax and catalyst particles. As the gas bubbles upwards through the slurry, it is diffused and converted into more wax by the FT synthesis. The heat generated is removed and the steam generated is used in the process. No clear indications are provided on the superiority of one design to the other as both present advantages and drawbacks. The lack of experience of the FT synthesis from syngas explains this uncertainty. Hamelinck<sup>63</sup> in his PhD thesis reviews the main differences between fixed bed and slurry phase reactors.

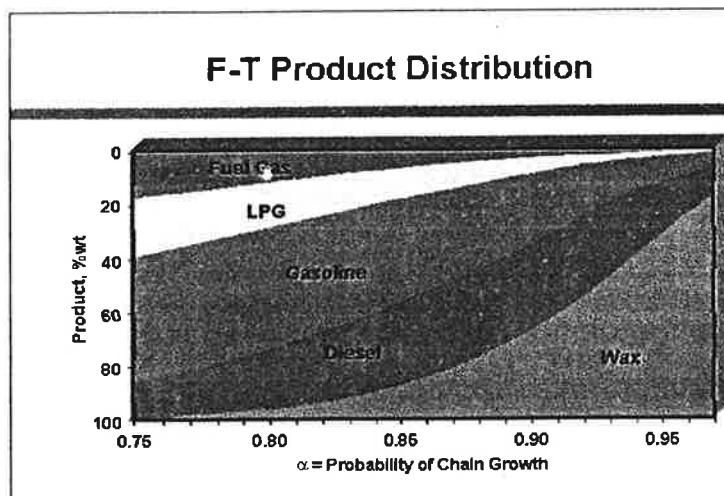


Figure 17: Fischer Tropsch product distribution<sup>66</sup>.

Due to the high level of wax formed, a hydro cracking step is required to catalytically convert wax into diesel by hydrogen addition. When operating under the diesel mode, up to 60% diesel is achieved (the balance is 15% Naphtha and 25% Kerosene). The overall carbon efficiency of the hydro-cracking step is close to 100%<sup>63</sup>. Reflecting its origins, FT processes produces diesel fuel with an energy density comparable to conventional diesel, but with a very high level of purity compared to oil-derived diesel and a higher cetane number permitting a superior engine performance. The cetane Number indicates how quickly the fuel will auto-ignite, and how evenly it will combust. Most countries require a minimum cetane number of around 45 to 50. A higher cetane number represents a lower flame temperature, limiting the formation of NOx that contributes to urban pollutions (ozone). FT diesel has a cetane number in excess of 70.

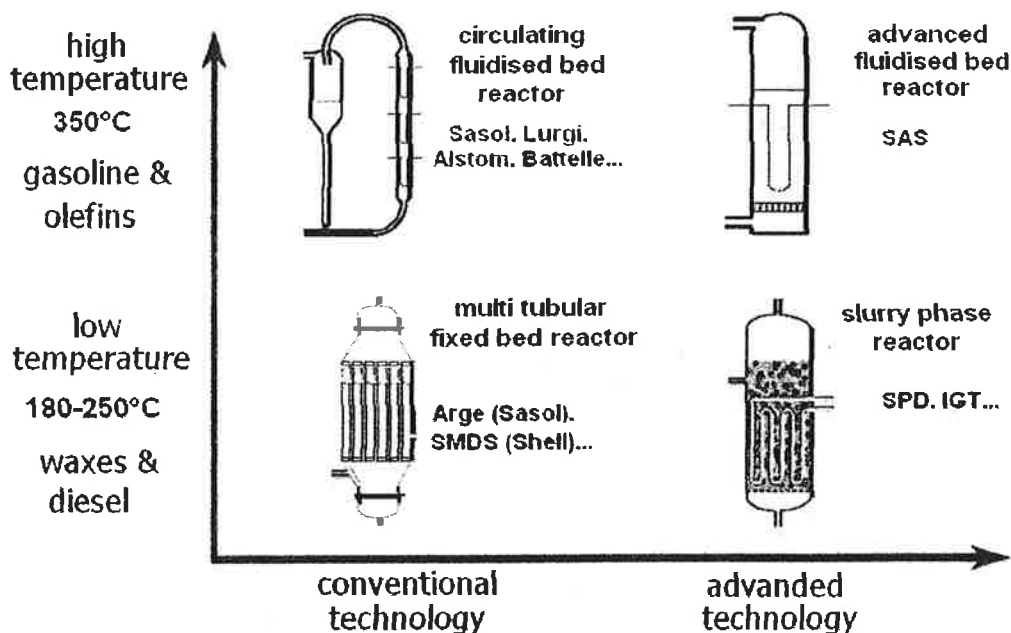


Figure 18: Fischer-Tropsch reactors <sup>67</sup>

At present there are several large R&D facilities under activity in Europe, briefly presented in the frames below to illustrate the description of the technology. Though there is no commercially available biomass to liquid plant operating, increasing interest from the European commission and the industrialists should rapidly bring this technology to maturity. The plans of the Choren Company are indeed the set up of 1 million tons of annual BTL capacity in Germany by year 2010.

**CHOREN INDUSTRIES GMBH, GERMANY** The BTL demonstration activities of Choren GmbH began in 1998 with the construction of a 1 MW pilot plant in Freiberg, Germany. A high temperature oxygen-blown slagging entrained flow gasification, developed by Choren in 1994 and patented in 1995 as the Carbo-V<sup>®</sup> process is used. The claimed thermal efficiency of the Carbo-V<sup>®</sup> process is 95-98 %, while the gasification efficiency is stated as 82 % for capacities larger than 10 MW. The experiments started with pre-gasification of clean wood, waste and coal. More recently, the use of pyrolysis slurry from herbaceous biomass has been investigated. The BTL automotive fuels option was added to the plant in 2002. With the support of the German Ministry of Economics and with the Cooperation of Daimler-Chrysler A.G. and Volkswagen, the first quantities of BTL fuels from wood chips were produced in 2003-2004. Under the methanol programme, totally 11,000 litres were produced in April and May 2003, while the first quantities of F-T liquids were produced in June 2003. In October 2003 Choren began the construction of its first industrial plant for manufacturing 15,000 tons of BTL fuels per year (the beta-plant), which is due for completion in 2005. Besides the co-operation of large corporations such as Daimler-Chrysler A.G. and Volkswagen A.G., the BTL activities of Choren are strongly driven by the exemption from fuel tax of all renewable automotive fuels in Germany, which will be valid until 2009 so far.

15 tons of bio oil have been shipped by Dynamotive for test purpose and significant production of biosyngas.

Source: adapted from Kavalov and Peteves<sup>52</sup>, Dynamotive web site<sup>37 78</sup>

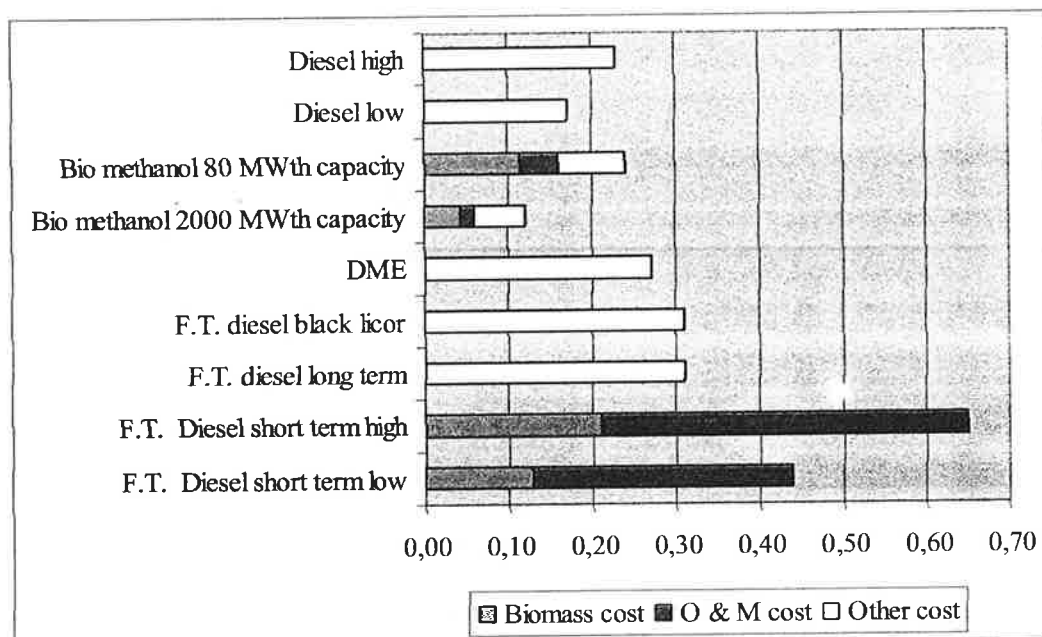
### 3.3.6. DME

DME can be produced directly from syngas in a slurry type reactor similar to the one used for methanol synthesis. It is estimated that approximately three tons of wood are required to produce one ton of DME. As discussed earlier, DME can also be produced from methanol, but the direct production route should be more efficient as it involves one process instead of two.

Before being used as a fuel, DME has been used as a propellant in spray cans. This is still its primary application. It is also used as an ignition improver in methanol engines. Even if the International DME Association expects large, economical supplies of natural gas-derived DME by 2005, it is still at an experimental stage. Being gaseous at ambient temperature, it would require large engine adaptation unless it is blended with LPG.

### 3.3.7. Economics of second generation biofuels

Key parameters influencing biosynfuels competitiveness are capital costs, operating costs of the plant with considerable scale effect, and feedstock costs. Figure 19 shows that in most cases biosynfuels are approximately 2-3 times more expensive to produce than conventional petrol diesel. In the short term, FT diesel competitiveness is within reach only when produced from very low cost residual feedstock like black liquor. In all other cases biosynfuels would need tax incentives to be competitive to petrol and diesel.



NB: When no details are provided all production cost are assimilated to other cost

Figure 19: Share of biomass cost in the total biofuel production cost in US\$/l<sup>68 69 2 63</sup>



Figure 19 shows that the feedstock cost can represent up to 60% of the total biofuel cost, depending on whether it is produced from cheap or expensive biomass. Comparing figures of FT biodiesel production costs with those of conventional biofuels is difficult because FT technology is only at an R&D stage of production and application and main data are estimates from natural gas plant figures. As gas treatment from syngas still presents numerous uncertainties, cost estimates along the FT diesel contain a very high degree of uncertainty reflected by the differences between high and low estimates. One of the main advantages of the biosynfuel routes remains that gasification allows for the use of several type of biomass including waste based biomasses.

For the production of 1 ton of FT diesel about 8.5 tons of wood are necessary, representing a yield of about 150 litres of FT diesel by ton of wood. Increasing efficiency is expected and 200 l/t should be reached through advanced gasification technology presenting a more appropriate H<sub>2</sub>/CO ratio. With such performance, fast growing plantation under the tropical climate conditions of various developing countries would considerably reduce FT diesel production cost<sup>70</sup>.

Compared to the estimate on the high side in figure 19, the estimate on the low side includes lower direct feedstock costs and a greater optimisation on fuel chains that can be expected by economies of scale and deeper integration of processes. Benefits in terms of spared capital costs, increased energy efficiency and reduced production costs of large plants are obvious. However, such big plants need large amounts of biomass feedstock, whose cost-efficient delivery is problematic, due to the low energy density of the biomass and its dispersed availability.

Currently capital costs for GTL plant from natural gas (projects) tend to be about twice capital costs of refineries, between US\$20,000 and US\$30,000 per daily barrel of capacity, compared with refinery costs of US\$12,000 to US\$14,000 per daily barrel. Prior to the GTL step, biomass route includes the gasification step which would account for a large part of the total capital cost (as well as operation cost independently from feedstock). If figure 20 shows that the gasification technology allows significant cost reduction between technology trains, its comparison with data of figure 19 show that the syngas step account for about 50% of the total biodiesel production cost.

Direct capital costs of bio-DME and bio methanol plants are supposed to be slightly lower than those of FT plants, due to higher conversion efficiencies thanks to more dedicated process than FT synthesis.

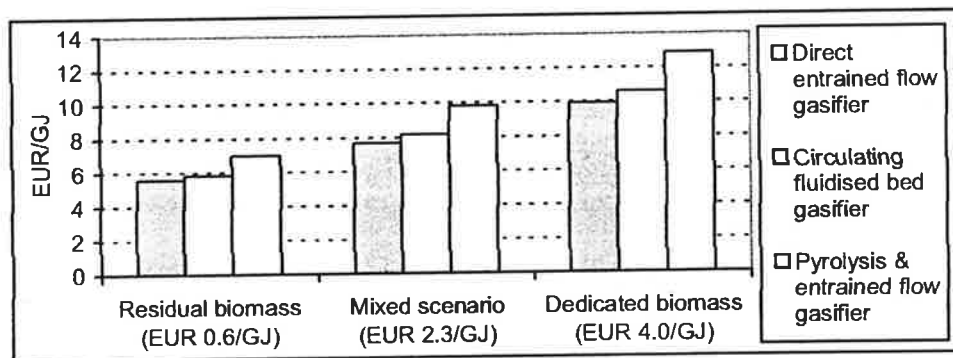


Figure 20: Biosyngas production cost at various biomass costs and depending on the type of gasification<sup>53</sup>.

Nevertheless, even with significant progress in technologies, biosynfuels will remain costly unless biomass preconditioning and homogenisation allow using all types of biomass that surrounds the plant, thus complementing high yield energy plantation. Such situation could be achieved in the developing countries where large quantities of agri-based residues would be sustainably available.

**SVZ Schwarze Pumpe GmbH**<sup>59</sup>: SVZ9 has converted some of the existing former East German era, FDV Process coal gasifiers in Schwarze Pumpe, Germany to convert biomass, coals, and wastes into clean fuel gas and synthesis gas. The plant gasifies a wide variety of waste materials along with low-rank coals in an updraft moving bed gasifier. Waste materials include demolition wood, used plastics, sewage sludge, auto-fluff, MSW, contaminated waste oil, paint and varnish sludge, mixed solvents, tars, and on-site process waste streams. The waste materials are blended with coal at a ratio of 4/1. SVZ has developed an effective feed handling system which employs thermal pre-treatment to convert heterogeneous feed materials to produce a nearly uniform gasifier feedstock. The oxygen-blown, 25 bar-pressurized, 14 t/h FDV process, similar to Lurgi's moving bed coal gasification process, converts the mixed feed stocks to MCV fuel gas or synthesis gas. The raw gas is subjected to conventional (Rectisol) gas cleaning to separate contaminants from the product gas. The SVZ facility has also built a 25 bar pressurized, 35 t/h capacity British Gas Slagging Lurgi gasification system for converting mixed feed stocks to MCV fuel gas or synthesis gas. As is the case with the FDV Process, the raw gas is subjected to conventional gas cleaning to produce a clean product gas and liquid and solid slurry waste stream. The third oxygen-blown, refractory lined gasifier is the FSV 15 t/h entrained flow gasifier, similar to the TEXACO process, which serves the role of a "bottoming" gasifier that effectively treats the hydrocarbons containing waste streams from gas processing into a contaminant-free synthesis gas and mineral slag. If required, a supplementary fuel, i.e. natural gas is used to maintain the reactor temperature in the range of 1,600° to 1,800°C. This process is today owned by Lurgi and called the MPG (Multi Purpose Gasifier). The SVZ plant is a first-of-a-kind integrated gasification, methanol and combined-cycle electricity production plant that converts contaminated and difficult to handle waste materials to clean, value-added products. The high gasification temperatures of up to 1,800°C are high enough to totally remove contaminants in the product gas or gas scrubbing effluent streams. The vitrified slag, the only gasifier waste product, safely encloses any residual pollutants and can be used as construction material.

Extracted from S Babu IEA

### 3.4. Complementarities of biofuels options: the biorefinery concept

As we discussed, economies of scale would be difficult to obtain due to the specificity of the biomass resource. Nevertheless, the capital costs of biofuels technology can be reduced via synergies with other processes like paper mills. The large-scale production of methanol and DME from black liquor which is a by-product from pulp and paper mills is under investigation<sup>71</sup>. Such design would ensure not only higher overall efficiency of the combined pulp/paper & FT manufacturing, it would also earn synergy benefits for both production lines, with the integration of processes.

Synergies with oil refinery processes are also possible. The scope would certainly be to retrofit existing unit so that they accept biomass as primary feedstock or rather to adopt co-processing in some steps of the unit, biomass supplying a relatively small percentage of the raw material as done in co-combustion power plant where biomass represents up to 10% of the feedstock.

Another way of earning synergy benefits and thus, increasing the overall energy efficiency of transport fuels and reducing their production costs, is integration. This integration can be achieved at two levels. The primary source of incomes or/and savings would be the better sales of co and by-products which as indicated previously can represent a large part of the raw material depending on the process. This is particularly true for the FT synthesis. The increasing oil price has a direct impact of energy costs but also

results in a price increase of carbon-based products. Therefore, large biomass processing plant should be designed as biorefinery where various sources of chemicals could be produced in parallel with transport fuels.

The use of pyrolysis liquids as a first step of homogenisation of the feedstock would offer double flexibility: on the biomass that can be used and on the bio-products obtained, whether energy or chemistry, depending on operating conditions. The pyrolysis process can be oriented indeed and would allow intermediate productions which can easily be separated from the main stream to energy products to be further converted into chemicals. Co-products are used as feedstock into an entrained flow reactor for syngas production. In addition, as mentioned earlier, the synthesis of almost all BTL products results in the generation of significant amounts of steam. This steam can be employed for either electricity generation, heat generation, or both. European and USA views slightly differ at this level. While the USA see bioethanol production from cellulose as the core of the refinery activity with pyrolysis and gasification converting residues (lignin), EU rather consider the syngas route as central.

The other argument supporting integration is the wide dissemination of biomass properties and dispersion of its properties. The set-up of a BTL plant would necessitate 1 to 10 million tons of biomass a year depending on the processes. It would be difficult to supply such a plant with a unique source of clean and cheap biomass. One way of limiting biomass transportation hence feedstock costs is by mobilising all biomass sources locally available including waste based products.

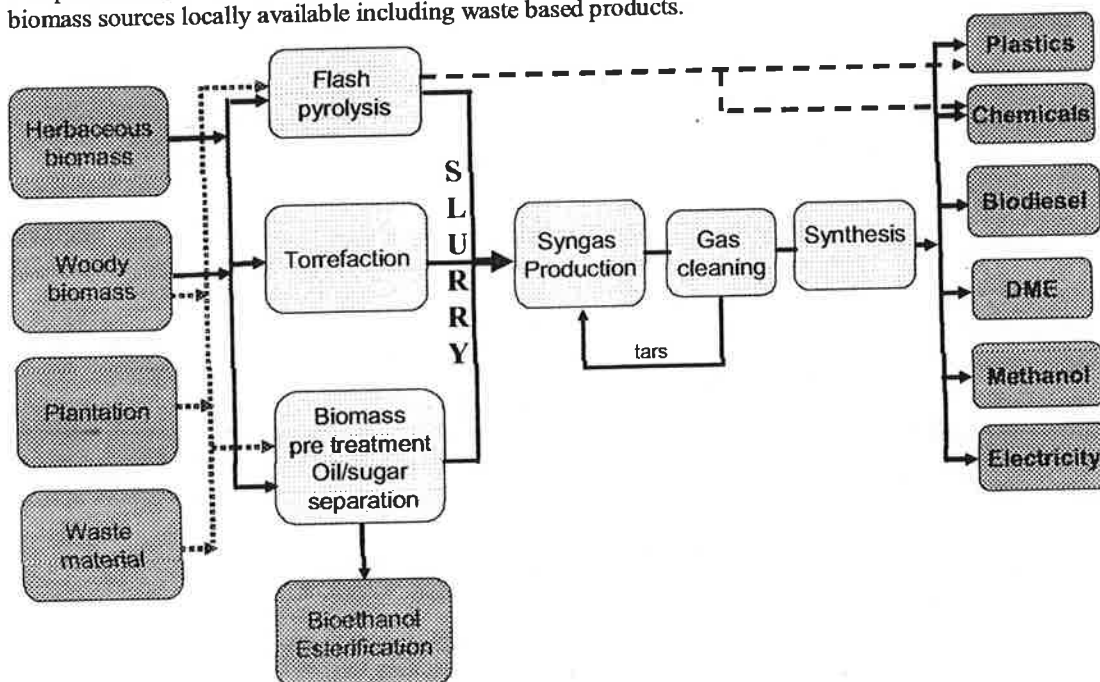


Figure 21: Biorefinery integrated approach

A direct correlation exists between biomass availability and biofuels production cost through biomass delivery costs. Therefore, the optimisation of biomass transportation, storage and handling is the main option to reduce the biofuel production cost.

### 3.5. Biofuel use for transports

Most biofuels present great potential to compare to other transport fuel alternatives due to their ability to be blended with current fuels, blended forms requiring almost no adaptations, neither on engines nor in infrastructure. Low percentage of ethanol such as 5 to 10% is already a common practice in many countries worldwide. It is also the case with biodiesel (esterified) which might be used in pure form like ethanol with minor adaptations. The FT fuels are so close to conventional diesel that they are fully adequate to any blending percentage or can even be used pure. Table 12 lists biofuels properties, in comparison with those of diesel and gasoline

Those properties are linked to the engine emissions. Using biofuels can reduce some of the vehicles pollutants. Compared to the fossil fuels they substitute to, biofuels generally lower carbon monoxide, hydrocarbons, sulphur dioxide and particulate emissions. Their impact on NOx is quite limited. However, due to limited experience with biosynfuels (2<sup>nd</sup> generation), few data are available so far regarding their potential for reducing engine emissions.

GHG emissions are proportional to energy consumption along the supply-chain and its carbon content. Therefore, estimating the net impacts of using biofuels on GHG emissions is a complex issue and requires a full understanding of the fuel chain on a life cycle analysis (LCA), from biomass growing to final use (well to wheels approach). Most studies are on ethanol and biodiesel in the USA or EU contexts, but only few analyse ethanols from sugar pathway and developing countries including Brazil. We won't present any result here as it is done in Larson's background paper on GHG LCA for the GEF/STAP workshop<sup>72</sup>.

Fuel properties	Ethanol	ETBE	RME	Methanol	DME	FT diesel	Diesel	Petrol
Chemical formula	C <sub>2</sub> H <sub>5</sub> OH	C <sub>4</sub> H <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	-	CH <sub>3</sub> OH	CH <sub>3</sub> OCH <sub>3</sub>	C <sub>15</sub> -C <sub>20</sub>	C <sub>12</sub> H <sub>26</sub>	C <sub>8</sub> H <sub>15</sub>
Octane number	109	118	-	110	-	-	-	97
Cetane number	8-11	-	51-58	5	55-60	70-80	50	8
Vapour pressure at 15°C	16.5	28	-	31.7	-	-	-	75
Density (kg/l) at 15°C	0.80	0.74	0.88	0.79	0.65	0.78	0.84	0.75
LCV (MJ/kg) at 15°C	26.4	36.0	37.3	19.8	28.4	44.0	42.7	41.3
LCV (MJ/l) at 15 °C	21.2	26.7	32.8	15.6	18.8	34.3	35.7	31.0
Stoichiometric air/fuel ratio [kg air/kg fuel]	9.0	-	(2)	6.5	9.0	-	14.59	14.7
Boiling temperature [°C]	78	72	12.3 n.a.	65	23	72 (1)	77 (1)	30- 190

NB: flash point at 20°C

Table 12: Biofuels properties compared to conventional fuels.

#### 3.5.1. 1<sup>st</sup> generation biofuels

Ethanol can be used in current spark ignition engines. The octane number of ethanol is higher than of petrol, thus ethanol has better antiknock characteristics. This quality of the fuel can be exploited only if the compression ratio of engines is adjusted accordingly. The oxygen content of ethanol also leads to a higher efficiency, which results in a cleaner combustion process at relatively low temperatures. Compatibility problems between ethanol and some component of the engines like some type of plastics of

metals are well known and progressively solved. As the concentration of ethanol increases adaptation problems may also increase, depending on both the biofuel type and the engine specificities. In Brazil new cars can run indistinctly on fuel with from 0 to almost 100% ethanol. It is also possible to blend ethanol into diesel. However its low cetane number has limited its use in compression engines. The main research goal in diesel- ethanol technology is to identify additives that would help ethanol to ignite by compression. Progresses are reported in this area particularly in the USA<sup>5</sup>.

Regarding engine emissions, the well established improvement is on CO emission which can be reduced by 25% or even more when blended at 10% with gasoline<sup>73</sup> Other pollution impacts of ethanol are less clear still.

Esterified biomass oils are suitable for application in diesel engines as their viscosity, density, and cetane number are similar to those of diesel. Table 12 with properties of rapeseed methyl ester (RME) indicates a higher cetane number for RME compared to regular diesel. This results in a good ignition quality, which means higher engine efficiency and a better prospect for emission reduction. RME density is slightly higher than of diesel, compensating for the reduced energy content of RME to some extent as per volume LCV are closer. This lower value is due to the much higher oxygen content of RME compared to diesel. Because vehicles using RME have, on an energy basis, the same fuel consumption as those running on diesel fuel, this lower energy content leads to larger fuel consumption. Biodiesel can be easily used in existing diesel engine in its pure form or in any blending ratio. Unlike ethanol though, the use of biodiesel in pure form requires minor engine adaptation as it is not compatible with some types of synthetic and natural rubbers. Biodiesel properties are related to the oil they come from. RME and soy methyl ester present better freezing point properties than palm oil methyl ester for instance.

Biodiesel have similar properties than diesel. However they shown better lubricity, no aromatic or sulphur contaminant and higher cetane number which allow lower emissions of most of the pollutants common with petroleum products. US Environment Protection Agency (EPA) reported that the potential for emission reduction of a fuel is almost linear to its biodiesel concentration, with the exception of NOx<sup>74</sup>. One of the major advantages to compare to diesel is its ability to reduce SOx emissions. Sulphur which increase lubricant properties of diesel can be replaced by a small quantity of biodiesel. However, this may require high concentrations of biodiesel depending on the goal sought after.

### 3.5.2. 2<sup>nd</sup> generation biofuels

Methanol can be applied in almost any vehicle type and can be used as a neat fuel or mixed with hydrocarbons. As shown in the table, methanol has a low cetane number indicating poor ignition quality which means that, as for ethanol, its use in compression ignition engines will be difficult. Methanol density is higher than of petrol. However, the calorific value is 50% lower than petrol. Because it is poisonous, extra precautions are needed making its use difficult. An existing petrol or diesel tank at a refuelling station can be retrofitted to handle methanol for 20, to 32,000\$. The capital costs of adding methanol storage and dispensers to an existing petrol station higher would cost between 55, and 100,000 US\$<sup>75</sup>.

FT-diesel is a high quality and clean transportation fuel with favourable characteristics for application in diesel engines. FT-diesel is similar to fossil diesel with regard to energy content, density, viscosity and flash point. It also presents a higher cetane number. Moreover, it has a very low aromatic content, which leads to cleaner combustion. This means that particle and NOx exhaust emissions are lower. Finally, sulphur emissions are avoided, because FT-diesel is sulphur free due to synthesis requirements. It can be used in current diesel engines and the existing diesel distribution infrastructure without any modifications.

Physical properties of DME are very similar to those of LPG. DME is gaseous at ambient temperature and pressure, but at 20°C and a pressure above 5 bar, it is a liquid. It is very clean and, for the same reason than FT-diesel, does not contain sulphur. DME cannot be mixed with diesel, but retrofitting diesel engines for the use of DME is possible. Because DME has a lower energy content and density than diesel, a higher fuel volume must be supplied for the same amount of energy. DME does not cause any cold start problems, due to its high volatility, to compare to methanol and ethanol. However like ethanol it may affect some kinds of plastics implying the selection of specific sealing materials for the fuel system. DME can also exploit the existing LPG infrastructure, which might be an opportunity for its market penetration when such infrastructure exists.

#### **4. Conclusion: what are the prospects for biofuels technologies in developing countries?**

Technology plays a central role in energy resource characterisation and in the assessment of potentials as well as of relative interests of competing supply-chains. It intervenes at the level of exploitation, transport, conversion processes and final consumption (energy service). Technology can increase energy efficiency, enlarge possibilities in terms of resources valorisation, and reduce risks and environmental impact, if such objectives are sought after. Nevertheless, aiming at those objectives with biofuel technology requires a clarification both of the objectives and the contexts where they are pursued.

In most developing countries, energy needs are considerable and linked to their economic development which at some points may be stuck until greater access to energy can be guaranteed at controllable conditions. To what extent can biofuels technologies offer the opportunity to reduce vulnerability towards international energy markets while increasing the value of local resources and generating employment?

The answer needs to consider that biomass resources are quite specific and different from those already used for biofuels, and the demand for liquid biofuels might also follow different patterns than those of industrialised countries. Unless those specificities are taken into account, biofuel technologies might fail at efficiently serving developing countries' interests. All the more capital costs of a biofuel industry would require outside investments for which drivers might diverge from domestic priorities.

##### **4.1. Energy for development**

The locally established energy-poverty link is more and more often mentioned by large international sponsors, namely regarding the UN Millennium Development Goals<sup>76</sup>. Macro-economically, the emergence of developing countries occurs with a strong increase of their energy needs, hence further pressure on energy resources and their prices, namely of fossil resources. Their specific advantage is due to their energy density but also to some captive uses (oil fuels in road and air transport for instance).

Therefore development is commonly associated to leaving firewood and other traditional biomass for fossil energy. However, the vulnerability of developing countries without domestic fossil resources is high in front of oil price increases. Even unclear about price levels to be reached and the fluctuations to expect,

there is a global consensus to recognise that oil price will remain high, due to the fact that demand will soon exceed production capacities.

At their present stage of development however, except for very favourable contexts (Centre South region of Brazil) biofuels do not appear competitive against fossil fuels, especially those biofuels using resources that would not directly compete with food supply, cf. figures 10, 12 and 19. Few countries may expect to reach low production costs in the short term thanks to ideal climate and soils conditions and infrastructure allowing a long harvesting period as in Brazil. And it would not be fair at the current levels of North-South disequilibrium regarding wealth and energy consumption, to put pressure on developing countries towards costly energy choices for the sake of international energy price stability and of global environment.

The relevance of biofuels energy choices for development is not trivial. Several points require discussion and further investigation.

#### **4.1.1. Economic performance of biofuels?**

Biofuel competitiveness is hampered by lock-in effects in favour of oil technologies. For many decades, they have benefited from learning and scale effects, making the adoption of alternatives costlier than further improvements in oil fuel supply-chains.

The question for biofuel technologies stands about the scale and learning effects that investments could generate in developing countries. To what extent could costs decrease through technical progress but also logistical and organisational improvements within a supply-chain? At what oil price levels are biofuels break-even prices? Or, by which time horizon could a biofuel technology learning curve (giving fuel costs as a function of volume produced and time) possibly meet fossil fuel cost curves?

The topic requires investigation led at a country level, specifying elements of the context: its workforce, available resource... It can also draw, but only to a limited extent accounting for contextual differences, on existing experiences of investments into energy alternative.

For instance South African case deserves special attention. For strategic rather than economic reasons and following the ban during the apartheid, South African government decided to develop alternative transport fuels. Having large coal reserves, they decided to use coal as raw material to produce through gasification and the FT synthesis, FT diesel and gasoline. They are today one of the world's most experienced synthetic fuels organisations and are now marketing GTL technology worldwide..

Brazilian case is a reference on the production of ethanol from sugar cane. Technology used in Brazil being well documented and the condition of the emergence of the sector quite specific, the Brazilian experience won't be further described here. However, it should be mentioned that sugar cane cultivation is a water intensive crop which cannot be grown easily. The 2004 draught which affected India and Thailand among others, has seriously frozen the interest of the sugar millers for bioethanol programmes despite government incentives and the set up of appropriate policies.

The Indian starting experience with *Jatropha* would also be very interesting to build on. *Jatropha* is often mentioned as potential oily raw material for biofuel production easier as crude oil (Mali, Madagascar) or esterified (India). Yet it has really taken off in India only, with the set up of a pilot project in the Gujarat state. The production has started early 2005.



Additionally to experiences acquired in large countries, others with specific contexts are useful to further study the issue of scale and learning effects.

Whatever the oil barrel price, some situations in small islands or land-locked countries with inadequate transport infrastructure to access ports or pipelines make investments in biofuel production profitable in the short term, particularly if crops and biofuel production can be located close to consumption centres. In Burkina Faso, cotton oil already suffering from slight overproduction might be attractively used as fuel. Its conversion into ester rather than being used as crude oil to fuel stand alone power generation facility is to be questioned and investigated.

Though not dealing with very large projects to start with, biofuels technology investments in such specific contexts will be a source of knowledge on how biofuels costs would evolve with experience and scale, first of all on feedstock issues.

#### **4.1.2. Biofuels giving value to local resources?**

Land potentially available for biofuel plantations is mainly to be found in tropical areas<sup>77</sup> which are in developing countries. This land is potentially available because food crops would not need it under most probable agro-demo-economic scenarios and climatic conditions are quite favourable.

However, land availability depends on the interest presented by biofuels plantations with regards to other land uses. To what extent and at what conditions do biofuels plantations sustainably generate value to local population? Are they the best way to development compared with other uses of land, water and workforce?

To be in a position to answer means to account for numerous parameters, including longer term issues where choices of development paths are at stake. For biomass plantations to represent added value beyond the sole incomes from selling biomass, conversion to energy needs to be considered locally or nationally, according to the country's own energy needs and the income generating opportunities through exports.

By (co-) providing local energy services (for irrigation, post-harvest value-adding activities...), biofuels production may indeed stimulate domestic agriculture production and expand markets for agricultural products. However, for reasons of scale economies and proximity to large-scale fuel demand, biomass supply may need to be centralised for fuel conversion in biorefineries (concept detailed earlier in 3.4) located near transport infrastructure. External demand being possibly strong, how would incentives compare for the satisfaction of local energy needs and that of external demand? Where are the complementarities (integration of a variety of feedstock, simultaneous production of a variety of products, cogeneration of BTL route contributing to improving local access to electricity...)? Under what conditions would they hold under growing external demand at higher prices than can local demand afford?

Whatever the availability of resources, biofuels development schemes need to be clarified in terms of value enhanced by different options under consideration, not only monetary values generated instantly but also within the longer term considering basic needs and development strategies.

#### 4.1.3. Employment in the biofuels industry?

A frequently cited benefit of biofuels production is job creation, especially in rural area. Coelho (2004) claims that the Brazilian sugarcane sector is employing around 700,000 people, responsible for around 3.5 million indirect jobs, corresponding to the production of 350 million tons of cane (not for the sole production of biofuels).

Depending on the type of feedstock and the technologies to convert into fuels, the workforce a biofuel supply-chain would contribute to employ or maintain in rural areas is more or less important. Biosynfuel production associated to fast growing trees like Eucalyptus offers the best opportunity in terms of employment as it would mix low, medium and high skilled workers. Similarly to Brazilian plantations for charcoal to the steel industry reduction, a better social impact should be expected as the ratio between skilled and unskilled labour is rather high.

However, workforce availability might be an issue. The countries where the highest potentials lie in terms of land are not necessarily endowed with large populations. For instance, the Republic of Central Africa has large uncultivated land and good climate conditions but the density of the population is below 10/km<sup>2</sup> in those areas.

#### 4.2. Appropriate biofuels technologies for developing countries ?

Best prospects both in terms of land availability<sup>77</sup> and yields per hectare (table 14) are in developing countries, with biofuels technologies differing from those currently in use in industrialised countries with agricultural surpluses.

gen.	Biofuels	l/ha	GJ/ha
1 <sup>st</sup>	Sun flower biodiesel	1,000	35.7
	Soy bean biodiesel	500-700	17.8- 25.0
	Rapeseed biodiesel	1,200	42.8
	Wheat ethanol	2,500	53
	Maize ethanol	3,100	65.7
	Sugar beat ethanol	5,500	116.6
	Sugar cane ethanol	5,300-6,500	112.4- 137.8
2 <sup>nd</sup>	FT biodiesel eucalyptus plantation	13,500-18,000	463.1- 617.4
	Methanol eucalyptus plantation	49,500-66,000	772.2- 1029.6
	DME eucalyptus plantation	45,000- 60,000	846.0- 1128.0

Table 14: Bio fuel yields per ha (l and GJ/ha)

Clearly, potential is higher with second generation fuels, presenting a potential contribution larger than conventional biofuels. Therefore is the maturity of the technology certainly the weak point as only conventional biofuel technologies are operational at the large scale today. Most promising routes in terms of productivity per hectare, which may at the same time use a wider range of biomasses including lignocellulosic biomass are not yet proven at large scales and still under intense research. Among all routes discussed earlier, FT-diesel is the only one that can be readily used to the market and which benefit from real large scale applications even if from coal. Obtaining a high quality synthesis gas from biomass for further transformation into biofuels (see above, section 2.2.5. on pre-treatment) appears to be the crucial step in the biomass to liquid pathway.

Same problem of lack of maturity applies for the enzymatic hydrolysis despite large R&D facilities in the USA particularly. It is not reasonable to expect significant contribution from biosynfuels for transport before 2010.

The development of the technology would need significant government support which is already the case in Europe or North America. It is important for developing countries to be associated to this development as they offer the best opportunities regarding biomass production potential. The risk is indeed to see developing countries exporting large volumes of raw biomass to be further processed in industrialised country harbour facility with very limited impact on the development. To avoid this, investment patterns require forward-looking investigation.

### 4.3. *Investment patterns for biofuels ?*

Investments always occur with eviction effects. Besides being in a mutual competition, biosynfuels production heavily competes with other alternative energy/environment solution for transport as well as with the other energy applications of land and biomass resources, among which power generation is of great concern in developing countries.

Capital cost is a main component of biofuel costs beside feedstock costs. Capital cost includes the debt service and the plant operation and maintenance and constitutes the main biofuels fixed cost particularly for small scale units. Table 15 provides an overview of short and long term investment costs. These values might diverge depending on the type of design and other technical choices even within the same route.

Thence figures given with the purpose of comparison should not be considered as absolute values. They show that biosynfuel routes, which offer highest productivity levels, are also the most capital intensive. Drastic cost reductions are expected in the longer term. Still, as conventional oil refinery is a well proven and efficient technology (continuously improving) able to earn great economies of scale, biosynfuel routes will have difficulties to compete in terms of prices without decisive initial support.

Biofuels	Investment costs	Investment costs
	Short term (€/kWth)	Long term (€/kWth)
RME	150	110
Ethanol (sugar crops)	290	170
Ethanol (wood)	350	180
Methanol	700	530
FT-diesel	720-770	500-540

Table 15: Overview of biofuels present and projected investment cost<sup>2</sup>.

## Abbreviations

CHP: co heat and power  
CNG: compressed natural gas  
DME: dimethylether  
FT: Fischer-Tropsch  
GHG: greenhouse gas  
HHV: higher heating value  
LHV: lower heating value  
LPG: liquefied petroleum gas  
RME: rape methyl ester

## Units:

°C: degree Celsius  
bpd: barrel per day  
cp  
EJ: exa joule =  $10^{18}$  J  
GJ: giga joule =  $10^9$  J  
ha: hectare  
J: joule  
Mt: million metric ton  
Mha: million hectare  
Mhl: million hecto litres  
MWe: million electric watt  
t: metric ton  
toe: ton of oil equivalent (1 toe = 42 GJ)  
US\$: dollar of the USA

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