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Biofuels in Perspective

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1.1 Fossil versus Renewable Energy Resources

Serious geopolitical implications arise from the fact that our society is heavily dependent on only a few energy resources such as petroleum, mainly produced in politically unstable oil-producing countries and regions. Indeed, according to the World Energy Council, about 82 % of the world's energy needs are currently covered by fossil resources such as petroleum, natural gas and coal. Also ecological disadvantages have come into prominence as the use of fossil energy sources suffers a number of ill consequences for the environment, including the greenhouse gas emissions, air pollution, acid rain, etc. (Wuebbles and Jain, 2001; Soetaert and Vandamme, 2006).

Moreover, the supply of these fossil resources is inherently finite. It is generally agreed that we will be running out of petroleum within 50 years, natural gas within 65 years and coal in about 200 years at the present pace of consumption. With regard to the depletion of petroleum supplies, we are faced with the paradoxical situation that the world is using petroleum faster than ever before, and nevertheless the 'proven petroleum reserves' have more or less remained at the same level for 40 years, mainly as a result of new oil findings (Campbell, 1998). This fact is often used as an argument against the 'prophets of doom', as there is seemingly still plenty of petroleum around for the time being. However, those 'proven petroleum reserves' are increasingly found in places that are poorly accessible, inevitably resulting in an increase of extraction costs and hence, oil prices. Campbell and Laherrère (1998), well-known petroleum experts, have predicted that the world production

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of petroleum will soon reach its maximum production level (expected around 2010). From then on, the world production rate of petroleum will inevitably start decreasing.

As the demand for petroleum is soaring, particularly to satisfy economically skyrocketing countries such as China (by now already the second largest user of petroleum after the USA) and India, petroleum prices are expected to increase further sharply. The effect can already be seen today, with petroleum prices soaring to over 90 $/barrel at the time of writing (September 2007). Whereas petroleum will certainly not become exhausted from one day to another, it is clear that its price will tend to increase. This fundamental long-term upward trend may of course be temporarily broken by the effects of market disturbances, politically unstable situations or crises on a world scale.

Worldwide, questions arise concerning our future energy supply. There is a continual search for renewable energy sources that will in principle never run out, such as hydraulic energy, solar energy, wind energy, tidal energy, geothermal energy and also energy from renewable raw materials such as biomass. Wind energy is expected to contribute significantly in the short term (Anonymous, 1998). Giant windmill parks are already on stream and more are being planned and built on land and in the sea. In the long run, more input is expected from solar energy, for which there is still substantial technical progress to be made in the field of photovoltaic cell efficiency and production cost (Anonymous, 2004). Bio-energy, the renewable energy released from biomass, is expected to contribute significantly in the mid to long term. According to the International Energy Agency (IEA), bio-energy offers the possibility to meet 50 % of our world energy needs in the 21st century.

In contrast to fossil resources, agricultural raw materials such as wheat or corn have until recently been continuously declining in price because of the increasing agricultural yields, a tendency that is changing now, with competition for food use becoming an issue. New developments such as genetic engineering of crops and the production of bio-energy from agricultural waste can relieve these trends.

Agricultural crops such as corn, wheat and other cereals, sugar cane and beets, potatoes, tapioca, etc. can be processed in so-called biorefineries into relatively pure carbohydrate feedstocks, the primary raw material for most fermentation processes. These fermentation processes can convert those feedstocks into a wide variety of valuable products, including biofuels such as bio-ethanol.

Oilseeds such as soybeans, rapeseed (canola) and palm seeds (and also waste vegetal oils and animal fats), can be equally processed into oils that can be subsequently converted into biodiesel (Anonymous, 2000; Du et al., 2003). Agricultural co-products or waste such as straw, bran, corn cobs, corn stover, etc. are lignocellulosic materials that are now either poorly valorized or left to decay on the land. Agricultural crops or organic waste streams can also be efficiently converted into biogas and used for heat, power or electricity generation (Lissens et al., 2001). These raw materials attract increasing attention as an abundantly available and cheap renewable feedstock. Estimations from the US Department of Energy have shown that up to 500 million tonnes of such raw materials can be made available in the USA each year, at prices ranging between 20 and 50 $/ton (Clark 2004).

1.2 Economic Impact

For a growing number of technical applications, the economic picture favours renewable resources over fossil resources as a raw material (Okkerse and Van Bekkum, 1999). Whereas

Table 1.1 *Approximate average world market prices in 2007 of renewable and fossil feedstocks and intermediates*

Fossil		Renewable	
Petroleum	400 €/t	Corn	150 €/t
Coal	40 €/t	Straw	20 €/t
Ethylene	900 €/t	Sugar	250 €/t
Isopropanol	1000 €/t	Ethanol	500 €/t

this is already true for a considerable number of chemicals, increasingly produced from agricultural commodities instead of petroleum, this is also becoming a reality for the generation of energy. The prices given in Table 1.1 are the approximate average world market prices for 2007. Depending on local conditions such as distance to production site and local availability, these prices may vary rather widely from one place to another. Also, protectionism and local subsidies may seriously distort the price frame. As fossil and renewable resources are traded in vastly diverging measurement units and currencies, one needs to convert the barrels, bushels, dollars and euros into comparable units to turn some sense into it. All prices were converted into Euro per metric ton (dry weight) for a number of fossil or renewable raw material as well as important feedstock intermediates such as ethylene and sugar, for the sole purpose of a clear indicative cost comparison of fossil versus renewable resources.

From Table 1.1, one can easily deduce that on a dry weight basis, renewable agricultural resources cost about half as much as comparable fossil resources. Agricultural co-products such as straw are even a factor 10 cheaper than petroleum. At the present price of crude oil (> 90 \$/barrel, corresponding to 400 €/t in September 2007), petroleum costs about three times the price of corn. It is also interesting to note that the cost of sugar, a highly refined very pure feedstock (> 99.5 % purity), is about the same as petroleum, a very crude and unrefined mixture of chemical substances. As the energy content of renewable resources is roughly half the value of comparable fossil raw materials, one can conclude that on an energy basis, fossil and renewable raw materials are about equal in price. Also volume wise, agricultural feedstocks and intermediates have production figures in the same order of magnitude as their fossil counterparts, as indicated in Table 1.2.

It is obvious that agricultural feedstocks are cheaper than their fossil counterparts today and are readily available in large quantities. What blocks their further use is not economics but the lack of appropriate conversion technology. Whereas the (petro)chemical technology base for converting fossil feedstocks into a bewildering variety of useful products is by now very efficient and mature, the technology for converting agricultural raw materials into chemicals, materials and energy is still in its infancy.

It is widely recognized that new technologies will need to be developed and optimized in order to harvest the benefits of the bio-based economy. Particularly industrial biotechnology is considered a very important technology in this respect, as it is excellently capable to use agricultural commodities as a feedstock (Demain, 2000, 2007; Dale 2003; Vandamme and Soetaert, 2004). The processing of agricultural feedstocks into useful products occurs in so-called biorefineries (Kamm and Kamm, 2004; Realff and Abbas, 2004). Whereas the gradual transition from a fossil-based society to a bio-based society will take time and

Table 1.2 Estimated world production and prices for renewable feedstocks and petrochemical base products and intermediates

	Estimated world production (million tons per year)	Indicative world market price (euro per ton)
Renewable feedstocks		
Cellulose	320	500
Sugar	140	250
Starch	55	250
Glucose	30	300
Petrochemical base products and intermediates		
Ethylene	85	900
Propylene	45	850
Benzene	23	800
Caprolactam	4	2000

effort, it is clear that renewable raw materials are going to win over fossil resources in the long run. This is particularly true in view of the perspective of increasingly rarer, difficult to extract and more expensive fossil resources.

1.3 Comparison of Bio-energy Sources

1.3.1 Direct Burning of Biomass

Traditional renewable biofuels, such as firewood, used to be our most important energy source and they still fulfill an important role in global energy supplies today. The use of these traditional renewable fuels covered in 2002 no less than 14.2 % of the global energy use, far more than the 6.9 % share of nuclear energy (IEA). In many developing countries, firewood is still the most important and locally available energy source, but equally so in industrialized countries. The importance is even increasing: in several European countries, new power stations using firewood, forestry residues or straw have recently been put into operation and there are plans to create energy plantations with fast growing trees or elephant grass (*Miscanthus* sp.). On the base of net energy generation per ha, such energy plantations are the most efficient process to convert solar energy through biomass into useful energy. An important factor in this respect is that such biofuels have (in Western Europe) high yields per ha (12 t/ha and more) and can be burnt directly, giving rise to an energy generation of around 200 GJ/ha/yr (Table 1.3).

1.3.2 Utilization Convenience of Biofuels

The energy content of an energy carrier is, however, only one aspect in the total comparison. For the value of an energy carrier is not only determined through its energy content and yield per hectare, but equally by its physical shape and convenience in use. This aspect of an energy source is particularly important for mobile applications, such as transportation. In Europe, the transport sector stands for 32 % of all energy consumption, making it a very

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Table 1.3 *Energy yields of bio-energy crops in Flanders (Belgium)*

	Yield (t dry matter/ha/yr)	Biofuel-type	Biofuel yield t/ha/yr	Gross energy yield	
				GJ/t	GJ/ha/yr
Wheat (cereal)	6.8	bio-ethanol	2.29	26.8	61
Sugar beets (root)	14	bio-ethanol	4.84	26.8	130
Rapeseed (seed)	3.1	biodiesel	1.28	37	50
Willow/poplar (wood)	10.8	firewood	10.8	18	194

important energy user. There is consequently a strong case for the use of renewable fuels in the transport sector, particularly biofuels. Whereas in principle, we can drive a car on firewood, this approach is all but user friendly. In practice, liquid biofuels are much better suited for such an application. It is indeed no coincidence that nearly all cars and trucks are powered by liquid fuels such as gasoline and diesel. These liquid fuels are easily and reliably used in classic explosion engines and they are compact energy carriers, leading to a large action radius of the vehicle. They are easily stored, transported and transferred (it takes less than a minute to fill up your tank) and their use basically requires no storage technology at all (a simple plastic fuel tank is sufficient). Our current mobility concept is consequently mainly based on motor vehicles powered by liquid fuels that are supplied and distributed through tank stations.

The current strong interest in liquid motor fuels such as bio-ethanol and biodiesel based on renewable sources is based strongly on the fact that these biofuels show all the advantages of the classic (fossil-based) motor fuels. They are produced from agricultural raw materials and are compact, user-friendly motor fuels that can be mixed with normal petrol and diesel, with no engine adaptation required. The use of bio-ethanol or biodiesel therefore fits perfectly within the current concept of mobility. Current agricultural practices, such as the production of sugar cane or beets, rapeseed or cereals also remain fundamentally unaltered. The introduction of these energy carriers does not need any technology changes and the industrial processes for mass production of biofuels are also available.

Table 1.3 compares the energy yields of the different plant resources and technologies. For comparison, rapidly growing wood species such as willow or poplar as a classical renewable energy source, are also included.

It is clear that the gross energy yield per hectare is the highest for fast growing trees such as willow or poplar. However, a car does not run on firewood. Even if we restrict ourselves to the liquid fuels, there remain big differences between the different bio-energy options to be explained.

1.3.3 Energy Need for Biofuel Production

At first sight, based on gross energy yield per hectare, bio-ethanol from sugar beets would appear the big winner, combining a high yield per hectare and a high energy content of the produced bio-ethanol. Bio-ethanol out of wheat is lagging behind and biodiesel out of rapeseed comes last. Yet, biodiesel produced out of rapeseed is currently rapidly progressing in production volume, especially in Europe. The comparison is clearly more complex than would appear at first sight, with several other facts to be considered.

1.3.3.1 Comparison of Biofuels to Fossil Fuels

The energy input in the cultivation of the plants, transport as well as the production process itself needs to be taken into account. During the production of bio-ethanol, the distillation process is a big energy consumer. The amount of energy needed to produce the bio-ethanol is even close to the amount of energy obtained from the bio-ethanol itself. Shapouri et al. (2003) have carefully studied the energy balance of corn ethanol and have concluded that the energy output:input ratio is 1.34. When all energy inputs are taken into account, the net energy yield can even be negative in poorly efficient production processes. It would then appear that more energy is being used than is produced. Ironically, this energy input often comes out of fossil energy sources, except in Brazil, where renewable sugar cane bagasse contributes increasingly to the energy input. Obviously, this point is frequently used by opponents of bio-ethanol; they even consider it as an unproductive way to convert fossil energy in so called bio-energy, for the only sake of pleasing the agricultural sector.

Dale (2007) has nicely shown the inconsistency of the ‘net energy’ debate, by pointing at the reality that all energy sources are not equal. One unit of energy from petrol is e.g. much more useful than the same amount of energy in coal. Whereas net energy analysis is simple and has great intuitive appeal, it is also dangerously misleading. For making wise decisions about alternative fuels, we need to carefully choose our metrics of comparison. Dale suggests two complementary metrics as being far more sensible than net energy. First, alternative fuels (e.g. ethanol) can be rated on their ability to displace petroleum; and second, ethanol could be rated on the total greenhouse gases produced per km driven.

Sheehan et al. (2004) have determined the Fossil Energy Replacement Ratio (FER), the energy delivered to the customer over the fossil energy used. This parameter is important in relation to the emission of carbon dioxide, the most important greenhouse gas. A high FER means that less greenhouse gases are produced (from the fossil fuel input) per unit of energy delivered to the customer. They have found a FER of 1.4 for bio-ethanol based on corn, and a FER as high as 5.3 for bio-ethanol based on lignocellulosic raw materials such as straw or corn stover. For comparison, the FER for gasoline is 0.8 and for electricity it is as low as 0.4.

In order to properly evaluate this development, one must also consider that bio-ethanol is a high-quality and energy-dense liquid fuel, perfectly usable for road transport. For its production, one needs mainly energy in the form of heat (for distillation), a fairly cheap, low-quality and non-portable energy source. The conversion of one energy form into another, especially if it becomes portable, is indeed a productive process. In the case of biofuel production, one converts cheap low-quality heat and biomass into high-quality portable liquid motor fuel, a relatively expensive but very convenient source of energy, particularly for transportation use. In the same way, cars do not run on petroleum either, but on the fuel that is being distilled out of it. The distillation, extraction and long-distance transport of petroleum also require a large energy input. The matter of the fossil energy-input into bio-ethanol production becomes a non-issue altogether, when biomass is used as the source of heat, as is commonly practised in Brazil where the sugar cane residue bagasse is burnt to generate the heat required for distillation. Similar production schedules may soon become a reality in the USA or Europe when e.g. ethanol is produced from wheat, with the wheat straw being burned to generate the heat for distillation.

Biodiesel has a lower energy input required for its production. However, the low yield of the crops from which it is produced per hectare dampens the perspectives for biodiesel. Concerning the difference in gross energy yield per hectare between sugar beet and wheat, it also has to be borne in mind that European farmers have traditionally obtained very high prices for their sugar beets. This high price was being maintained by the sugar market regulation (quota regulation) in Europe, which is now under reform. Even if the yield per hectare is higher for sugar beets, with the current price structure it is today more economical to produce ethanol out of wheat or other cereals, unless the ethanol production can be coupled to the sugar production, a production scheme that offers technical advantages.

1.4 Conclusion

The use of bio-ethanol and biodiesel derived from agricultural crops is a technically viable alternative for fossil-based gasoline or diesel. Moreover, their use fits perfectly in the present concept and technology of our mobility. Liquid energy carriers are an (energetically) expensive but very useful energy carrier for mobile applications such as transportation. It is clear that energy sources for mobile applications should not only be compared on the basis of simple energy balances or costs, but also on the base of their practical usefulness, quality, environmental characteristics and convenience in use of the obtained energy carrier. It is interesting to note that Henry Ford, when designing his famous model T car, presumed that ethanol would become the car fuel of the future. Although initially petrochemistry got the upper hand, it now seems as though Henry Ford was way ahead of his time and proven right in the long run. Even as the discussion about the sense or nonsense of biofuels is ongoing, the transition process from a fossil-based to a bio-based society is clearly moving forward, with impressive growth in the USA, Brazil, China and Europe finally catching on. There is little doubt that in the medium term, we will all fill up our car with a considerable percentage of biofuels, probably unaware of it and without noticing any difference.

The large-scale introduction of biofuels can reconcile the interests of environment, mobility and agriculture and can be seen as an important step with high symbolic value towards the sustainable society of the future.

References

Anonymous (1998) Renewable energy target for Europe: 20 % by 2020. Report from the European Renewable Energy Council (EREC).

Anonymous (2000) Biodiesel: The Clean, Green Fuel for Diesel Engines (Fact sheet). NREL Report No. FS-580-28315; DOE/GO-102000-1048.

Anonymous (2004) Renewable Energy scenario to 2040: Half of the Global Energy Supply from renewables in 2040. Report from the European Renewable Energy Council (EREC).

Campbell, C.J. (1998) The future of oil. *Energy Explor. Exploit.* **16**: 125–52.

Campbell, C.J. and Laherrère, J.H. (1998) The end of cheap oil. *Sci. Am.* **278**: 78–83.

Clark, W. (2004) The case for biorefining. National Renewable Energy Laboratory. www.sae.org/events/sfl/pres-clark.pdf

Dale, B.E. (2007) Thinking clearly about biofuels: ending the irrelevant net energy debate and developing better performance metrics for alternative fuels. *Biofpr, Biofuels, Bioproducts, Biorefining* **1**: 14–17.

Demain, A.L. (2000) Small bugs, big business: the economic power of the microbe. *Biotechnol. Adv.* **18**: 499–514.

Demain, A.L. (2007) The business of industrial biotechnology. *Industrial Biotechnology* **3**(3): 269–83.

Dale, B.E. (2003) 'Greening' the chemical industry: research and development priorities for biobased industrial products. *J. Chem. Technol. Biotechnol.* **78**: 1093–1103.

Du, W., Xu, Y. and Liu, D. (2003) Lipase-catalysed transesterification of soy bean oil for biodiesel production during continuous batch operation. *Biotechnol. Appl. Biochem.* **38**: 103–6.

IEA Bioenergy. www.ieabioenergy.com

Kamm, B. and Kamm, M. (2004) Principles of biorefineries. *Appl. Microbiol. Biotechnol.* **64**: 137–45.

Lissens, G., Vandevivere, P., De Baere, L., Biey, E.M., Verstraete, W. (2001). Solid waste digestors: process performance and practice for municipal solid waste digestion. *Water Science and Technology* **44**: 91–102.

Okkerse, C. and Van Bekkum, H. (1999) From fossil to green. *Green chem.* **1**(2): 107–14.

Realff, M.A. and Abbas, C. (2004) Industrial symbiosis : refining the biorefinery. *J. Industrial Ecology* **7**: 5–9.

Shapouri, H., Duffield, J.A. and Wang, M. (2003) The energy balance of corn ethanol: an update. USDA report no. 814.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J. et al. (2004) Energy and environmental aspects of using corn stover for fuel ethanol. *J. Industrial Ecology* **7**: 117–46. NREL Report No. JA-510-36462.

Soetaert, W., and Vandamme, E.J. (2006) The impact of industrial biotechnology. *Biotechnology. J.* **1**(7–8): 756–69.

Vandamme, E.J. and Soetaert, W. (2004) Industrial biotechnology and sustainable chemistry. BACAS-report, Royal Belgian Academy, 34p. http://www.europabio.org/documents/150104/bacas_report_en.pdf

Wuebbles, D.J. and Jain, A.K. (2001) Concerns about climate change and the role of fossil fuel use. *Fuel Process. Technol.* **71**: 99–119.