

Second-Generation Biofuels

Economics and Policies

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Abstract

Recent increases in production of crop-based (or first-generation) biofuels have engendered increasing concerns over potential conflicts with food supplies and land protection, as well as disputes over greenhouse gas reductions. This has heightened a sense of urgency around the development of biofuels produced from non-food biomass (second-generation biofuels). This study reviews the economic potential and environmental implications of production of second-generation biofuels from a variety of various feedstocks. Although second-generation biofuels could significantly contribute to

the future energy supply mix, cost is a major barrier to increasing commercial production in the near to medium term. Depending on various factors, the cost of second-generation (cellulosic) ethanol can be two to three times as high as the current price of gasoline on an energy equivalent basis. The cost of biodiesel produced from microalgae, a prospective feedstock, is many times higher than the current price of diesel. Policy instruments for increasing biofuels use, such as fiscal incentives, should be based on the relative merits of different types of biofuels.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department to analyze economic, social and environmental impacts of biofuels. Policy Research Working Papers are also posted on the Web at <http://econ.worldbank.org>. The author may be contacted at grimilsina@worldbank.org.

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Second-Generation Biofuels: Economics and Policies[#]

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1 Introduction

Biofuels production and consumption has been rapidly growing in the last few years. Led by Brazil and the United States, global production of fuel ethanol more than doubled during the last four years, increasing from 31.3 billion liters in 2005 to over 72.8 billion liters (estimated) in 2009 (F.O. Licht 2009). Although being produced in smaller quantities than ethanol, the relative growth experience by biodiesel is even stronger, surpassing 12.8 billion liters in 2008 (estimated) up from 3.9 billion liters in 2005 (F.O. Licht 2008).

Currently, biofuels provide for over 1.5% (about 34 mtoe) of the energy used for transport (IEA 2008). The Energy Information Administration (EIA) of the United States Department of Energy projects the 2030 world energy consumption of liquid forms on 112.5 million barrel of oil equivalent per day (about 238 EJ/yr). Of this, 60% or 142.8 EJ/yr would be consumed by the transport sector. On the other hand, EIA (2009) projects that the total production of biofuels will be between 10.1 and 15.1 EJ per year by 2030 depending on the assumptions on oil prices.²

Several reasons can be advanced as fueling growth in biofuels. Salient drivers are increased oil prices over the past decade, as well as oil price volatility. This has led to increased public support for renewable fuels (e.g., subsidies, mandated consumption, etc.) by many countries (REN21 2009). The oil crisis of the 1970s prompted some interest in biofuels. However, that impulse was short lived and faded in most countries with the subsequent decline in the price of petroleum. Brazil is an exception to this pattern, with ethanol production continuing to expand (with the help of blending mandates) throughout the 1980s.³ Without blending and oxygenations mandates, and other forms of intervention, the market for biofuels would be limited when the price of crude oil is below US\$60-70 per barrel (OECD-FAO 2009).

² The original units are in million barrels per day (4.8-7.2). For conversion, a barrel a day is about 50 tons of oil per year. A ton of oil contains 41.868 GJ.

³ It should be noticed that low crude oil prices in the 1990s proved challenging to the ethanol industry, which only resumed significant growth earlier this decade with the raise in crude oil prices and the advent of flex fuel vehicles (able to use ethanol and gasoline in any blend).

The rapid recent growth of biofuel production has become controversial. The wide support that biofuels enjoyed just three or four years ago has eroded more recently as new studies began to emerge linking their production to raising food prices, questioning their ability to displace fossil energy, and criticizing their potential contribution to monoculture and deforestation (Searchinger et al. 2008; Fargione et al. 2008; Mitchell 2008).

The combined impacts of these effects have stimulated greater interest, and even some sense of urgency, for the development of biofuels produced from non-food biomass – commonly referred to as second-generation biofuels.⁴ These are less land and water intensive, and/or use residues from agriculture. Despite increased interest in expanding second-generation biofuels, however, and progress made in recent years, significant hurdles still need to be overcome before second-generation biofuels can be produced at commercial scale, even with the massive investments in R&D observed in recent years (IEA 2008).⁵

This paper provides an assessment of the key economic factors influencing the economic potential of second-generation biofuels – factors that will shape the size of potential markets for second-generation biofuels in the future. The economic potential for second-generation biofuel production depends critically on both the amount of land that would be used, relative to other land uses; the productivity of biomass cultivation; and the cost of converting various types of biomass to liquid fuels. The impacts of these factors on the future economic potential of second-generation biofuels are necessarily uncertain and thus to a degree a matter of speculation. Nevertheless, our analysis leads to the conclusion that while second-generation biofuels could make significant contributions to global energy supply, the economic potential market for these biofuels will likely be

⁴ There is currently no strict technical definition for the terms first and second-generation biofuels, and the distinction between the two mainly hinges around the feedstock used in production (Larson 2008). In general terms, we refer to the first-generation biofuels as those mainly based on sugars, grains, or seeds, and generally requiring relatively simple processing to produce the fuel. In contrast, second-generation biofuels would be generally made from non-edible lignocellulosic biomass, including residues of crops or forestry production (corn cobs, rice husks, forest thinning, sawdust, etc), and whole plant biomass (e.g. energy crops such as switchgrass, poplar, and other fast growing trees and grasses). Biofuels obtained from vegetable oils produced from sources that do not directly compete with crops for high quality land (e.g., jatropha, microalgae) can also be labeled as second-generation biofuels.

⁵ UNEP (2009) report that new investments in (both first and second-generation) biofuels amounted to \$16.9 billion in 2008 alone.

more limited due to the amount of feedstocks that can be produced at affordable costs with available land, as well as the costs of production relative to liquid fossil fuels.

The paper is organized as follows. Section 2 presents a description of the main feedstocks for second-generation biofuels, an assessment of their availability, and an overview of global potential for bioenergy production. Land needs for feedstock production and availability are presented next (Section 2.3). Costs of production and environmental impacts are considered in Sections 3 and 4 respectively. Section 5 describes several policies affecting the advanced biofuels supply chain and challenges faced by these fuels. This is followed by conclusions, final remarks and policy recommendations.

2 Potential Feedstocks

The potential feedstocks for second-generation biofuels production considered in this study are biomass from crops residues, other non-food energy crops, wood/forestry residues, and jatropha and algae.

A description and global availability of selected feedstock for second-generation biofuel production is provided in Sections 2.1 and 2.2 covering lignocellulosic and vegetable oils respectively. A general overview of the potential of land to produce the second-generation biofuels is presented in Section 2.3.

2.1 Lignocellulosic feedstocks

The major components of lignocellulosic feedstocks are cellulose and hemicellulose (over 67% of dry mass), which can be converted to sugars through a series of thermochemical and biological processes and eventually fermented to bioethanol.⁶ In general, lignocellulosic feedstocks are divided into three categories: (1) agricultural residues (e.g., crop residues, sugarcane bagasse), (2) forest residues, and (3) herbaceous and woody energy crops. Current availability and potential energy contribution of each feedstock are discussed next.

⁶ Detailed descriptions of biomass feedstock structure and the key conversion technologies can be found in various studies (e.g., Hamelinck, Hooijdonk, and Faaij 2005).

2.1.1. Agricultural residues

Agricultural residues differ in their chemical composition, which leads to different biofuel yields per unit of feedstock. Table 1 shows the composition of select agricultural residue feedstocks, fraction of crop residues produced, and potential ethanol yield.

Table 1: Composition and yields of different feedstocks (based on dry mass)

	Residue /crop ratio	Crop Dry matter (%)	Lignin (%)	Carbohydrates (%)	Biofuel yield (L kg ⁻¹ of dry biomass)	Yield (kg/ha)	Biofuel yield lt/ha
Barley straw	1.2	88.7	9.0	70.0	0.31	1,184	367
Corn stover	1.0	86.2	18.7	58.3	0.29	1,734	503
Rice straw	1.4	88.6	7.1	49.3	0.28	1,399	392
Sorghum straw	1.3	89.0	15.0	61.0	0.27	736	199
Wheat straw	1.3	89.1	16.0	54.0	0.29	1,413	410
Sugarcane bagasse	0.6	26.0	14.5	67.2	0.28	11,188	3,133

Source: NRC (1958), EIA (2001), Kim and Dale (2004), and US DOE (2008a). Potential biofuel yields are estimated from the “Theoretical Ethanol Yield Calculator” (US DOE 2008b). Biofuel per hectare is calculated from average world yields.

We estimate the availabilities of agricultural residues extending the approach followed by Lal (2005) to calculate the global amount of crop residue production. Since data on the amount of crop residues produced is usually unavailable, these are approximated using the ratio between residue and crop production (by commodity, see Table 1) and the commodities production levels. A second step would involve determining how much of the crop residues produced could be actually removed and used for biofuel production.

Medium-run (2015/16) projected crop production levels for major producing countries were obtained from FAPRI (2009). The amount of residues that can be sustainably collected is still a contentious issue, and is affected by many factors, including topography, nutrient management, crop yields, climate, and tillage practices (Andrews 2006; Blanco-Canqui and Lal 2009). Given the large geographic distribution of potential availability and possible feed and other usage, following Kim and Dale (2004) we assume in this study that 40% of total produced residues can be used for biofuel

production for most crops.⁷ The exceptions would be (according to these authors) rice straw and sugarcane bagasse where 100% of the residues can be removed. Note that the numbers estimated here are the maximum potential, not necessarily the realistic potential.

Tables 2 (a) and (b) show the regional amount of feedstock produced, and the associated levels potential for second-generation ethanol production in the medium term (2015/16). The crops included in this study are corn, sorghum, barley, rice, wheat, and sugarcane. Given the environmental constraints, the potential global availability of crop residues is about 1529 million tons, and could contribute 436 billion liters of bioethanol in the medium term.

Table 2: Potential availability of selected agricultural residues and biofuel production in 2015/16

Unit: million tons for feedstock; billion liters for biofuels

(a) Corn stover, sorghum straw and barley straw

	Corn Stover		Sorghum Straw		Barley Straw	
	Feedstock	Biofuel	Feedstock	Biofuel	Feedstock	Biofuel
Asia	80.18	23.25	3.68	0.99	2.47	0.77
Africa/Middle East	8.79	2.55	0	0	6.80	2.11
CIS	6.18	1.79	0	0	14.87	4.61
European Union	20.94	6.07	0	0	27.03	8.38
Other Eastern European Countries	1.28	0.37	0	0	0	0
Latin America	34.17	9.91	1.46	0.39	1.09	0.34
North America	135.37	39.26	7.90	2.13	8.02	2.49
Oceania	0	0	0.99	0.27	3.18	0.99
ROW	2.87	0.83	10.51	2.84	0.63	0.19
Total	289.78	84.04	24.55	6.63	64.08	19.86

Source: ROW=rest of the world.

⁷ The same approach was used by Smeets et al. (2007), but a lower removal rate was used in that work.

(b) Rice Straw, wheat Straw, and sugarcane bagasse

	Rice Straw		Wheat Straw		Sugarcane Bagasse	
	Feedstock	Biofuel Production	Feedstock	Biofuel Production	Feedstock	Biofuel Production
Asia	489.69	137.11	105.42	30.57	101.87	28.52
Africa/Middle East	13.01	3.64	30.45	8.83	5.54	1.55
CIS	0	0	51.26	14.86	0	0
European Union	2.13	0.60	68.60	19.90	0	0
Other Eastern European Countries	0	0	0.69	0.20	0	0
Latin America	13.98	3.91	11.51	3.34	136.37	38.18
North America	8.78	2.46	41.97	12.17	12.70	3.56
Oceania	0	0	11.28	3.27	5.92	1.66
ROW	37.41	10.47	1.51	0.44	0	0
Total	565.00	158.20	322.69	93.58	262.40	73.47

Source: Elaborated by the authors. ROW=rest of the world.

A major advantage of using residues for biofuel production when compared to the grain crops and dedicated energy crops is that no additional land is needed. By avoiding the competition for land, residue based biofuel production should have minimal direct impact on food prices. Furthermore, greenhouse gas emissions associated to direct and indirect land use changes are also avoided, improving their carbon balance (Searchinger et al 2008). Crop residue removal can also be beneficial for some crops (and situations) as it may help control pests and diseases, and increase soil temperature in the spring facilitating seed germination (Andrews 2006).

On the other hand, crop residues are important to conserve soil properties, conserve water, enhance soil productivity, and to sequester carbon in soils. Excessive removal will have adverse impacts not only on soil properties and the environment, but also on crop production (Blanco-Canqui and Lal, 2009).

2.1.2 Forest residues

Forest residues include logging residues produced from harvest operations, fuel wood extracted from forestlands, and primary and secondary wood processing mill residues (Perlack et al. 2005). Table 3 shows the composition of different forest residues feedstocks. Note that conversion rates obtained in commercial production are likely to be lower than these theoretical yields, with the difference decreasing over time. While NREL (2007) assumed yields of 65 gallons (246 liters) per ton of feedstock, the same

source provides target yields of 90 and 94 gallons (341 and 356 liters) of ethanol per ton of cellulosic feedstocks by 2012 and 2020 respectively.

Table 3: Composition of forest residues feedstocks (% dry mass)

	Hardwood		Softwood		Switchgrass
	Black Locust	Hybrid Poplar	Eucalyptus	Pine	
Cellulose	41.61	44.70	49.50	44.55	31.98
Hemicellulose	17.66	18.55	13.07	21.90	25.19
Carbohydrates (%)	59.27	63.25	62.57	66.45	57.15
Lignin (%)	26.70	26.44	27.71	27.67	18.13
Ash	2.15	1.71	1.26	0.32	5.95
Heating value (GJ/ton)	19.5	19.6	19.5	19.6	18.6
Theoretical ethanol yield (liters/dry ton)	390	416	411	436	377

Source: Hamelinck, Hooijdonk, and Faaij (2005). Potential biofuel yields are calculated using the “theoretical ethanol yield calculator” (US DOE 2008b).

Several factors restrict the potential use of forest residues for biofuel production (Perlack et al. 2005). The first factor is the economic costs of transportation. Limited accessibility largely increases operation costs of logging/collection activities. Another factor is a potential reduction of recoverability in harvest areas due to environmental considerations (Richardson 2008).

2.1.3 Biofuel crops

Dedicated energy crops represent an additional potential source of feedstock for biofuel production. Biofuel crops can be broadly classified between grassy (herbaceous or forage) and woody (tree) crops. The former are described in the next section. Woody biofuel crops and their potential contribution are discussed in Section 2.1.3.2.

2.1.3.1 Perennial forage crops

Perennial forage crop species are a promising source of feedstock for second-generation biofuels. Switchgrass (*panicum virgatum* L.) is frequently mentioned because of its relatively low water and nutrition input and requirement costs, positive environmental impact, and adaptability to low quality land (Keshwani and Cheng 2009). Other perennial forage crops such as alfalfa (*Medicago sativa* L.), reed canarygrass (*Phalaris arundinacea* L.), napiergrass (*Pennisetum purpureum* Schumach.), and bermudagrass (*Cynodon* spp.)

could also serve as potential bioenergy crops. In this section, we will focus on switchgrass's characteristics, while briefly introducing other crop species.

a) Switchgrass

Among 34 herbaceous species, switchgrass is identified as a leading candidate of dedicated bioenergy crop by the Biofuels Feedstock Development Program at Oak Ridge National Laboratory (ORNL 2008). Switchgrass is widely and naturally distributed from Central America to Southern Canada. Research indicates that while soil type does not have much impact on switchgrass production, water-holding-capacity is important in its growth.

A wide range of yield expectations have been reported in the literature. Given ideal establishment and growing conditions, Thompson et al. (2005) reports dry mass potential yields based on for upland populations as high as 18 to 20 Mg/ha, while yields in lowland forms could reach 23-27 Mg/ha.

b) Other Species

Miscanthus is a grass native to Asia and a compelling herbaceous biomass feedstock for Europe (Lewandowski et al. 2003), in part because of its cold tolerance and low levels of nitrogen needed. A drawback to this species is that it takes 2-3 years to start full production as it must be established and propagated via rhizome cuttings. Other major limitations identified are: (1) limited availability of genotype, (2) important losses over winter, and (3) high costs of establishments (Lewandowski et al 2003).

Reed canarygrass is commonly used for hay and forage. It is well adapted to temperate agro-economic regions and to weathered soils (Carlson, Oram, and Suprenant 1996). Reed canarygrass can be slow to establish and become an invasive species in native wetland (Merigliano and Lesica 1998).

Alfalfa is a forage crop that can be used to both supply biomass feedstock and as a high quality animal feed (DeLong et al. 1995). Several other subtropical and tropical grasses have been explored as potential biomass feedstocks in the US, including bermudagrass (Boateng, Anderson, and Phillips 2007), napiergrass (Schank et al. 1993), eastern gamagrass and prairie cordgrass (Springer and Dewald 2004; Boe and Lee 2007).

The yield of these perennial species in terms of biofuel per ton of feedstock (and thus by hectare) will depend on their theoretical potential, and the conversion efficiency of the process. For switchgrass, the theoretical potential is around 100 gallons (377 liters) per dry ton (see Table 3). Liebman and Heggenstaller (2008) used yields of 79 gallons (300 liters) per ton for both switchgrass and miscanthus. As mentioned above, targets of 340 liters per ton of cellulosic feedstock have been set forth (NREL 2007).

2.1.3.2 Woody energy crops

Broadly referred to as woody energy crops, some fast growing tree species have also shown promise for biofuel production. Important attributes include the relatively high yield potential, wide geographical distribution, and relatively low levels of input needed when compared to annual crops (Smeets et al 2007). Their versatility as a source of solid and liquid energy is also a plus according to these authors. Poplar (*Populus* spp.), willow (*Salix* spp.), and eucalyptus are among the species most frequently mentioned for this end.

Dedicated energy crops as feedstocks for biofuel production have some advantages over the feedstocks currently used to that end. These energy crops are in general less demanding in terms of inputs, reduce erosion and improve soil properties, and provide better wildlife habitat. Additionally more energy per unit of land can be obtained from these crops as a higher proportion of the biomass can be utilized.

On the other hand, while highly yielding, dedicated energy crops do not entirely escape the food versus fuel debate as additional land is needed for their production. In order not to compete for land with food production, these crops (woody or forages) should only be installed in lands where neither food crop production nor grazing pastures are feasible activities, or that are not needed.

As with the case of crop and forest residues, the logistics of feedstocks obtained from dedicated energy crops is still a challenging issue to be resolved. These feedstocks are simply bulky and difficult to transport. For the case of switchgrass, Epplin et al. (2007) indicated that the corresponding infrastructure for harvest, storage, transportation, and spot markets still do not exist. In addition, a narrow harvesting window and yield

variability may potentially increase feedstock cost and force biorefineries to maintain a feedstock buffer for continuous biofuel production.

2.2 Biodiesel feedstocks

2.2.1. Jatropha

Jatropha (*Jatropha curcas*) is one of the oilseeds species that generated more excitement regarding its potential for biodiesel production. It is a multipurpose bush/low-growing tree, native of tropical America that can be used as a hedge, to reclaim land, and as a commercial crop (Openshaw 2000). *Jatropha* is now grown in many tropical and subtropical regions of Asia and Africa. The oil derived from *jatropha* has been shown to produce biodiesel that meets European and American quality standards (Azam, Waris, and Nahar 2005).

Jatropha can be grown in semi-arid conditions, and/or marginal soils without large investments in inputs (Jongschaap et al 2007). While non-edible, its oil could be burnt directly or processed into biodiesel, which makes it especially attractive for remote rural areas (Jongschaap et al 2007). This hype has been fueled by very optimistic claims in the gray literature of a concurrent capability of producing high oil yields and recover wasteland (Achten et al 2008). However, up to date, critical questions remain regarding its ability to be economically viable when grown on poor environmental conditions. Attainment of consistent high yields has only been achieved with relatively high levels of inputs and on good soils (IEA 2008).

Jatropha yields are highly influenced by site characteristics, genetics, management, and plant age. There are still many issues and questions regarding yield levels and optimal practices for *jatropha*, as systematic yield monitoring has only recently begun. Yields in the wide range of 0.4 to over 12 t/ha/yr have been reported (Openshaw 2000; citing work of Jones and Miller 1992), but as Heller (1996) points out many reported yields are not coherent. For seeds, these figures would be approximately equivalent to a 0.2 to 5.5 t/ha/yr range.

Table 4 summarized some of the seed yields reported in the literature for different growing settings, for the environmental conditions outlined in Achten et al. (2008). It is worth noting that there are some experiences documenting reasonable productivity levels

on marginal lands. The key seems to be to enhance growth in the initial phases of the plant by using additional inputs (Jongschaap et al. 2007 and references therein). The table also provides typical oil contents.

Table 4: Achievable Dry Seed Yields for *Jatropha curcas*

Reference	Achievable Yield (t/ha/yr)	Growing conditions
Heller (1996), Francis et al (2005)	2-3*	Semi-arid area and wasteland
Francis et al (2005)	5	Good soils, annual rainfall of 900-1200mm, optimal management
Jongschaap et al (2008)	7.8	Potential
	Oil content (%)	Plant part
Kandpal and Madan (1995), Ginwal et al (2004)	33-39	Seed
	46-58	Kernel ^a

*With water availability of 500-600 mm/yr Euler and Gorroz (2004) reported yields of less than 1 t/ha. ^a Accounts for roughly 65% of the seed.

Notice that the ranges of yields and oil contents of these seeds make for very wide ranges of oil yields per hectare. Typical production levels could be placed at 3.75 t/ha, with an oil concentration of 30-35% by weight, leading to oil yields of 1.2 t/ha (Gonsalvez 2006). Biodiesel yields between 1800 and 2800 liters per hectare have been mentioned as realistic for current conditions by industry sources (F.O. Licht 2009b).

To the best of our knowledge, there are no reliable estimates of the global extent of *Jatropha* cultivation. The British company D1 (D1 Oils 2008) is reported to acquire almost 260 thousand hectares distributed across India (73%), South-East Asia (21%), and Africa (6%). The site Jatrophabook.com asserts that over 3 million hectares will be in production within 3 years, mostly in India and Pakistan.⁸

2.2.2. *Micro-algae*

Microalgae are a diverse group of aquatic photosynthetic microorganisms that grow rapidly and have the capability to yield large quantities of lipids adequate for biodiesel production (Li et al 2008; WWI 2007). Algae as a potential source of fuel was initially investigated during the gas scare of the 1970s (Li et al 2008). The NREL started its algae feedstock studies in the late 1970s, but their research program was discontinued in 1996.

⁸ http://www.jatrophabook.com/statistics_jatropha_curcas_projects.asp.

Recent renewed interest has led the NREL to restart their research in algae (Donovan and Stowe 2009).

The potential for algae to provide biomass for biofuel production is now widely accepted. Further, algae are recognized among the most efficient means for this purpose, and some studies (e.g., Chisti 2007) assert it is the “only source of biodiesel that has the potential to completely displace fossil diesel”. One of the main advantages is its ability to produce large amounts of biodiesel per unit of land. Additionally, it can be grown on saline water, coastal seawater, and on non-arable land, hence softening or eliminating the competition for land with conventional agriculture (Khan et al. 2009), and opening economic opportunities in arid or salinity affected regions (Schenk et al. 2008).⁹

Cultivation is being done mainly on open ponds, on closed bioreactors, and in hybrid systems. While conventional open ponds are old systems for biomass production and account for the majority of microalgae cultivated today, closed bioreactors that achieve higher biomass productivity are being developed (Khan et al. 2009; Schenk et al. 2008). Open ponds are often perceived to be less expensive than bioreactors, as they require less capital and are cheaper to operate (Khan et al. 2009). On the other hand, open ponds are more susceptible to contamination from unwanted species (Schenk et al. 2008), and suffer from high evaporative water losses.

In addition to saving water, energy, and chemicals, other advantages such as a higher biomass concentration are increasingly making closed bioreactors the system of choice for biofuel production (Schenk et al. 2008). The larger productivity relative to reactor volume (and/or unit of land) is an important factor when considering the environmental footprint per unit of product.

A large amount of research is being conducted with the goal of improving the efficiency and lowering the overall costs of bioreactor systems. Advances in design and understanding of algal physiology, kinetics, and growth dynamics are paths being pursued to achieve economical viability. Hybrid systems are also being developed

⁹ These authors argue that appropriate strains need to be identified and/or engineered to be able to use water of varied quality and thus preserve freshwater. For references on research on this topic the reader is referred to Schenk et al. (2008).

attempting to combine the best of both production methods. In a hybrid system, the bioreactor is usually used to cultivate the inoculums that will be established on the ponds.

After the biomass has been produced it needs to be harvested to be used in biofuel production. Low biomass concentration in the culture (due to limited light penetration) and the small size of algal cells complicate harvesting leading to high costs (Li et al. 2008).

Table 5: Oil yields of algae and other oilseeds

Plant source	Oil yield (L/ha/yr)	Plant source	Oil yield (L/ha/yr)
Soybeans	446	Palm	5,950
Rapeseeds/canola	1,190	Algae ^a	12,000-98,5000
Jatropha	1,892	Algae ^b	58,700-136,900

Source: Chisti (2007), and Schenk et al. (2008). ^a Range from 10 g/m²/d at 30% Triacylglycerids (TAG) to 50 g/m²/d at 50% TAG (Schenk et al 2008), ^b Range from 30% to 70% oil by weight in biomass (Chisti 2007).

Microalgal can reach large productivity levels. Its yield per hectare has been reported to be several times that of the most productive tropical oilseeds such as palm (Table 5). The two crucial parameters determining algal yield are biomass productivity and oil content of the algae. These two parameters differ widely across algae strains and hence different strains can achieve very different biomass and oil yields.¹⁰

The algae yield scenarios reported by Schenk et al. (2008), included in Table 5, are based on existing production systems and their potential.¹¹ In terms of potential, Li et al. (2008) reports that the maximum theoretical yield for algal biomass production has been calculated at 365 tons of dry biomass per hectare per year (100 g/m²/d). For these of yields to be achieved, high concentrations of CO₂ would need to be fed.

In summary, significant barriers are still standing before the commercialization of algal biofuels is economically viable and the risks remain high. Despite this, algae could be a promising feedstock for biofuels. As of late 2008, Darzin (2008) indicated that seven US government laboratories, thirty US universities, and around sixty biofuels companies were conducting research in this area. Intense efforts are also taking place in other parts

¹⁰ Oil contents between 16% and 77% have been reported by Chisti (2007) for different strains.

¹¹ The examples given are Seambiotic Israel with current production levels of 20 g/m²/d at 8-40% TAG and HR BioPetroleum INC Hawaii which aims at obtaining 50 g/m²/d at 30% TAG. Schenk et al. (2008) actually report liters of biodiesel per hectare.

of the world including (among many others) Australia, Europe, the Middle East, and New Zealand (Pienkos and Darzin 2009).

2.3 Land availability for feedstock production and the long-run technical potential of biomass energy

The availability of land is one of the key variables determining the potential (and actual) production of biomass for energy. Land will be needed to produce biofuels based on dedicated energy crops such as switchgrass, miscanthus, and jatropha. Biofuels produced from crop and forest residues, and from microalgae will be less demanding in this aspect.¹²

Several estimates of the long run potential land available for bioenergy production are available in the literature, especially at the regional levels. Usually, the studies begin by defining the amount of land that would be suitable for rain-fed cultivation. Land already under cultivation, additional land for future demands for food, housing and infrastructure, and forests are deducted to obtain the amount of land that would be available for bioenergy production. In this procedure, the implicit assumption is that biomass for energy acts as a residual claimant of land.

However, the aggregate number for the amount of land that could be used for biofuels is strongly influenced by the criteria used to define the potential for rainfed cultivation (the starting point in Table 6). This distinction becomes important, if attempts to produce biomass for energy on marginal lands (e.g. jatropha) succeed.

An estimate of the levels of global land availability for bioenergy production was reported by Hoogwijk et al. (2005). Different scenario runs yielded that abandoned agricultural land could provide between 0.6 and 1.3 Gha by 2050. An additional 2.3 Gha would be available as rest land in that year, for an overall potential between 2.9 and 3.6 Gha. These areas are roughly doubled by the year 2100. More recently, Smeets et al. (2007) placed the potential in the 0.7-3.6 Gha range (see Table 6). The bulk of the area in the calculations shown would come from land that is not suitable for conventional

¹² Microalgae ponds and bioreactors can in principle be placed in areas land with no potential for agricultural activities.

commercial crop production. However, these could be available for bioenergy crops, but with appropriately discounted yields.

Table 6: Total area of agricultural land in 1998 and the potential surplus agricultural in 2050

Region	Total agricultural area 1998	Potential surplus
	Million Ha	
North America	493	54-348
Oceania	480	216-428
Japan	5	0
West Europe	147	12-61
East Europe	66	4-40
CIS and Baltic States	574	113-491
Sub-Saharan Africa	991	104-717
Caribbean and Latin America	760	152-555
Middle East and North Africa	461	23-372
East Asia	765	15-510
South Asia	224	36-63
World	4,966	729-3,585

Source: Smeets et al. (2007)

Notice however, that the figures reported refer to the global technical potential for biomass to produce energy and should be viewed as a maximum contribution that can be expected. Only a portion of that biomass will be used for biofuel production (and some will be lost during the conversion process). Given the uncertainties involved in projecting the amount of land available for biomass for energy production and its yield, the actual technical potential may be outside the range reported by most authors.¹³

3 Production Economics

The previous sections showed that second-generation biofuels can potentially make significant contributions to the energy mix. However, whether that potential will be realized depends on the economics of their production. In particular, biofuels will need to be cost-competitive with fossil fuels for their commercial scaling-up. The costs of different second-generation biofuels are reviewed in this section.

¹³ With the exception maybe of the authors reporting the widest ranges such as Hoogwijk et al. (2003) and IEA (2007).

The production costs we consider in this study include feedstock costs, capital costs, operating and maintenance costs (including labor and other energy sources). For bioethanol production, we limit our consideration to the enzymatic hydrolysis and fermentation process (also called EHF process), which is by now the most mature production process. For details relating to the technological aspects of production, we refer to the descriptions provided in other studies (e.g., Hamelinck, Hooijdonk, and Faaij 2005). Our aim here is to present a comparative picture of production costs second-generation biofuels using various feedstocks.

3.1 Feedstock costs¹⁴

Feedstocks are one of the main costs of second-generation biofuel production. Compared with those used for first-generation biofuels, lignocellulosic feedstocks are reported to cost less and be more readily available. As Hamelinck and Faaij (2006) point out feedstock costs accounts for 45-58% of total production costs for second-generation biofuels, depending on conversion efficiency and applied technology. The potential second-generation feedstocks considered in this study include (1) residues from agricultural food and non-food crops, (2) residues and waste products from the forestry industry, (3) dedicated energy crops, and (4) jatropha and algae.

3.1.1 Production cost of lignocellulosic feedstocks for ethanol

Existing estimates of cost of production, delivery, and storage vary widely among sources. This is not surprising given the lack of actual large scale production experiences. Although enhanced interest in second-generation biofuels is fairly recent, the literature in this area is vast. We report here summaries of estimates presented in select representative studies and feedstocks (see Table 7).

¹⁴ For comparison purposes, all the costs considered in this section are expressed in 2008 dollars, unless otherwise noticed.

Table 7: Estimated costs of selected agricultural residues (corn stover and crops straws) delivered to a bio-refinery¹⁵

Source	Feedstock	Estimated cost ^a	
		\$/ton	\$/lt ethanol
Gallagher et al. (2003)	Corn stover	17.13-18.21	0.0591-0.063
Perlack & Turhollow (2003)		43.10-51.60	0.149-0.178
Petrolia (2008)		57-69 ^b	0.188-0.224
Petrolia (2006)		38-43	0.131-0.148
Tokgoz et al. (2007)		76.00	0.262
Frederick et al. (2008)		54.67	0.189
Gallagher et al. (2003)	Winter wheat, continuous	20.16-28.04	0.070-0.097
Gallagher et al. (2003)	Winter wheat, fallow	38.18	0.132
Gallagher et al. (2003)	Spring wheat, continuous	24.17	0.083
Gallagher et al. (2003)	Sorghum	21.25-23.16	0.079-0.086
Gallagher et al. (2003)	Barley	21.78	0.070
Gallagher et al. (2003)	Oats	23.18	0.089
Gallagher et al. (2003)	Rice	25.21	0.090

Source: Elaborated by authors. See Table 1 for yields used to convert \$/ton to \$/lt. ^a Inflation adjusted to 2008. ^b These numbers are for a 50 million gallon a year plant. Costs between \$55 and \$93 per ton were obtained by varying the plant size and the harvesting method.

Table 7 shows that crop residue costs range from \$17 to \$76 per ton delivered. This wide range reflects differences in items to include in the cost calculation, and their magnitudes. Among the factors differentiating estimates are different perspectives on the sizes of yields, distances to conversion facilities, and storage needs, as well as the margin garnered by the grower as return on investment in producing feedstock versus other uses of land. As an example, the estimate by Gallagher et al. (2003) includes only harvest, transport, and increased fertilizer costs. Feedstock acquisition, storage, and opportunity costs such as their feed value are not included here. ¹⁶ Tokgoz et al. (2007) assume significantly higher baling and transport cost, in addition to a margin of roughly \$10 per ton garnered by farmers. Perlack and Turhollow (2003) include costs of collecting,

¹⁵ Sugarcane bagasse is an exception to the harvest cost calculations. The harvest, transport, and fertilizer replacement costs for bagasse are associated with the primary sugar crop. Thus, the incremental costs of harvesting and delivering bagasse to the processing plant are essentially zero.

¹⁶ On the other hand, opportunity costs such as hunting rights on areas with standing rice residues are included. According to the authors, the competition with feed uses is relevant in situations where crop residues are in limited availability. Higher opportunity costs (feed values, at about 48\$/ton for corn stover) are included only if there is a need to bid the residues away from the livestock sector.

handling, and hauling corn stover to the conversion facility, in addition to a \$10 per ton margin received by growers as payment for potential soil compaction, decreased surface organic matter, and return on their own effort. These studies highlight that the biofuel conversion plant size (determining feedstock demand) and density of residue availability can lead to significant differences in estimates through their impact on transport costs. This observation is also confirmed by the work of Petrolia (2008), who did not include a payment for farmers in his cost estimates, but acknowledged that some compensation may be needed for growers to make their stover available.

Opportunity costs depend on local conditions, including impacts of residue removal on expected yields and remedy costs (e.g., stemming from additional fertilizer or tilling), potential feed value of the residues, etc. Therefore, it is expected that these costs and the associated total costs of crop residues for biofuel production to vary across studies.

Estimated costs of residues of the forestry industry as well as woody energy crops reported in the literature are presented in Table 8. The prices reported by NREL (1998) (which are for U.S. forest products industry residues) vary greatly with local conditions. An aggregate U.S. supply curve for primary mill residues, estimated by Walsh (2008), indicates that a large proportion of these residues could enter the market when prices move from \$40 to \$45 per dry ton (the quantities supplied double in that price range). In this price range, an increasingly large proportion of primary mill residues could be bid away from their current use (e.g., wood). Further price increases would have much smaller impacts on residue availability, indicating a lower supply elasticity for prices above \$45 per dry ton. This indicates that higher price increases are needed for the other uses considered to release the raw materials needed for biofuel production. Additionally, lower quantities of residues remain to be bid away from these uses. A similar price range (\$40 to \$46 per ton) would also bring forth significant supplies of forestland feedstocks (including logging residues, removal residues, thinnings from timberlands, primary mill residues, etc) according to analysis performed by BR&Di (2008).

Table 8: Forest products residues and some woody energy crops costs for the bio-refineries

Source	Feedstock	Estimated cost	
		\$/ton	\$/lt ethanol
NREL (1998)	Hardwood primary mill residue	33.9	0.113
NREL (1998)	Softwood primary mill residue	34.6	0.115
NREL (1998)	Hardwood secondary mill residue	30.5	0.102
NREL (1998)	Softwood secondary mill residue	30.4	0.102
Junginger et al. (2005) ^a	Primary forest fuel (residues)	27	0.09
Frederick et al. (2008)	Yellow poplar	48.1	0.160
Frederick et al. (2008)	Loblolly pine	67.0-71.5	0.22-0.24
Manzone et al. (2009) ^b	Poplar	110-132	0.365-0.438

Source: Elaborated by the authors. ^a Original reported in 2002 euros/Gj, and was converted using 21.1 Mj/lt of ethanol (LHV) a yield of 300lt/ton of forest residues, an exchange rate of 1.08 euros/dollar, and updated to 2008 dollars using the GDP deflator (multiplied by 1.175). ^b Under conditions in Italy; original in euros/ton, converted with an exchange rate of 0.68 euros/dollar and 300lt of ethanol per ton of biomass.

As with other feedstocks, the estimation of production costs of herbaceous energy crops is not standardized, and thus not surprisingly the literature reports widely divergent figures (see Table 9). Their costs of production change with yield and land rent charges, which can vary widely. This is because land rent charges vary spatially reflecting the expected profitability of the options available to producers. *Ceteris paribus*, better soils will have higher agricultural returns and thus higher per hectare opportunity costs for feedstock production. On the other hand, higher yields tend to lower the opportunity cost of land by diluting these over more tons of feedstock. Some examples of the impacts of these assumptions can be obtained from Table 9. Epplin et al. (2007) used land rent costs in Tennessee of \$60 per acre for long term leases, and yields of 5.5 tons/ acre. For production in Nebraska and South Dakota, Perrin et al. (2008) used land rents ranging from \$26 to \$90 per acre, contingent on the field location. For his base case, Duffy (2007) assumed land costs in Iowa of \$80 per acre and yields of 4 tons/acre. The author also conducted a sensitivity analysis over a range of values for these parameters, as well as storage and transportation costs. Also for the case of Iowa, Babcock et al. (2007) obtain relatively high costs of production, using a different approach. These authors argue that in order for switchgrass to bid area away from corn and soybeans in the Corn Belt, the herbaceous crop should provide similar expected returns over variable costs of

production, roughly \$250 per acre. These differences across studies, combined with different production and harvesting practices make for different cost calculations in the literature.

Table 9: Estimated costs of herbaceous energy crops delivered to a bio-refinery

Source	Feedstock	Estimated cost ^a	
		\$/ton	\$/lt ethanol
Epplin et al. (2007)	Switchgrass	50-67	0.167-0.222
Graham et al. (2000)	Switchgrass	44-71	0.147-0.237
Pimentel and Patzek (2005)	Switchgrass	29	0.097
Mapemba et al. (2007)	Grassy biomass	27-59	0.090-0.197
Duffy (2007)	Switchgrass	116	0.387
Babcock et al. (2007)	Switchgrass	92-121	0.307-0.402
Vadas et al. (2008)	Switchgrass	56-60	0.187-0.200
Hallam et al. (2001)	Switchgrass	56-67	0.187-0.223
Perrin et al. (2008)	Switchgrass	46-88 ^b	0.153-0.293 ^b
Vadas et al. (2008)	Alfalfa	77-90	0.257-0.3
Hallam et al. (2001)	Alfalfa	78-83	0.26-0.277
Hallam et al. (2001)	Reed canarygrass	65-98	0.217-0.327

^a Inflation adjusted to 2008. ^b Does not include transportation costs to the biorefinery.

3.1.2 Production cost of biodiesel feedstocks

3.1.2.1 *Jatropha*

While the literature on *jatropha* production and properties is vast and there exist several numbers provided by technology developers and invested parties, only a few detailed cost estimates were provided by independent studies. Given this fact, and the lack of established optimal production practices and limited experience in commercial cultivation, it is again not surprising that these estimates vary widely across sources. Labor is needed at the feedstock production level to prepare land, set up nurseries, plant, fertilize, prune, and harvest. However, consistent and verifiable estimates of the amount of labor needed for *jatropha* production are not available, and different authors seem to present contradicting estimates (see e.g., Jongschaap et al. 2007; Lele 2006).

Early estimates were provided by Openshaw (2000). The calculated costs of establishing, tending and harvesting the crops are given in Table 10. Including downstream processing of the seeds, this author placed the costs of producing *Jatropha* oil in the 80-89 cents per liter range.

Table 10: Costs of producing and harvesting a jatropha crop (\$/ha)

	Years 1-5 (total)	Year 6 and onwards	Total 1-6
Establishment and tending the crop			
Labor ^a	67	26	93
Fertilizer	187	125	312
Seed	4	0	4
Plough Hire	11	0	11
Subtotal	269	151	420
Harvesting the crop ^b			
Yield ^c	9.25	7.5	16.75
Collect	26	21	47
De-coat	26	21	47
Shell	21	17	38
Subtotal	72	59	131
Total	342	209	551
Cost per ton of fruit	37	28	33

Source: Openshaw (2000), actualized to 2008 dollars. ^a The labor costs used by this author were \$1 a day (\$1.22 actualized to 2008). ^b Labor accounts for 95% of the harvesting costs. ^c Air dry tons.

More recently Francis, Edinger, and Becker (2005) placed the present value of life cycle costs at \$1,459/ha. These authors seem to have only included minimal (if any) inputs other than labor.¹⁷ The seeds yield is assumed to stabilize at 1.8 t/ha after the fifth year, with a 28% oil content, leading to a jatropha oil productivity of about 504 kg/ha. Including seed crushing, the feedstock costs were estimated at \$407.8 per ton of jatropha oil (\$442 per ton in 2008 terms).

Perhaps the most detailed estimates were recently provided by Kukrika (2008) for the case of India (see Table 11). This study calculates costs on a per year basis for a project that lasts 10 years. Many assumptions are behind these estimates. Yield levels, which are highly uncertain, are by far the most important assumption driving the results according to the author.¹⁸

¹⁷ These labor costs were offset from years 5 and onwards by a \$109 per hectare income derived from vegetable intercropping.

¹⁸ Yields are assumed at 1kg per tree for the first harvest year (fourth of the crop), increasing to 3 by year 8. There are 667 trees per acre. The oil content is assumed at 25%.

Table 11: Estimated Costs of Producing Jatropha Oil in India

	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
	(\$/lt ^a)						
Annual variable plantation costs							
Lease	0.15	0.04	0.02	0.02	0.02	0.02	0.02
Harvesting	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Maintenance	0.37	0.09	0.06	0.05	0.05	0.04	0.04
Retainership (including irrigation costs)	0.41	0.10	0.06	0.05	0.05	0.05	0.05
Sub-total	1.01	0.31	0.22	0.21	0.20	0.18	0.18
Annual variable logistics costs							
Seed collection center	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Warehousing	0.04	0.01	0.01	0.01	0.01	0.01	0.01
Transport	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sub-total	0.07	0.04	0.04	0.04	0.04	0.03	0.03
Annual extraction operating costs							
Seed preparation	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Decorticator and oil extraction unit operations	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Sub-total	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Oil distribution (to biodiesel production plant)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	1.16	0.44	0.36	0.33	0.33	0.31	0.31

Source: Kukrika (2008). ^a The original figures are in 2007 Rs/lt, and were converted to \$/lt using and exchange rate of 42.4 Rs/\$ as of 2007 and inflation adjusted to 2008.

3.1.2.2 *Microalgae*

The economic viability of some projects dedicated to the production of higher value products (such as taxanthin and nutraceuticals) has already been demonstrated (Schenk et al. 2008). However, economics are the main current impediment to large scale cultivation of microalgae for lower value uses. Simply stated, in order for microalgal biodiesel to be commercially viable, production costs need to be sharply reduced from current levels.

Assessing the costs of producing algal oil is a challenge, mainly because of existing uncertainty of potential yields and evolving technologies. Early estimates (Benemann and Oswald 1996) placed achievable cost for open ponds in the \$51-90¹⁹ per barrel range, for two different yield levels. A summary of their calculations is presented in Table 12. These calculations considered two alternative production systems. In the first system, the power plant and the algae farm are located nearby to allow for direct flue-gas utilization. In the second system, the flue gas captured from a remote power plant is purified to CO₂ and transported to the algae farm. The second option would obviously

¹⁹ Inflation adjusted to 2008.

have higher operating costs as compared to the first one due to the purification and transportation costs. In each production system, two different yield levels (109t/ha/y and 218t/ha/y) were included. Although the levels of the yield considered could be theoretically plausible, such high yields have yet to be consistently obtained in practice (Schenk et al. 2008).

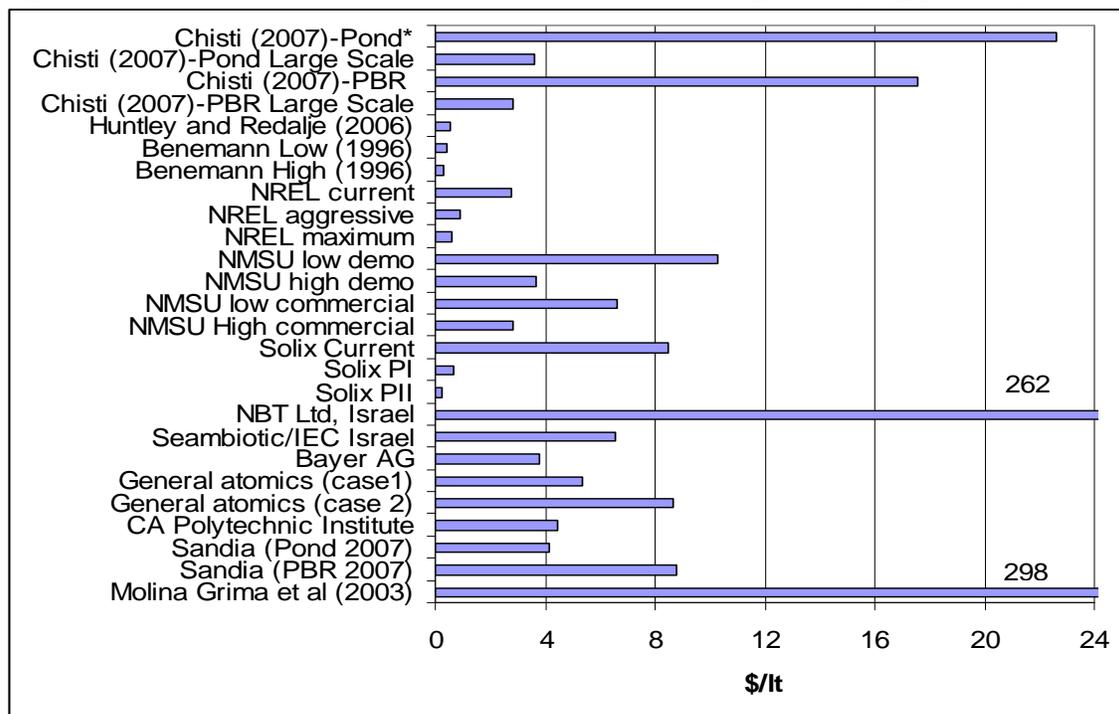
Table 12: Capital and operating costs for an open pond system

	30 g/m ² /d 109 t/ha/y		60 g/m ² /d 218 t/ha/y	
	Remotely Supplied CO ₂	On-site flue gas	Remotely Supplied CO ₂	On-site flue gas
Capital costs (\$)	96,756	90,884	136,228	122,658
\$/mt-yr biomass	887	835	626	561
Operating costs (\$) ^a	19,795	14,184	21,752	19,925
Capital charge (15%)	14,484	13,701	20,421	18,399
Total annual costs (\$)	34,279	27,885	42,173	38,324
\$/mt biomass	315	256	193	176
\$/barrel of algal oil	90	73	55	51
\$/lt of algal oil	0.57	0.46	0.34	0.32

Source: Benemman and Oswald (1996). Inflation adjusted to 2008. ^a Labor and overhead would amount to about \$3,915 and \$5,219 for the low and high productivity cases respectively.

More recently, and with the renewed interest on microalgae production, several widely diverging estimates of the cost of production emerged. Interestingly, almost all of the recent estimates are much higher than the numbers presented by Benemman and Oswald (1996), mostly due to the difficulty of attaining such large yields. A summary of several of the most recent estimates is presented in Figure 1.

Figure 1: Recent Estimates of Costs of Production of Algal Oil (triglyceride)



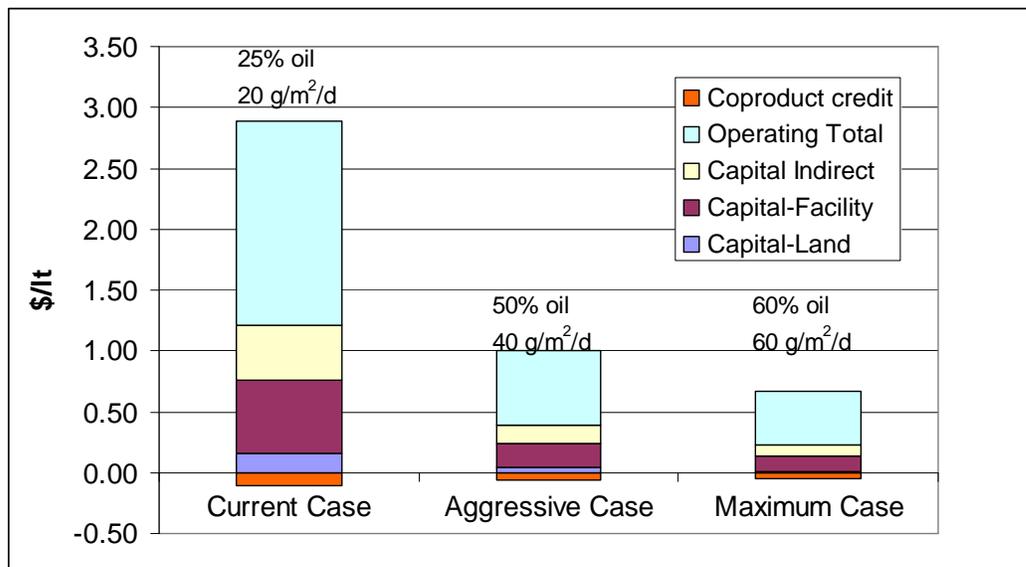
Source: Pienkos (2009). *Assumes that 50% of the oil is accounted for by the recovery process. PBR=Photobioreactor. Pond=refers to open ponds and raceways. Estimates in the chart without a year assigned were presented in 2008. Low and High refer to algae productivity. Benemann and Oswald (1996) is cited as Benemann (1996) to reduce clutter in the figure. To the best of our knowledge, of the number in the graph, only Molina Grima et al. (2003) and Chisti (2007) have been published in peer reviewed journals.

The average and standard deviation of cost across the studies presented in Figure 1 are \$25 and \$72 per liter, respectively.²⁰ However, the mean is strongly affected by the (large) cost estimates of Molina Grima (\$298 per liter) and NBT Ltd (\$262 per liter). The median (which is less affected by extreme values) is \$4.3 per liter. The costs uncertainties are large, with uncertainty in capital cost (facility investments) being more substantial than for operating cost (Pienkos 2008). It also should be emphasized that most of the lowest estimates in the figure (e.g., Benemann 1996, NREL aggressive, NREL maximum, and NMSU High commercial) refer to targets costs to be achieved at different points in the future, contingent on the possibility of realizing significant and consistent yield gains. Estimates of costs given current technologies are clearly much higher, and there is no assurance the hoped-for advances will materialized as assumed.

²⁰ A list of the main assumptions behind the disparate results presented in figure can be found in Pienkos (2008).

A large proportion of the discrepancies observed can be attributed to differences in algal oil yield per unit of area. This indicates that improvements in algal oil yields per unit of area should be targeted as a cost reducing strategy. The importance of yields in driving costs can be observed in Figure 2, along with a break down on cost components. The major two components each accounting for roughly 30% of the operating costs are water and the supply of CO₂ (Pienkos 2008). The three cases in the figure refer to differences in biomass and oil yield per unit of land, and correspond to the NREL (current, aggressive, and maximum) scenarios presented in figure 1. The “aggressive” and “maximum” indicate assumptions regarding yields that need to be attained, and assume algae oil yields of roughly 73 and 131.4 tons per hectare. Clearly, significant breakthroughs are needed to achieve these yield levels on a consistent basis.

Figure 2: **Impacts of productivity on costs of production**



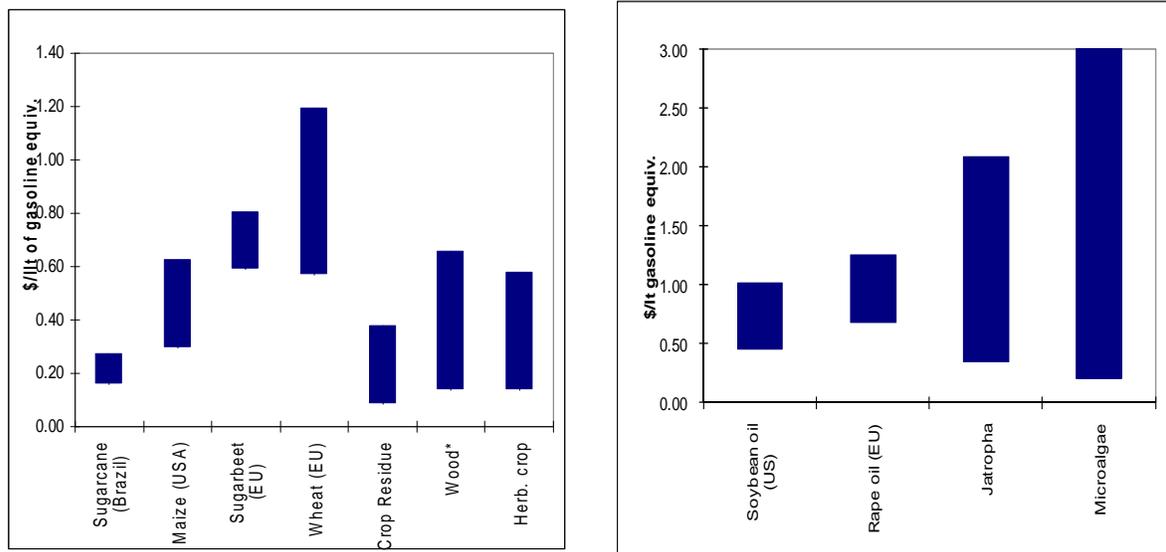
Source: Pienkos (2008).

In this line, many attempts have been made in recent years to refine the design and materials of algae cultivation systems in order to increase their productivity. The enhanced interest and research in this area is yielding fruit. As an example, GreenFuel Technologies Corporation developed a new production system called 3D Matrix System (3DMS), that achieved productivities of 98 g/m²/d over a 19 period trial under field conditions. These yields, which were externally evaluated (Pulz 2007), are remarkably close to the theoretical maximum indicated above. However, despite the rapid advances

in this area, the risks are still high. In May 2009, GreenFuel Technologies had to close its operations as it was unable to raise the money needed to continue their research efforts to lower costs of production (F.O. Licht 2009a).²¹

In short, widely divergent estimates of feedstock costs have been published in the past few years. Ranges of feedstock production costs obtained from the representative studies surveyed are summarized in Figure 3.

Figure 3: Cost of various feedstocks for first and second-generation biofuels.^a



Source: ^a For cellulosic ethanol, a yield of 0.3 liters/ton of feedstock is assumed (see Table 1). A one to one conversion was assumed for vegetable oils into biodiesel. * Includes forest residues and dedicated woody energy crops. Feedstock costs for first-generation ethanol were obtained from IEA (2008) for the 2005-2007 period (co-product credits are not assigned). Rapeseed oil and soybean oil prices are from FAPRI (2009) for the 2005-2007 period.

3.2 Biofuel capital investment and production costs

Based on the current state of technology, second-generation biofuels will come at very high capital cost, over five times that of similar capacity starch ethanol plants (Wright and Brown 2007). The estimated capital investment cost for a 220 million liters per year cellulosic ethanol plant using wood or switchgrass as feedstock along with the magnitude

²¹ These costs have been estimated in 2007 by Dimitrov to result in biodiesel costs exceeding \$800 per barrel, even using very optimistic (in the words of the author) assumptions

of different components are listed in Table 13. The largest capital cost components are for feedstock pretreatment, simultaneous saccharification and fermentation, and energy utilities.

Table 13: Estimated investment for a 220 million liters per year cellulosic ethanol plant^a

Cost category	Million \$	Share (%)
Feedstock handling (wood or switchgrass)	13.3	5.1%
Pretreatment	44	16.8%
Xylose fermentation	11.4	4.3%
Cellulose production	5.2	2.0%
Simultaneous saccharification and fermentation	38.8	14.8%
Ethanol recovery	7.5	2.9%
Off-site tankage	7.6	2.9%
Environmental systems	7.3	2.8%
Utilities (steam, electricity, water)	94.5	36.0%
Miscellaneous	8.9	3.4%
Fixed capital investment	238.5	90.9%
Start-up costs	12	4.6%
Working capital	11.9	4.5%
Total investment	262.4	100.0%

Source: Solomon, Barnes, and Halvorsen (2007). ^a Inflation adjusted to 2008

A different break-out of the capital investment components was recently presented by Piccolo and Bezzo (2009) for the EHF process, which consists of five major steps: (1) biomass feedstock pre-treatment, (2) cellulose hydrolysis, (3) fermentation, (4) separation, and (5) effluent treatment. The investments needs for the different steps of this process are summarized in Table 14.

In general, based on currently available technology, capital investments for cellulose based ethanol production are estimated to be in the range of \$1.06 to \$1.48 per liter of ethanol annual capacity (Wright and Brown 2007). Currently, the operation costs associated to these plants are between \$0.35-\$0.45 per liter depending on assumed feedstocks and corresponding technologies. Anticipated improvements of biofuel conversion technologies are expected to reduce the capital investments to \$0.95-\$1.27 per liter ethanol annual capacity and to reduce the operating cost to \$0.11-\$0.25 per liter of ethanol (Hamelinck, Hooijdonk and Faaij 2005). Again, however, there exists significant

uncertainty as to what cost reductions actually will be achieved, since these are conditional on significant technological breakthroughs.

Table 14: Total investment required for an EHF process

Cost category	Installation costs (M\$)	Share (%)
Pre-treatment	31.52	8.95%
Heat exchangers	10.87	3.09%
Stills	4.27	1.21%
Fermentation section	12.86	3.65%
Compressors	0.31	0.09%
Steam turbine	44.5	12.64%
Water Waste Treatment	10.4	2.95%
Onsite installation costs	114.74	32.59%
Other costs and investments ^a	237.28	67.41%
Total project investment	352.02	100.00%

Source: Piccollo and Bezzo (2009). The plant is assumed to process 700 thousand dry tones of biomass per year. ^a Piccollo and Bezzo (2009) did not include this category (only onsite installation costs and total investments were reported) .

A breakdown of the production costs for lignocellulosic ethanol from four studies is presented in Table 15. Given the variability in feedstock costs reviewed in the previews section, it is to be expected that production costs of second-generation biofuels would be wide-ranging. A recent literature review reported current production costs of second-generation ethanol in the \$0.60-1.30/liter range (IEA 2008). Technological advances are expected to drive production costs down to as low as \$0.30-0.40 per liter by 2020 (IEA 2005; Perlack et al. 2005). More ambitious targets for production cost reductions (achieving costs of \$0.28 per liter by 2012) were included in the U.S. Biofuels Initiative (US DOE 2008).

Despite small differences in the relative weight of some cost categories, estimates are largely consistent with each other for the first three studies, yielding an estimated cost of \$0.6 per liter of lignocellulosic ethanol. Capital costs account for roughly 40% of the overall costs in the studies. It should be noticed, that these sources used very similar assumptions in terms of feedstock costs, implying comparable costs for all the other

categories (in order to obtain the same total cost). More variations in costs are introduced in the study by Frederick et al. (2008). Note that feedstock accounts for between 32% and 52% of total costs of production across all studies. This is in marked contrast with first-generation ethanol, where feedstock accounts for roughly 55% to over 70% of the total costs of production (IEA 2008).

Table 15: Production costs for the lignocellulose process (\$/lt)^a

	Sassner et al (2008)			McAloon et al (2000)	Solomon et al (2007)
	Salix (willow)	Spruce	Corn stover	Corn stover	Switchgrass or Wood
Feedstock	0.23-0.28	0.21-0.23	0.21-0.28	0.19	0.20
Other costs	0.19-0.26	0.17-0.19	0.18-0.26	0.20	0.22
Co-products	-0.09--0.16	-0.1--0.12	-0.09--0.16	-0.02	-0.04
Total operating costs	0.32-0.37	0.28-0.3	0.3-0.37	0.36	0.38
Capital costs	0.25-0.31	0.24-0.25	0.23-0.31	0.24	0.22
Total costs	0.57-0.69	0.52-0.55	0.53-0.68	0.60	0.60

	Frederick et al (2008)		
	Yellow Poplar	Loblolly Pine (1) ^b	Loblolly Pine (2)
Feedstock	0.15	0.23	0.27
Other costs	0.12	0.11	0.07
Co-products	-0.02	-0.02	-0.11
Total operating costs	0.25	0.32	0.23
Capital costs	0.14	0.12	0.42
Total costs	0.39	0.44	0.65

Source: ^a Inflation adjusted to 2008. ^b Two different pretreatments of the biomass are considered here.

For the case of jatropha based biodiesel, costs of production have been reported in the range of \$0.44-2.87 per liter for developing country settings (see Table 16). Wide ranges are reported even within studies for a given location, reflecting persisting uncertainty regarding jatropha yields and associated feedstock costs of production (Peters and Thielman 2008). Estimates at the lower end of the range seem to be based on fairly optimistic assumptions on production costs. Some authors expect costs to decline as large scale production and oil extraction improves the efficiency of the process and economies of scale are exploited (GTZ 2005). Other authors indicate that stakeholders should be cautious in front of these cost projections, since they may remain high even in large scale operations (Peters and Thielman 2008).

Some support for that view can be gleaned from the Indian experience. The Indian government mandated their state-owned distribution firms to buy biodiesel at the fixed

price of 25Rs, or 0.59 \$/lt (at an exchange rate as of 2007 of 42.4 Rs/\$). Kukrika (2008) indicated that few producers are selling to these distribution centers, as the prices are below the costs of production. Peters and Thielman (2008) also caution that their projected estimates could be rather optimistic.

Table 16: Cost of Jatropha based Biodiesel Production (inflation adjusted to 2008)

Item	Costs (\$/lt)	Country setting and comments
Gonsalvez (2006)	0.44	India
Francis et al (2005)	0.54	India (feedstock at 441.8\$/ton ^a)
Peters and Thielman (2008) ^b	1.44-2.87	India-current
Peters and Thielman (2008)	0.42-1.30	India-projected
Peters and Thielman (2008)	2.29-2.45	Tanzania-current
Peters and Thielman (2008)	0.72-0.82	Tanzania-projected
Kukrika (2008)	0.72-1.67	India-see table 11

Source: ^a Assuming a seed cost of 0.12 US\$/kg, an oil extraction rate of 28%, and a processing cost of 21.2 US\$/ton. ^b The original ranges are reported in 2004 dollars per 1.09 liters of biodiesel to facilitate the comparison with its fossil alternative. The numbers reported here are in 2008 dollars per liter. Costs for management overhead were not included.

Table 17: Estimated costs of producing biodiesel from jatropha trees

	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
	(\$/lt ^a)						
Delivered Jatropha oil cost ^b	1.16	0.44	0.36	0.33	0.33	0.31	0.31
Biodiesel production (total refining costs)	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Methanol	0.11	0.11	0.11	0.11	0.11	0.11	0.11
KOH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity, water and other	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Yield loss (10%)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Depreciation of fixed costs	0.11	0.03	0.02	0.01	0.01	0.01	0.01
Sub-total costs for biodiesel before distribution to end-users	1.43	0.63	0.53	0.51	0.50	0.48	0.48
Distribution to end-users	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Producer's margin	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Assumed tax (excise and sales)	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total cost of biodiesel (delivered)	1.67	0.87	0.77	0.75	0.74	0.72	0.72

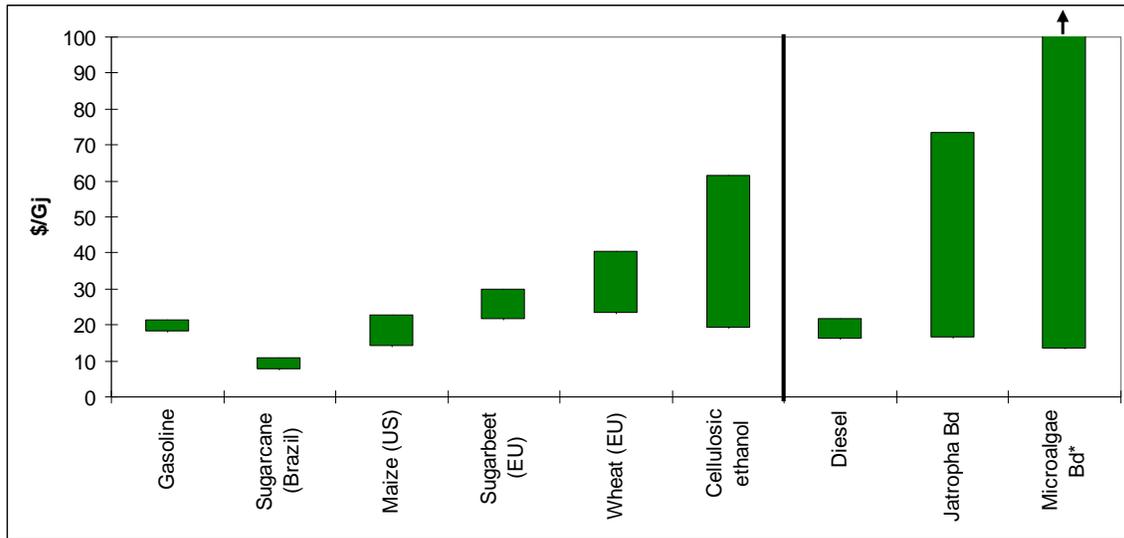
Source: Kukrika (2008). ^a The original figures are in 2007 Rs/lt, and were converted to \$/lt using an exchange rate of 42.4 Rs/\$ as of 2007 and inflation adjusted to 2008. ^b From Table 11.

One of the most explicit estimates available for the costs of producing jatropha based biodiesel in India was provided by Kukrika (2008) (see Tables 11 and 17). The estimates

started in year 4 of the crop, the first year in which *Jatropha* fruits yield seeds (Kukrika 2008). Estimates of the costs of establishing and maintaining the crop for the first three years are reported in Appendix I(a) of Kukrika (2008). However, it is unclear to us how these costs were allocated to the production of subsequent years.

Again, the cost of the energy provided by second-generation biofuels varies widely across studies. However, most sources indicate that these biofuels are still a relatively expensive form of energy when compared to fossil fuels. The total production costs per unit of energy reported in the literature are summarized in Figure 4, along with the fossil energy forms they would replace. The data provided in the graph partially explains the lack of second-generation biofuel production at commercial scales. The cost of cellulosic ethanol shown in the figure is between 1.1 and 2.9 times higher (per unit of energy) than the price of gasoline. The most optimistic assumptions reviewed would place the target (hoped-for) cost of second-generation biodiesel (from either *Jatropha* or algae oil) at a similar level to the price of diesel. However, these low costs have not been obtained in large scale production. This is especially true for the case of algae oil based biodiesel, for which some estimates (based on facilities currently producing algae oil) would make it over 100 times more expensive than diesel. It is worth noticing that the prices for fossil fuels presented in the figure correspond to the 2007-2008 years, a period of relatively high energy prices. Thus, significant breakthroughs are still needed in order for a second-generation biofuels industry to develop.

Figure 4: Biofuel production cost (\$/Gj) from various feedstocks



Source: IEA (2008). For gasoline and diesel prices, the range is given by wholesale prices (excluding taxes) in years 2007 and 2008 in the U.S.. The assumed energy content are as follows: ethanol 21.1 mj/lt; gasoline 32 mj/lt; biodiesel 33.3 mj/lt; and diesel 36.4 mj/lt. Capital and operating costs for processing algae oil into biodiesel were assumed equal to those of converting other vegetable oils into biodiesel and set to \$0.122 per liter (Paulson and Ginder 2007). First-generation ethanol costs are from IEA (2008). * The upper values for feedstock costs would imply costs of production per Gj in the thousands for algae biodiesel.

4 Environmental Impacts of Second-Generation Biofuels

In this section we discuss issues related to energy balance, GHG emissions, water use, and impact on biodiversity of second-generation biofuels. The interested reader is referred to some detailed and recent reviews published by OECD (2008), IEA (2008), and WWI (2007).

4.1 Fossil energy displaced by biofuels

Many life cycle analyses (LCA) of different biofuels, produced following different technologies and in distinct regions have been conducted in recent years. A consensus seems to have been reached in that when considering only the LCA, biofuels can contribute to displace fossil energy and reduce GHG emissions in that process. The (fossil) energy balance of a sample of possible biofuel pathways is presented in Table

18²². The table indicates that the energy balance of second-generation biofuels has the potential to be much higher than that of their first-generation counterparts, with the exception of sugarcane ethanol and perhaps biodiesel from waste grease or oil. It is worth noting that the numbers presented should be looked as a rough approximation, and care should be exercised when comparing them to each other. As Farrell et al. (2006) indicated, different studies will in general rely on different assumptions and system boundaries, and thus direct comparison of the results of their LCAs is often misleading. For example, the US Natural Resources Defense Council (NRDC 2006) surveyed studies of fossil energy balances, reporting figures between 4.4 and 6.6 (units of energy produced for every unit of energy used) for lignocellulosic ethanol.²³

Table 18: Fossil energy balance of a sample of the fuel types^a

Fuel	Approximate fossil energy balance ^b
Cellulosic ethanol	2-36
Corn ethanol	~1.5
Wheat ethanol	~2
Sugarbeets ethanol	~2
Soybeans biodiesel	~3
Sugarcane ethanol	~8
Rapeseed biodiesel (EU)	~2.5
Waste vegetable oil biodiesel	~5-6
Palm oil biodiesel	~9

Source: WWI (2007). ^a For the full list of fuels/feedstocks and references see table 10.2 in WWI (2007) ^b Ratio of energy contained in the fuel to the fossil energy used to produce it.

4.2 GHG emission reductions

By displacing fossil fuels, second-generation biofuels have the potential to reduce GHG emissions (EPA 2007). Several studies have estimated the GHG mitigation potentials of different feedstocks, conversion, process technologies, and handling of co-product. Table 19 compares GHG mitigation potentials of various biofuels using LCA techniques.

²² The fossil energy balance is a measure of the amount of energy obtained as a biofuel per unit of fossil energy utilized in the biofuel production process.

²³ For the sake of completeness, we should mention that there is a study (Pimentel and Patzek 2005) which contradicts these consensus findings, reporting that both corn and lignocellulosic ethanol would result in negative energy balances. Major departures from other studies are that Pimentel and Patzek (2005) did not credit co-products for the energy they contain, and assume higher levels of inputs and lower productivities than most authors.

Table 19: GHG Emission reductions of select biofuels compared to gasoline and diesel excluding land use change impacts

Biofuel	Emission Reductions (%) ^a
Sugarcane ethanol	65 – 105
Wheat ethanol	-5 – 90 ^b
Corn ethanol	-20 – 55
Sugarbeet ethanol	30 – 60
Lignocellulose ethanol	45 – 112 ^c
Rapeseed biodiesel	20 – 80
Palm oil biodiesel	30 – 75
Jatropha biodiesel	50 – 100 ^d
Lignocellulose diesel	5 – 120

Source: OECD (2008), WWI (2007), Wang et al. (2007) and Whitaker and Heath (2009) data. ^a Values are approximate, as some reports only reported results in graphical form. ^b Negative numbers mean increases in GHG emissions. ^c Includes forest residues, energy crops (such as short tree rotations (e.g., poplar), and switchgrass), and crop residues (e.g., corn stover). ^d Whitaker and Heath (2009), their base base resulted in 62% GHG emission reductions when compared to diesel. Previous studies by Ecofys BV (2008, commissioned by D1 Oils) and Prueksakorn and Gheewala (2006) reported values within that range (70% and 77% respectively).

Most studies coincide in that most biofuel pathways reduce emissions of GHG when compared to the petroleum energy they displace, especially when land use changes are not included in the analysis. The second-generation biofuels appear to have higher potentials of GHG mitigation as compared to the first-generation biofuels. The inclusion of land use change (both direct and indirect) may reduce some or all GHG emission gains, or even result in net emission increases (Searchinger et al. 2008). Note however that the indirect GHG emissions through land use change would be smaller in the case of second-generation biofuels as compared to that of first-generation biofuels.

4.3 Water footprints

Water scarcity is one of the major constraints of future potential production of second-generation biofuels, which has been largely ignored in the literature. The increasing demand for fuels produced from biomass will intensify the pressure on clean water resources because (1) large quantities of water are needed to grow certain feedstocks such as energy crops, and (2) agricultural drainage (containing fertilizer, pesticides, and sediments) is likely to increase with crop production.

The water footprint is a measure commonly applied in the literature to represent the extent of water use. For example, the water footprint of a country refers to the volume of fresh water needed for the goods and services produced to be consumed by the people in the country (Hoekstra and Chapagain 2007). The water footprint of a biofuel is defined

as the total volume of fresh water used to produce a unit of the biofuel (Gerbens-Leenes, Hoekstra, and van der Meer 2009). The most water intensive stage in the biofuels production process is the cultivation of feedstocks (in particular dedicated energy crops).

The estimated water footprints for the production of several biofuels, using various feedstocks are presented in Table 20. Compared to other feedstocks, sugarcane has the lowest water footprint. Bioethanol production based on corn and sugarbeets have a relatively higher water demand. Biodiesel produced from rapeseed and soybean oils has higher water footprint than biomass-based ethanol.

Table 20: Average water footprint of biofuel produced with different feedstocks

Biofuel type	Feedstock	Water footprint of biofuel (m ³ /L)
Bioethanol	Maize	2.01
Bioethanol	Cassava	2.64
Bioethanol	Sugarcane	1.47
Bioethanol	Sugarbeets	2.24
Bioethanol	Sweet potato	1.83
Biodiesel	Rapeseeds	5.82
Biodiesel	Soybean	15.63

Source: Yang, Zhou, and Liu (2009)

The water footprints of biofuels vary significantly over (1) the type of feedstock applied; (2) the climate conditions during the agricultural production period; and (3) crop yields and related agricultural practices. Compared to some food crops including barley, rice and wheat, oilseeds, such as rapeseed and jatropha, have low water efficiency. On the other hand, sugarcane, corn, and sugarbeets are the most efficient crops in terms of freshwater demand. A low water efficiency of jatropha when compared to other feedstock sources was also reported by Rajagopal and Zilberman (2007). However, and as of 2007, little was known about water use and efficiency of jatropha, as (differently from other crops) no study was conducted to evaluate actual water usage in crop production (Jongschaap et al. 2007).

4.4 Biodiversity impact

Intensification of feedstock production for second-generation biofuels can have both positive and negative impact on biodiversity (Anderson, Haskins, and Nelson 2004).

While growing dedicated biomass crops can result in large scale land use changes that affect biodiversity, producing biofuels from crop/forest residues or waste should have much less of an negative impact.

The overall impact on biodiversity depends on (Anderson and Fergusson 2006): (1) the biomass crop's intrinsic biodiversity value, which is largely determined by the crop and management practices (e.g., perennial woody or grass crops may provide benefits to wildlife, but crops that are more intensively managed are more likely to have a negative impact), (2) the relative biodiversity value of the biomass crop to other land uses they replace (as more marginal land, known to provide biodiversity benefits, is replaced by intensively managed biomass crop, the effect on overall biodiversity is likely to be negative), (3) landscape scale effects, the location, intensity, and spatial distribution of the biomass crops. In this line, the consequences of relatively low energy contents of major feedstocks for second-generation biofuels include: (i) large quantities of feedstocks need to be produced in order to meet energy demand, which will potentially induce large scale land use changes. (ii) The transportation costs of these bulky raw biomass materials are likely to have the effect of limiting biomass processing facilities to be close to the monocultures of biomass feedstocks. In these cases, the overall biodiversity effect is likely to be negative.

In general, biomass energy crops will be more biodiversity friendly if they are native and perennial species that can be produced with few inputs. However, if it is developed as a high-yield monoculture variety is likely to have worse biodiversity effect than native species. Second-generation biofuels produced from crop residues, perennial species or wood may prove to be more ecologically friendly than grain and grass feedstocks (Groom, Gray, and Townsend 2008).

5 Challenges and Policies

A myriad of policies affect the markets for biofuels. Keeping track of the fast changing policy environment in which biofuels are produced, consumed and traded is challenging as new policies are being rapidly enacted by different countries and previous legislation is frequently modified. REN21 (2009) reports that 73 (many of them developing) countries had bioenergy targets as of early 2009. These include not only biofuels, but also

other forms of renewable energy, such as electricity derived from biomass, wind and solar energy. At least 23 countries were reported as having mandates to blend biofuels into fossil transportation fuels. While 2008 was relatively calmer than previous years for the enactment of new biofuels policies, many countries adjusted their tax incentives, national targets, and blending mandates (REN21 2009).²⁴

A vast majority of these policies do not differentiate between first and second-generation biofuels. That is, they would incentivize the supply and utilization of both generations at the same levels, regardless of costs of production and or the relative value of the benefits they may provide (e.g., net carbon reduction). However, exceptions can be found in the renewable energy legislations of some countries, including the US and the EU. The US Energy Independence and Security Act (EISA) of 2007 guarantees a market for advanced biofuels. The minimum size of that market is set at 21 billion gallons (79.5 billion liters) by 2022, of which 16 billion gallons (60.5 billion liters) are reserved for cellulosic biofuels. Additionally, it provides for funds in the form of grants and loans for R&D, and development and construction of advanced biorefineries. Regulations implementing EISA indicate that cellulosic ethanol will be counted at a rate of 2.5 to 1 towards the renewable fuel standard. In practice, this means that the Renewable Identification Numbers associated with cellulosic biofuels can potentially be worth 2.5 times that of corn ethanol, which tends to reduce the costs differential between them. On a separate piece of legislation, the Farm Bill of 2007 increased the blender's tax credit for cellulosic ethanol to \$1.01 per gallon, while reducing that of conventional (corn) ethanol to \$0.45 per gallon. Financial incentives for the production of crops for bioenergy and assistance with collection, harvesting, storage and transportation of biomass to biorefineries are among the measures in the farm bill directed towards second-generation biofuels.

The EU also provides additional benefits for second-generation biofuels, compared to those given to conventional biofuels, but to a lesser extent than the US. Under the draft Directive proposal of 2008, requiring 10% of renewable energy used in

²⁴ A listing of important features of biofuels policies implemented by several countries can be found in REN21 (2009) and in Timilsina and Shrestha (2009). Examples of policies directed at different points of the supply chain, from the production of biomass until the consumption of fuels can be found in OECD (2008).

transport, the contributions of second-generation biofuels, other biofuels, and electric cars among others are credited with a multiplier of 2.5 towards that target (REN21 2009).

The main challenge second-generation biofuels are facing is economic in nature. When compared on a private cost of production basis (i.e. excluding external costs to society), they are still simply too expensive to produce, relative to the fossil fuels they could replace. Considerable research is still needed to foster the technological breakthroughs needed for second-generation biofuels to achieve the costs reductions along the supply chain indicated in section 3. Different technologies are at varied stages of development. While commercial deployment of ethanol produced from cellulosic ethanol is expected to happen by 2015 (IEA 2008), microalgae, biodiesel is not likely to be commercially viable according to industry sources until the next 10-15 years (F. O. Licht 2009c). Given the public good characteristics of investments in R&D, economic theory would indicate that underinvestment from the private sector is likely (Rajagopal and Zilberman (2007).

Policy interventions could help accelerate the transition from first-generation to the commercial deployment and uptake of second-generation biofuels. However, it is also crucial that policies are tailored in such a way to support the development of the most advantageous biofuels and discourage production of “bad biofuels” (IEA 2008). The same source highlights the importance of support for basic R&D and deployment to improve the competitiveness of the preferred pathways.

Several public investments in R&D to accelerate the transition to advanced biofuels have shown great promise. Investments in part financed by the US Department of Energy have been very effective at reducing the costs of producing enzymes for cellulosic ethanol production. Reductions in the order of 30 fold are cited by WWI (2007). Support of research leading to more valuable co-products, also has the potential of lowering the overall cost of second-generation biofuels, facilitating the arrival of these technologies.

Government funding for biofuels R&D, applied research, demonstration projects and/or feasibility studies is common in OECD countries. This is a strong indicator that policymakers in these countries acknowledge the importance of the public sector’s involvement in this area (OECD 2008). The US is by far the country with the largest

investments in bioenergy R&D. As an example, the US DOE will invest over \$600 million over the next 4 or 5 years in several joint demonstration projects with private players. In addition, almost \$800 million were announced under the American Recovery and Reinvestment Act to accelerate the research and commercialization of biofuels (US DOE 2009). Other countries funding R&D for biofuels are Japan, Canada, and several EU members including Germany, The Netherlands, and Sweden (OECD 2008; Rajagopal and Zilberman 2007). EU wide support measures are also expected through the EU Commission (OECD 2008).

Improvement in feedstock production is another area showing promise to lower the cost of producing advanced biofuels. It is clear that the productivity of different feedstock per unit of land has a strong potential not only to lower overall cost of production but also to improve the energy balance and minimize the environmental footprint of biofuels. In this regard, given the early stage of genetic improvement of energy crops, significant yield gains can be expected in relatively short times. Some sources indicate that energy crop yields could be at least doubled through aggressive breeding efforts (Smeets, Faaij, and Lewandowski 2004; WWI 2007).

Biotechnology developments have the potential to lower feedstock production costs and accelerate the increase in yields of biofuels per unit of land. These increases could be the result of accelerated growth in biomass yield improvements, of the production of biomass that is more easily transformed into biofuels (e.g., with higher efficiency of conversion), or a combination of both paths.²⁵ Biotechnology has the potential to improve yields even in relatively difficult growing conditions. Current regulations and some resistance to biotechnology may slow down the progress in this area. According to Moschini (2008), the resistance to genetically modified (GM) organisms can, broadly speaking, be classified into; a) fear that their intake as food may be harmful, b) concern that GM crops production technologies result in damages to the environment, c) ethical and religious considerations, and d) proprietary technologies owned by multinational corporations. While the production of GM feedstocks for

²⁵ Biofuels from feedstocks that have been modified to facilitate conversion are sometimes labeled 3rd generation biofuels.

bioenergy may face less opposition, by sidestepping concerns related to human health (from food intake), all the other sources of resistance will still exist.

One important policy question concerns the priorities for cost reduction: feedstock, plant cost, conversion or yield? For the second-generation biofuels, the conversion cost is the key cost component as it involves a series of conversion, such as conversion from cellulose to starch and conversion from starch to alcohol. In the case of first-generation biofuels, feedstock is the main cost component. Unlike the first-generation biofuels, collection of raw materials (e.g., agricultural residues) would be relatively expensive in the case of second-generation biofuels.

6 Conclusions and Final Remarks

The limited potential of first-generation biofuels to make a significant contribution to displace fossil fuels and reduce GHG emissions highlighted by several studies unleashed a sense of urgency for the transition towards second-generation biofuels. The premise is that these biofuels would be less intensive in their demand for agricultural land, resulting in better energy balances, improved reductions in GHG emission reductions, and lesser competition for prime land with food crops, when compared to first-generation biofuels. While dedicated energy crops would still be competing for land with food crops, it is envisioned that either by using lesser quality soils (jatropha) or by providing more utilizable biomass per unit of land (e.g., switchgrass or short tree rotations), the pressure for prime quality soils will be reduced. Residues from agricultural and forest activities, and micro-algal oil would result in minimal competition for land.

Depending upon type of biofuels, feedstock prices and conversion costs, the cost of cellulosic ethanol is found to be two to three times as high as the current price of gasoline on energy equivalent basis. The cost of biodiesel produced from microalgae, a prospective feedstock, is many times higher than the current price of diesel. As compared to the case of first-generation biofuels, where feedstock, can account for over two-thirds of the total costs, the share of feedstock in the total costs is relatively lower (30% to 50%) in the case of second-generation biofuels. To date, there is no large scale commercial production of second-generation biofuels. If external costs of production of fossil fuels were considered, the cost differential will generally be lower for many second-generation

biofuels. Moreover, the impacts of biofuels on economic welfare (e.g., through rural development and/or energy security) should also affect the social cost differential.

Given the current state of technology, and the uncertainty remaining about the future breakthroughs that would potentially make some second-generation biofuels cost-competitive, policymakers need to carefully consider what goals are to be pursued in providing support to different biofuels. Biofuels that simultaneously advance multiple policy goals could warrant greater support when designing incentive mechanisms. An integrated approach combining economically sustainable rural development, climate change mitigation, and alternative energy provision provides a good policy framework for second-generation biofuels. It also is necessary to consider regional and international developments in policies and trade in order to maximize the potential benefits achievable through the policies implemented. As an example, support of biofuels that would not comply with international standards (e.g., on quality or sustainability criteria) will hardly result in the deployment of an industry able to expand beyond some local or domestic markets.

Various policy instruments might be used to provide different incentives for various types of biofuels, based on their contributions to policy objectives. For example, stronger incentives could be provided to biofuels with greater contributions to GHG reductions. Biodiesel plants that procure certain feedstock from family farms in some regions of Brazil (among other requirements) can claim a “social seal” that qualifies them for government provided tax benefits.²⁶ Policy makers also need to consider the type of instrument to use. Tax benefits and direct subsidies are common approaches, but are less precisely targeted and create more pressure on public budgets than the pricing of externalities created by fossil fuels. Those policies in turn can engender much stronger political opposition and efforts to evade the additional levies.

²⁶ It may still be too soon to make a definite evaluation of the effectiveness of this policy. However, some authors have already expressed some doubts on whether it will achieve the desired goals (Gordon 2008).

References

- Achten, W. M. J., L. Verchot, Y. J. Franken, E. Mathijs, V. P. Singh, R. Aerts, and B. Muys. 2008. Jatropha bio-diesel production and use. *Biomass and Bioenergy*, 32: 1063-1084.
- Anderson, G., and M. Fergusson. 2006. Energy from biomass in the UK: sources, processes and biodiversity implications. *British Ornithologists Union, Ibis* 148: 180-183.
- Anderson, G., L. Haskins, and S. Nelson. 2004. The effects of bioenergy crops on farmland birds in the UK: a review of current knowledge and future predictions. In Parris, K. and T. Poincet (eds) *Biomass and Agriculture: Sustainability, Markets, and Policies* 199-218. Paris: OECD.
- Andrews, S. S. 2006. "Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations." White Paper, USDA-Natural Resource Conservation Service.
http://soils.usda.gov/sqi/management/files/agforum_residue_white_paper.pdf
- Azam, M. M., A. Waris, and N. M. Nahar. 2005. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. *Biomass and Bioenergy*, 29: 293-302.
- Babcock, B. A., P. H. Gassman, M. J. Jha, and C. L. Kling. 2007. "Adoption Subsidies and Environmental Impacts of Alternative Energy Crops." CARD Briefing Paper 07-BP- 50, Center for Agricultural and Rural Development, Iowa State University.
- Benemann, J., and W. Oswald. 1996. "Systems and Economic Analysis of Microalgae Ponds for Conversion of CO₂ to Biomass, Final Report to the US Department of Energy. Pittsburgh, Energy Technology Center.
- Blanco-Canqui, H., and R. Lal. 2009. "Crop Residue Removal Impacts on Soil Productivity and Environmental Quality." *Critical Reviews in Plant Sciences*, 28 (3): 139-163.
- BR&Di. 2008. "Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications, and the Role of Research."
<http://www.brdisolutions.com/default.aspx> (Accessed June 2009)

- Boateng, A., W. Anderson, and J. Phillips. 2007. Bermudagrass for Biofuels: Effect of Two Genotypes on Pyrolysis Product Yield. *Energy and Fuels* 21: 1183-1187.
- Boe, A., and D. Lee. 2007. Genetic variation for Biomass Production in Prairie Cordgrass and Switchgrass. *Crop Science* 47: 929-934.
- Carlson, I., R. Oram, J., and J. Suprenant. 1996. *Reed Canarygrass and Other Phalaris Species*. In *Coolseason Forage Grasses*. Moser, L., D. Buxton, and M. Casler, Eds. American Society of Agronomy, Madison, WI.
- Chisti, Y. 2007. Biodiesel from Microalgae. *Biotechnology Advances*, 25: 294-306.
- D1 Oils. 2008. Interim Results for the Six Months Ended 30 June 2008. <http://www.d1plc.com/investorsAnalyst.php>. Accessed, May 2009.
- Darzins, A. 2008. "Recent and Current Research & Roadmapping Activities: Overview." National Algal Biofuels Technology Roadmap Workshop, University of Maryland, December 9.
- Delong, M., D. Swanberg, E. Oelke, C. Hanson, M. Onishak, M. Schmid, B. Wiant. 1995. Sustainable Biomass Energy Production and Rural Economic Development Using Alfalfa as a Feedstock. In *Proceedings of the 2nd Biomass Energy Conference of the Americas*. Klass, D. Ed. Portland, OR, August 21-24.
- Dimitrov, K. 2007. "Greenfuel Technologies: A Case Study for Industrial Photosynthetic Energy Capture." <http://www.nanostring.net/Algae/CaseStudy.pdf>
- Donovan, J., and N. Stowe. 2009. "Is the Future of Biofuels in Algae?" *RenewableEnergyWorld.com* 06/12/2009. (Accessed: June 2009) <http://www.renewableenergyworld.com/rea/news/article/2009/06/is-the-future-of-biofuels-in-algae>.
- Duffy, M. 2007. "Estimated Costs for Production, Storage, and Transportation of Switchgrass." Iowa State University, University Extension, PM 2042. (Accessed July 2009) http://www.econ.iastate.edu/research/webpapers/paper_12917.pdf
- Ecofys BV. 2008. GHG Performance of Jatropha Biodiesel. <http://www.d1plc.com/pdf/GHG%20Performance%20of%20Jatropha%20Biodiesel.pdf>

- Energy Information Administration (EIA). 2009. International Energy Outlook. Energy Information Administration, Office of Integrated Analysis and Forecasting, US Department of Energy, Washington D.C. May.
- . 2001. Emissions of Greenhouse Gases in the United States 2000. DOE/EIA-0573. U.S. Department of Energy 2001.
- Environmental Protection Agency, Office of Transportation and Air Quality, EPA 420-F-07-035.
- Epplin, F., C.D. Clark, R.K. Roberts, and S. Hwang. 2007. Challenges to the Development of a Dedicated Energy Crop. *American Journal of Agricultural Economics* 89: 1296-1302.
- Euler, H., and D. Gorriz. 2004. "Case Study *Jatropha curcas*". Global Facilitation Unit for Unerutilized Species (GFU) and Deutsche Gessellschaft fur Technische Zusammenarbeit (GTZ), Frankfurt, Germany. 63p.
- Fabiosa, J., J. Beghin, F. Dong, A. Elobeid, S. Tokgoz, T. Yu. 2010. "Land Allocation Effects of the Global Ethanol Surge: Predictions from the International FAPRI Model." *Land Economics, forthcoming*.
- FAPRI. 2009. US and World Agricultural Outlook. Food and Agricultural Policy Research Institute, Iowa State University and University of Missouri
- Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land Clearing and the Biofuel Carbon Debt. *Science* 319 (5867): 1235-1238.
- Farrell, A., R. J. Plevin, b. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol Can Contribute to Energy and Environmental Goals. *Science*, 311, 506 (January): 506-508.
- F.O. Licht. 2008. "World Biodiesel Production Estimated 2008- Growth Continues to Slow Down." World Ethanol & Biofuels Report." September 23.
- . 2009. "2009 World Ethanol Production Growth to Hit Five-Year Low." World Ethanol & Biofuels Report." May 26.
- . 2009a. Greenfuel Technologies Closes Algae Biofuels Venture. F.O. Licht's World Ethanol & Biofuels Report, May 14.
- . 2009b. "SG Biofuels Tests Cold Tolerant *Jatropha* Strains". World Ethanol & Biofuels Reports, F.O. Licht, June 9th.

- . 2009c. Large-scale biodiesel from algae seen in 10-15 years. *World Ethanol & Biofuels Reports*, F.O. Licht, June 4th.
- Francis, G., R. Edinger, and K. Becker. 2005. A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: Need, potential and perspectives of *Jatropha* plantations. *Natural Resources Forum*, 12-24.
- Frederick, W.J., S.J. Lien, C.E. Courchene, N.A. DeMartini, A.J. Ragauskas, K. Iisa. 2008. Co-production of Ethanol and Cellulose Fiber from Southern Pine: A Technical and Economic Assessment. *Biomass and Bioenergy* 32: 1293-1302.
- Gallagher, P., M. Dikeman, J. Fritz, E. Wailes, W. Gauthier, and H. Shapouri. 2003. Biomass from Crop Residues: Cost and Supply Estimates. USDA Agricultural Economic Report 819.
- Gerbens-Leenes, W., A.Y. Hoekstra, and T.H. van der Meer. 2009. The water footprint of bioenergy. *Proceedings of the National Academy of Science (PNAS)*, June 2, 2009. doi: 10.1073/pnas.0812619106.
- Ginwal, H. S., P. S. Rawat, and R. L. Srivastava. 2004. "Seed Source Variation in Growth Performance and Oil Yield of *Jatropha curcas* L. in Central India." *Silvae Genet.* 53: 186-92.
- Gonsalves, J. B. 2006. An Assessment of the Biofuels Industry in India. United Nations Conference on Trade and Development, UNCTAD/DITC/TED/2006/6.
- Gordon, G. 2008. Biofuels: Fueling Development or Disaster? *Berkeley Review of Latin American Studies*, Fall.
<http://clas.berkeley.edu/Publications/articles/fall2008/other/BRLAS-Fall2008-Gordon.pdf> (Accessed June 2009).
- Graham, R., B. English, and C. Noon. 2000. A Geographic Information System-based Modeling System for Evaluating the Cost of Delivered Energy Crop Feedstock. *Biomass Bioenergy* 18: 309-329.
- Groom, M, M. Elizabeth, and P. Townsend. 2008. Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conservation Biology* 22: 602-609.
- GTZ. 2005. "Liquid Biofuels for Transportation in Tanzania-Potential and Implications for Sustainable Agriculture and Energy in the 21st Century." Deutsche Gesellschaft

- fur Technische Zusammenarbeit (GTZ), German Ministry for Food, Agriculture, and Consumer Protection (BMELV), German Agency for Renewable Resources (FNR).
- Hallam, A., I. C. Anderson, and D. R. Buxton. 2001. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production." *Biomass and Bioenergy* 21: 407-424.
- Hamelinck, C., and A. Faaij. 2006. Outlook for Advanced Biofuels. *Energy Policy* 34: 3268-3283.
- Hamelinck, C., G. Hooijdonk, and A. Faaij. 2005. "Ethanol from Lignocellulosic Biomass: Techno-economic Performance in Short-, Middle- and Long-term." *Biomass and Bioenergy* 28: 384-410.
- Heller, J. 1996. Physic Nut, *Jatropha curcas* L. Promoting the conservation and use of underutilized and neglected crops. PhD dissertation, Institute of Plant Genetic and Crop Plant Research, Gatersleben, Germany, and International Plant Genetic Resource Institute, Rome, Italy. <http://www.ipgri.cgiar.org/Publications/pdf/161.pdf>.
- Hoekstra, A.Y., and A.K. Chapagain. 2007. Water footprints of nations: water use by people as a function of their consumption pattern. *Water Resource Manage.* 21, 35-48.
- Hoogwijk, M., A. Faaij, R. van den Broek, G. Berndes, D. Gielen, and W. Turkenburg. 2003. "Exploration of the Ranges of the Global Potential of Biomass and Energy." *Biomass and Bioenergy*, 25: 119-133.
- Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg. 2005. "Potential of Biomass Energy Out to 2100, for Four IPCC SRES Land-Use Scenarios." *Biomass and Bioenergy*, 29: 225-257.
- International Energy Agency (IEA). 2005. Biofuel for Transport: an international Perspective. OECD/IEA, Paris.
- International Energy Agency (IEA). 2007. Potential Contribution of Bioenergy to the World's Future Energy Demand. IEA Bioenergy, ExCo: 2007:02.
- International Energy Agency (IEA) Bioenergy. 2008. From 1st- to 2nd-Generation Biofuel Technologies: An Overview of Current Industry and RD&D Activities. November, 2008.

- Jones, N., and J. H. Miller. 1992. *Jatropha curcas*: a multipurpose species for problematic sites. Washington DC: The World Bank.
- Jongschaap, R. E. E., W. J. Corre, P.S. Bindraban, and W. A. Brandenburg. 2007. "Claims and Facts on *Jatropha curcas* L." Report 158, Plant Research International, Wageningen.
- Junginger, M., A. Faaij, R. Bjorheden, and W. C. Turkenburg. 2005. Technological Learning and Cost Reductions in the Wood Fuel Supply Chains in Sweden. *Biomass and Bioenergy*, 29 (6): 399-418.
- Kandpal, J. B., and M. Madan. 1995. "*Jatropha curcas*: a Renewable Source of Energy for Meeting Future Energy Needs." *Renewable Energy*, 6 (2): 159-60.
- Keshwani, D., and J. Cheng. 2009. Switchgrass for Bioethanol and Other Value-added Applications: A Review. *Bioresource Technology* 100: 1515-1523.
- Khan, S. A., Rashmi, M. Z. Hussain, S. Prasad, and U. C. Banerjee. 2009. Prospects of biodiesel production from microalgae in India. *Renewable and Sustainable Energy Review*. (doi:10.1016/j.rser.2009.04.005).
- Kim, S., and B. Dale. 2004. Global Potential Bioethanol Production from Wasted Crops and Crops Residues. *Biomass and Bioenergy* 26: 361-375.
- Kukrika, N. 2008. Vegetable Oil Based Biofuels in India: An Overview of the Value Chain and Analysis of Biofuel's Pro-Poor Potential. Environment and Natural Resources Program Discussion Paper 2008-01, Belf Center for Science and International Affairs, John F. Kennedy School of Government, Cambridge, MA, January.
<http://belfercenter.ksg.harvard.edu/files/Kukrika%20ENRP%20Paper%2008%20final.pdf>. (Accessed May 2009).
- Lal, R. 2005. "World Crop Residues Production and Implications of its Use as a Biofuel." *Environment International*, 31: 575-584.
- Larson, E. 2008. "Biofuel Production Technologies: Status, Prospects and Implications for Trade and Development." United Nations Conference on Trade and Development, New York and Geneva.
http://www.unctad.org/en/docs/ditcted200710_en.pdf. (Accessed May 2009)
- Lele, S. 2006. *Biodiesel and Jatropha Plantation*. Published by Agrobios, Jodhpur, India.

- Lewandowski, I., J. Scurlock, E. Lindvall, and M. Christou. 2003. The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy* 25: 335-361.
- Li, Y., M. Horsman, N. Wu, C. Q. Lan, and N. Dubois-Calero. 2008. Biofuels from Microalgae. *Biotechnology Progress*, 24: 815-820.
- Liebman, M., and A. H. Heggenstaller. 2008. Stoking the Dragon: Can We Produce Feedstocks Sustainably? The Bioeconomy Conference, Iowa State University, Ames, Iowa, September.
- Manzone, M., G. Airolid, and P. Balsari. 2009. Energetic and economic evaluation of a poplar cultivation for the biomass production in Italy. *Biomass & Bioenergy* 33: 1258-1264.
- Mapemba, L., F.M. Eppin, C.M. Taliaferro, and R.L. Huhnke. 2007. Biorefinery Feedstock Production on Conservation Reserve Program Land. *Review of Agricultural Economics* 29: 227-246.
- McAloon, A., F. Taylor, W. Yee, K. Ibsen, R. Wooley. 2000. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks. NERL Technical Report 580-28893.
- Merigliano, M., and P. Lesica. 1998. The Native Status of Reed Canarygrass in the Inland Northwest, USA. *Natural Areas Journal* 18: 223-230.
- Mitchell, D. 2008. "A Note on Rising Food Prices" Policy Research Working Paper No. 4682. The World Bank, Washington DC.
- Moschini, G. 2008. Biotechnology and the Development of Food Markets: Retrospects and Prospects. *European Review of Agricultural Economics*, 35 (3): 331-355
- Molina Grima E., E. H. Belarbi, F. G. Acien Fernandez, A. Robles Medina, and Y. Chisti. 2003. "Recovery of Microalgal Biomass and Metabolites: Process Options and Economics." *Biotechnology Advances*, 20: 491-515.
- National Research Council (NRC). 1958. Composition of Cereal Grains and Forages.
- NRDC. 2006. "Ethanol: energy well spent – a survey of studies published since 1990." Natural Resources Defense Council and Climate Solutions, New York, NY.
- National Renewable Energy Laboratory (NREL). 1998. Lignocellulosic Feedstock Resource Assessment. TP-580-24189, Sep. 1998.

- . 2007. Research Advances; Cellulosic Ethanol. NREL/BR 510-40742, March.
(accessed July 2009) <http://www.nrel.gov/biomass/pdfs/40742.pdf>
- Oak Ridge National Laboratory (ORNL). 2008. Exploring Potential U.S. Switchgrass Production for Lignocellulosic Ethanol. ORNL/TM-2007/183.
- OECD. 2008. Economic Assessment of Biofuel Support Policies. Organization for Economic Cooperation and Development. OECD, Paris.
www.oecd.org/tad/bioenergy.
- OECD-FAO. 2009. "OECD-FAO Agricultural Outlook 2009-2018." <http://www.agri-outlook.org/dataoecd/2/31/43040036.pdf>.
- Openshaw, K. 2000. A review of *Jatropha curcas*: an Oil Plant of Unfulfilled Promise. *Biomass and Bioenergy* 19: 1-15.
- Paulson, N. D., R. G. Ginder. 2007. "Growth and Direction of the Biodiesel Industry in the United States." CARD Working Paper 07-WP-448, Center for Agricultural and Rural Development, Iowa State University.
- Perlack, R.D., and A.F. Turhollow. 2003. Feedstock Cost Analysis of Corn Stover Residues for Further Processing. *Energy* 28: 1395-1403.
- Perlack, R., L. Wright, A. Turhollow, R. Graham, B. Stokes, and D. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: the Technical Feasibility of a Billion-Ton Annual Supply. Department of Energy/GO-102005-2135. April, 2005.
- Perrin, R. K. Vogel, M. Schmer, and R. Mitchell. 2008. "Farm-Scale Production Cost of Switchgrass for Biomass." *Bioenergy Resources*, 1: 91-97
- Peters, J. and S. Thielmann. 2008. Promoting Biofuels: Implications for Developing Countries. *Energy Policy*, 36: 1538-1544.
- Petrolia, D.R. 2006. Ethanol from Biomass: Economic and Environmental Potential of Converting Corn Stover and Hardwood Forest Residue in Minnesota. Paper presented at the American Agricultural Economic Association Annual Meeting, Long Beach, CA. July 23-26.
- . 2008. The Economics of Harvesting and Transporting Corn Stover for Conversion to Fuel Ethanol: A Case Study for Minnesota. *Biomass and Bioenergy* 32: 603-612.

- Piccolo, C., and F. Bezzo. 2009. A Techno-economic Comparison between Two Technologies for Bioethanol Production from Lignocellulose. *Biomass and Bioenergy* 33: 478-491.
- Pienkos, P. T. 2008. "Historical Overview of Algal Biofuel Technoeconomic Analysis." National Algal Biofuels Technology Roadmap Workshop, University of Maryland, December 9.
- . 2009. "Algal Biofuel: Ponds and Promises." 13th Annual Symposium on Industrial and Fermentation Microbiology, May 1.
- Pienkos, P. T., and A. Darzins. 2009. "The Promise and Challenges of Microalgal-Derived Biofuels." *Biofuels, Bioproducts and Biorefining*, 3; 431-440.
- Pimentel, D., and T.W. Patzek. 2005. Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. *Natural Resources Research* 14: 65-76.
- Prueksakorn, K., and S. H. Gheewala. 2006. Energy and Greenhouse Gas Implications of Biodiesel Production from *Jatropha curcas* L. Proceedings of the 2nd Joint International Conference on Sustainable Energy and Environment, 21-23 November, Bangkok, Thailand.
- Pulz, O. 2007. Performance Summary Report: Evaluation of GreenFuel's 3D Matrix Algae Growth Engineering Scale Unit.
http://www.greenfuelonline.com/gf_files/Performance%20Summary%20Report.pdf
- Rajagopal, D., and D. Zilberman. 2007. Review of Environmental, Economic and Policy Aspects of Biofuels. Policy Research Working Paper WPS4341, Development Research Group, The World Bank, September.
- REN21. 2009. Global Status Report. Renewable Energy Policy Network for the 21st Century. (Accessed June 2009).
http://www.ren21.net/pdf/RE_GSR_2009_Update.pdf
- Richardson, J. 2008. "Production of Biomass for Energy from Sustainable Forestry Systems: Canada and Europe." Short Rotation Crops International Conference, August

- Rubin, O.D, M.A. Carriquiry, and D.J. Hayes. 2008. Implied Objectives of US Biofuels Subsidies. CARD Working Paper 08-WP-459, Center for Agricultural and Rural Development, Iowa State University.
- Sassner, P., M. Galbe, and G. Zacchi. 2008. "Techno-economic Evaluation of Bioethanol Production from Three Different Lignocellulosic Materials." *Biomass and Bioenergy*, 32: 422-430
- Schank, S., D. Chenoweth, C. Turick, and P. Mendoza. 1993. Napiergrass Genotypes and Plant parts for Biomass Energy. *Biomass and Bioenergy* 4: 1-7.
- Schenk, P., S. R. Thomas-Hall, E. Stephens, U. C. Marx, J. H. Mussnug, C. Posten, O. Kruse, and B. Hankamer. 2008. Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production. *Bioenergy Research*, 1: 20-43.
- Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change." *Science*, 319(5867) 29 February: 1157-1268.
- Smeets, E. M. W., A. Faaij, and I. M. Lewandowski. 2004. "A Quicksan of Global Bioenergy Potentials to 2050." Utrecht, Copernicus Institute, Utrecht University.
- Smeets, E. M. W., A. Faaij, I. M. Lewandowski, and W. C. Turkenburg. 2007. A bottom-up Assessment and Review of Global Bio-Energy Potentials for 2050. *Progress in Energy and Combustion Science*, 33: 56-106.
- Solomon, B., J. Barnes, K. Halvosen. 2007. Grain and Cellulosic Ethanol: History, Economics, and Energy Policy. *Biomass and Bioenergy* 31: 416-425.
- Springer, T., and C. Dewald. 2004. Eastern Gamagrass and Other Tripsacum Species. In *Warm-season (C₄) Grasses*. Moser, L., B. Burson, L. Sollenberger. Eds. American Society of Agronomy. Madison, WI.
- Thompson, W., W. Raun, G. Johnson, C. Taliaferro, K. Freeman, K. Wynn, and R. Mullen. 2005. Switchgrass response to Harvest frequency and Time and Rate of Applied Nitrogen. *Journal of Plant Nutrition* 27: 1199-1226.
- Timilsina, G. R., and A. Shrestha. 2009. "Biofuel: An Overview of Technology, Market and Impact." Unpublished Manuscript

- Tokgoz, S., A. Elobeid, J. Fabiosa, D. J. Hayes, B. A. Babcock, T. Yu, F. Dong, C. E. Hart, and J. C. Beghin. "Emerging Biofuels: Outlook of the Effects on US Grain, Oilseeds, and Livestock Markets." Staff Report 07-SR-101, Center for Agricultural and Rural Development, Iowa State University. May.
- UNEP 2009. Global Trends in Sustainable Energy Investments. United Nations Environmental Programme.
- U.S. Department of Energy (DOE). 2008. Biomass Program Biofuels Initiative. http://www1.eere.energy.gov/biomass/biofuels_initiative.html.
- . 2008a. Biomass Feedstock Composition and Property Database. Available at: http://www1.eere.energy.gov/biomass/feedstock_databases.html.
- . 2008b. Theoretical Ethanol Yield Calculator. Available at: http://www1.eere.energy.gov/biomass/ethanol_yield_calculator.html
- . 2009. Secretary Chu Announces Nearly \$800 Million from Recovery Act to Accelerate Biofuels Research and Commercialization. <http://www.energy.gov/news2009/7375.htm> (Accessed: June 2009)
- Vadas, P. A., K. H. Barnett, and D. J. Undersander. 2008. Economics and Energy of Ethanol Production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA. *Bioenergy Resources*, (1): 44-55.
- Wang, M., M. Wu, and H. Huo. 2007. Life-Cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types. *Environmental Research Letters* 2: 1-13.
- Walsh, M. 2008. U.S. Cellulosic Biomass Feedstock Supplies and Distribution. University of Tennessee and M&E Biomass, Unpublished.
- Whitaker, M, and G. Heath. 2009. Lifecycle Assessment of the Use of Jatropha Biodiesel in Indian Locomotives. Technical Reports NREL/TP -6A2-44428, National Renewable Energy Laboratory, March (accessed June 2009) <http://www.nrel.gov/docs/fy09osti/44428.pdf>
- World Watch Institute (WWI). 2007. Biofuels for Transport: Global Potential and Implications for Sustainable Energy and Agriculture." Eds S. Hunt. Sterling VA.

Wright, M., and R. Brown. 2007. Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms. *Biofuels, Bioproducts, and Biorefining* 1: 49-56.

Yang, H., Y. Zhou, and J. Liu. 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. *Energy Policy* 37, 1876-1885.

Acronyms

BR&Di	Biomass Research & Development Initiative
Btu	British thermal unit
DOE	Department of Energy
EHF	Enzymatic Hydrolysis and Fermentation
EIA	Energy Information Administration
EISA	US Energy Independence and Security Act
EJ	Exajoule
FAO	Food and Agriculture Organization
FAPRI	Food and Agricultural Policy Research Institute
IEA	International Energy Agency
g	Gram
Gha	Giga hectare
GHG	Greenhouse gasses
Gj	Gigajoule
ha	Hectare
IEA	International Energy Agency
L, lt	Liter
LCA	Life Cycle Analysis
LHV	Low Heating Value
M\$	Million US dollars
m ²	Squared meter
m ³	Cubic meter
Mg	Mega grams
Mha	Mega hectare
mm	Millimeter
Mtoe	Million tons of oil equivalent
MWh	Mega watt hour
NRC	National Research Council
NRDC	Natural Resources Defense Council and Climate Solutions
NREL	National Renewable Energy Laboratory
Odt	Oven dry ton
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
USDA	United States Department of Agriculture
t	Tons
WWI	Worldwatch Institute
Yr	Year