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# Second generation biofuels: Economics and policies

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ABSTRACT

This study reviews economics of production of second generation biofuels from various feedstocks, including crop and wood/forestry residues, lignocellulosic energy crops, jatropha, and algae. The study indicates that while second generation biofuels could significantly contribute to the future energy supply mix, cost is a major barrier to its commercial production in the near to medium term. Depending upon type of biofuels, feedstock prices and conversion costs, the cost of cellulosic ethanol is found to be two to three times higher than the current price of gasoline on an energy equivalent basis. The median cost (across the studies reviewed) of biodiesel produced from microalgae, a prospective feedstock, is seven times higher than the current price of diesel, although much higher cost estimates have been reported. As compared with the case of first generation biofuels, in which feedstock can account for over two-thirds of the total costs, the share of feedstock in the total costs is relatively lower (30–50%) in the case of second generation biofuels. While significant cost reductions are needed for both types of second generation biofuels, the critical barriers are at different steps of the production process. For cellulosic ethanol, the biomass conversion costs needs to be reduced. On the other hand, feedstock cost is the main issue for biodiesel. At present, policy instruments, such as fiscal incentives and consumption mandates have in general not differentiated between the first and second generation biofuels except in the cases of the US and EU. The policy regime should be revised to account for the relative merits of different types of biofuels.

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## 1. Introduction

Production and consumption of biofuels has been growing rapidly 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 85.6 billion liters in 2010 (F.O. Licht, 2010b). Although biodiesel is being produced in smaller quantities than is ethanol, its relative growth is even stronger, surpassing 18.1 billion liters in 2010 (F.O. Licht, 2010a), up from 3.9 billion liters in 2005 (F.O. Licht, 2008).

The rapid growth of biofuel production has not been free of controversy, however. The wide support that biofuels enjoyed just three or four years ago has eroded more recently as new studies have linked their production to rising food prices, questioned their ability to displace fossil energy, and analyzed their potential contribution to monoculture and deforestation (Searchinger et al., 2008; Fargione et al., 2008; Mitchell, 2008; Timilsina et al., 2010). The combined impacts of these effects have stimulated a more urgent interest in the development of biofuels produced from non-food biomass, which are less land and water intensive and/or use residues from agriculture. These biofuels have received the broad name of second generation biofuels.[3]

Despite the sense of urgency, and progress made in recent years, some crucial concerns surround the commercial scaling up of the second generation biofuels. How expensive are the second generation biofuels compared with first generation biofuels and fossil fuels? What policy instruments would be needed to make them competitive with fossil fuels? What level of investment in

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[3] There is currently no strict technical definition for the terms first and second generation biofuels, and the distinction between the two mainly hinges on 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 and microalgae) can also be labeled as second generation biofuels.

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research and development (R&D) would be needed to slash their costs so that they can compete with their fossil fuel counterparts? Even if the economics of second generation biofuels is supported through policy instruments, what is their potential to meet the demands of the global energy supply mix? Finding answers to these questions is essential in order to design a market and policy framework for stimulating second generation biofuels and realizing their benefits.

In the existing literature, there are relatively few comprehensive studies on the development of second generation biofuels from economic and policy perspectives. A few recent papers (e.g., Naik et al., 2010; Lange, 2007; Sims, 2010) focus on technological concepts and associated challenges and only briefly touch on economics and policy issues, while some studies deal with production costs for particular feedstock types and/or for specified geographical locations (e.g., Manzone et al., 2009; Tao and Aden, 2009). A limited scope of coverage makes it hard to draw a minimally complete picture of the fast-evolving biofuel industry. This study pulls together results from a large number of existing studies carried out across different geographical locations in an attempt to derive some generic knowledge.

The objective of this study is to compile information on second generation biofuel production technologies and associated costs based on secondary sources, mainly published literature, so that some generalized information can be developed that could help policymakers and other stakeholders in designing a policy framework to promote second generation biofuels. In Section 2, we present a description of the main feedstocks for second generation biofuels and follow this with a comparison of production costs in Section 3. Then, in Section 4, we describe several policies affecting the advanced biofuels supply chain and challenges faced by producers of these fuels. Finally we draw some key conclusions that have implications for policy recommendations.

## 2. Potential feedstocks

The potential feedstocks for second generation biofuels production considered in this study are lignocellulosic and biodiesel feedstocks.

### 2.1. Lignocellulosic feedstocks

The major components of lignocellulosic feedstocks are cellulose and hemicellulose, which can be converted to sugars through a series of thermochemical and biological processes and eventually fermented to bioethanol.[4] In general, lignocellulosic feedstocks are divided into three categories: (1) agricultural residues (e.g., crop residues and sugarcane bagasse), (2) forest residues, and (3) herbaceous and woody energy crops.

#### 2.1.1. Agricultural residues

The crops considered are corn, sorghum, barley, rice, wheat, and sugarcane. A major advantage of using residues for biofuel production when compared with 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 with direct and indirect land use changes are also avoided, improving a fuel's 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). While the National Renewable Energy Laboratory (NREL) (2007) assumed yields of 271 L/tonne of feedstock, the same source provides target yields of 376 and 392 L of ethanol per tonne of cellulosic feedstocks by 2012 and 2020, respectively.

Several factors restrict the potential use of 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. Energy crops

By destination, energy crops can be used as solid biomass for firing power plants but they can also used as gas biomass to supplement the anaerobic digester or biogas production. Energy crops are classified as liquid biomass when they are processed into liquid fuel. Dedicated energy crops are non-food energy crops representing an additional potential source of feedstock for biofuel production. While crops such as corn and soybeans have been considered by some to be the first generation energy crops, the second generation energy crops can be broadly grouped into grassy (herbaceous or forage) and woody (tree) energy crops.

*2.1.3.1. Perennial forage crops.* Perennial forage crop species, including switchgrass and miscanthus, are a promising source of feedstock for second generation biofuels. Switchgrass is frequently mentioned because of its relatively low water and nutrition input requirement and costs, positive environmental impact, and adaptability to low-quality land (Keshwani and Cheng, 2009). A wide range of yield expectations have been reported in the literature. Given ideal establishment and growing conditions, Thompson et al. (2005) report dry mass potential yields based on upland populations as high as 18–20 tonnes/ha, while yields in lowland forms could reach 23–27 tonnes/ha.

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 is that it takes two to three 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).

*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 with annual crops

[4] Detailed descriptions of biomass feedstock structure and the key conversion technologies can be found in various studies (e.g., Hamelinck et al., 2005).

(Smeets et al., 2007). Poplar, willow, and eucalyptus are among the species most frequently mentioned for this application.

In summary, dedicated energy crops as feedstocks are in general less demanding in terms of inputs, reduce erosion and improve soil properties, and provide better wildlife habitat than annual crops. Additionally, more energy per unit of land can be obtained from these crops (relative to food crops) as a higher proportion of the biomass can be utilized.

On the other hand, while their yields are high, dedicated energy crops do not entirely escape the food versus fuel debate because 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 on lands where neither food crop production nor grazing pastures are feasible activities, or on lands that are not needed for any production activity.

### 2.2. Biodiesel feedstocks

#### 2.2.1. Jatropha

Jatropha (*Jatropha curcas*) is one of the oilseeds species that has generated much excitement regarding its potential for biodiesel production. Jatropha is now grown in many tropical and subtropical regions of Asia, Africa, and Latin America, with a planted area estimated at 900,000 ha in 2008 (FAO/IFAD, 2010).

Jatropha can be grown in semi-arid conditions and/or marginal soils without large investments in inputs (Jongschaap et al., 2007). However, consistently high yields have only been achieved with relatively high levels of inputs and on good soils (International Energy Agency (IEA), 2008). 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). Critical questions remain regarding its ability to be economically viable when grown on poor soils and/or in dry climates.

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 tonnes/ha/yr have been reported (Openshaw, 2000), but many of these reports lack coherence (Heller, 1996).

Table 1 summarizes some of the seed yields reported in the literature for different growing settings outlined in Achten et al. (2008). Notice that the ranges of yields and oil contents of these seeds make for very wide ranges of oil yields per hectare. But biodiesel yields between 1800 and 2800 L/ha have been mentioned as realistic for current conditions by industry sources (F.O. Licht, 2009b).

**Table 1**
Achievable dry seed yields for *Jatropha curcas*.

| Reference | Achievable yield (tonnes/ha/yr) | Growing conditions |
|---|---|---|
| Heller (1996) and Francis et al. (2005) | 2–3[a] | Semi-arid area and wasteland in India |
| Francis et al. (2005) | 5 | Good soils in India, annual rainfall of 900–1200 mm, optimal management |
| Jongschaap et al., 2007 | 7.8 | Potential |
| **Reference** | **Typical oil content (%)** | **Plant part** |
| Ginwal et al. (2004) | 33–39 | Seed |
| | 46–58 | Kernel[b] |

[a] With water availability of 500–600 mm/yr. Euler and Gorriz (2004) reported yields of less than 1 tonne/ha.
[b] Accounts for roughly 65% of the seed.

**Table 2**
Oil yields of algae and other oilseeds.
*Source*: Compiled by the authors.

| Plant source | Oil yield (L/ha/yr) | Plant source | Oil yield (L/ha/yr) |
|---|---|---|---|
| Soybeans (US)[a] | 588 | Palm (Indonesia)[a] | 4770 |
| Rapeseeds/canola (EU)[a] | 1412 | Algae[c] | 12,000–98,500 |
| Jatropha[b] | 1800–2800 | Algae[d] | 58,700–136,900 |

[a] Average of the yields of the 2007/09–2009/10 marketing years as reported by the United States Department of Agriculture, and an oil density of 0.9 g/ml.
[b] F.O. Licht (2009b).
[c] Schenk et al. (2008), range from 10 g/m$^2$/d at 30% Triacylglycerids (TAG) to 50 g/m$^2$/d at 50% TAG.
[d] Chisti (2007), range from 30% to 70% oil by weight in biomass.

#### 2.2.2. Microalgae

Microalgae are capable of yielding large quantities of lipids adequate for biodiesel production (Li et al., 2008; World Watch Institute (WWI), 2007). With its ability to grow in saline water, coastal seawater, wastewater and non-arable land, the algae's potential to provide biomass for biofuel production with limited competition from conventional agriculture is now widely accepted. One of the main advantages is its ability to produce large amounts of oil per unit of land (see Table 2). Some authors highlight its potential to open economic opportunities in arid or salinity affected regions (Schenk et al., 2008).[5]

In terms of potential, Schenk et al. (2008) report that the maximum theoretical yield for algal biomass production has been calculated at 365 tonnes of dry biomass per hectare per year (100 g/m$^2$/d). Despite significant barriers in terms of costs of production, interest in the microorganism as a biofuel feedstock is high. Darzins (2008) indicated that as of 2008, 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 of the world, including (among many others) Australia, Europe, the Middle East, and New Zealand (Pienkos and Darzins, 2009).

In summary, an array of different feedstocks could be tapped for the production of second generation biofuels. However, some authors (e.g., Pimentel et al., 2009) caution that given current levels of capture of solar energy by plants and the amount of biomass collected and already utilized for other purposes, the net availability of these feedstocks may be lower than previously thought. Table 3 summarizes potential advantages and disadvantages of various biofuel feedstocks from the literature cited.

## 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. The production costs we consider in this study include feedstock costs, capital costs, operating and maintenance costs (including labor and other energy sources).

[5] 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).

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**Table 3**
Advantages and disadvantages of various biofuel feedstocks.

| Feedstocks | Potential advantages | Potential disadvantages |
|---|---|---|
| *Lignocellulosic feedstocks* | | |
| Agricultural residues | Have minimal direct impact on food price<br>Avoid GHG emissions associated with direct and indirect land use changes<br>New source of revenue for farmers | Excess removal will have adverse impacts on soil, crop production and the environment<br>Needs specially designed harvest equipment and storage system |
| Forest residues | Large in amount and widely used sources<br>Removal of excess woody material improves forest health and productivity | Limited accessibility<br>Potential reduction of recoverability in harvest areas<br>Competes with current uses |
| Energy crops | | |
| Perennial forage crops | Low water and nutrition input requirement<br>Adaptability to low quality land<br>Positive environmental impact<br>Native to North America | Takes 2–3 years to start full production<br>Limited availability of genotype<br>Important losses over winter |
| Woody energy crops | High yield potential<br>Wide geographical distribution<br>Relatively low levels of input needed<br>Reduce erosion and improve soil properties<br>Provide better wildlife habitat | Compete for land with food production if not installed on marginal land |
| *Biodiesel feedstocks* | | |
| Jatropha | Can grow in poor soil and dry climate | Consistent high yields are hard to achieve with low input costs<br>Need to develop optimal production practice |
| Microalgae | High yield potential<br>Can be grown in saline water, coastal seawater, wastewater and non-arable land | In early stage of development |

### 3.1. *Feedstock costs*[6]

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 account for 45–58% of total production costs for second generation biofuels, depending on conversion efficiency and applied technology.

#### 3.1.1. *Production cost of lignocellulosic feedstocks*

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 for select feedstocks (see Table 4).

Table 4 shows that crop residue costs range from $19 to $84 per tonne delivered. This wide range reflects differences in assumptions regarding the items to include in the calculation (e.g., payments to farmers, opportunity costs), yields, distances to conversion facilities, storage needs, and the level at which each of these items is compensated. As an example, the estimate by Gallagher et al. (2003) includes only harvest, transport, and increased fertilizer costs. Even these costs are low when compared with the other more recent studies summarized in the table. Feedstock acquisition, storage, and opportunity costs such as their feed value are not included here.[7] Tokgoz et al. (2007) assume significantly higher baling and transport cost, in addition to an incentive of roughly $11 per tonne for farmers. Perlack and Turhollow (2003) include costs of collecting, handling, and hauling corn stover to the conversion facility, in addition to an $11 per tonne compensation paid to growers for potential soil compaction, decreased surface organic matter, and some amount of profit requested by farmers. These studies highlight that the biofuel 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 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 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 4. The prices reported by National Renewable Energy

[6] For comparison purposes, all the costs considered in this section are expressed in 2008 US dollars, unless otherwise noted.

[7] 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 in which crop residues have limited availability. Higher opportunity costs (feed values, at about 53$/tonne for corn stover) are included only if there is a need to bid the residues away from the livestock sector.

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**Table 4**
Estimated costs of selected feedstocks delivered to a bio-refinery.
*Source*: Elaborated by authors.

| Source | Feedstock | Estimated cost[a] | | States/country |
|---|---|---|---|---|
| | | $/tonne | $/L ethanol | |
| **Agricultural residues (corn stover and crops straws)** | | | | |
| Gallagher et al. (2003) | Corn stover | 19–20 | 0.063–0.067 | Kansas, Iowa |
| Perlack and Turhollow (2003) | | 48–57 | 0.158–0.190 | US |
| Petrolia (2008) | | 57–69[b] | 0.190–0.230 | Minnesota |
| Petrolia (2006) | | 41–47 | 0.135–0.158 | Minnesota |
| Tokgoz et al. (2007) | | 84 | 0.279 | US |
| Frederick et al. (2008) | | 55 | 0.184 | US |
| Gallagher et al. (2003) | Winter wheat, continuous | 22–31 | 0.067–0.093 | Kansas |
| Gallagher et al. (2003) | Winter wheat, fallow | 42 | 0.140 | Kansas |
| Gallagher et al. (2003) | Spring wheat, continuous | 27 | 0.089 | Minnesota |
| Gallagher et al. (2003) | Sorghum | 23–26 | 0.071–0.077 | Kansas |
| Gallagher et al. (2003) | Barley | 24 | 0.080 | Minnesota |
| Gallagher et al. (2003) | Oats | 26 | 0.085 | Minnesota |
| Gallagher et al. (2003) | Rice | 28 | 0.093 | Arkansas |
| **Forest products residues and some woody energy crops** | | | | |
| National Renewable Energy Laboratory (NREL) (1998) | Hardwood primary mill residue | 37 | 0.125 | US |
| National Renewable Energy Laboratory (NREL) (1998) | Softwood primary mill residue | 38 | 0.127 | US |
| National Renewable Energy Laboratory (NREL) (1998) | Hardwood secondary mill residue | 34 | 0.112 | US |
| National Renewable Energy Laboratory (NREL) (1998) | Softwood secondary mill residue | 34 | 0.112 | US |
| Junginger et al. (2005)[c] | Primary forest fuel (residues) | 27 | 0.090 | Sweden |
| Frederick et al. (2008) | Yellow poplar | 48 | 0.160 | US |
| Frederick et al. (2008) | Loblolly pine | 71–82 | 0.238–0.272 | US |
| Manzone et al. (2009)[d] | Poplar | 110–132 | 0.366–0.439 | Italy |
| **Herbaceous energy crops** | | | | |
| Epplin et al. (2007) | Switchgrass | 55–74 | 0.184–0.245 | Tennessee |
| Graham et al. (2000) | Switchgrass | 44–71 | 0.147–0.237 | US |
| Mapemba et al. (2007) | Grassy biomass | 29–65 | 0.097–0.217 | US |
| Duffy (2008) | Switchgrass | 125 | 0.418 | Iowa |
| Babcock et al. (2007) | Switchgrass | 92–124 | 0.308–0.413 | Iowa |
| Vadas et al. (2008) | Switchgrass | 56–60 | 0.187-0.200 | US |
| Hallam et al. (2001) | Switchgrass | 56–67 | 0.186–0.224 | Iowa |
| Perrin et al. (2008) | Switchgrass | 46–88[e] | 0.154–0.294[e] | N. Dakota/Nebraska |
| Vadas et al. (2008) | Alfalfa | 77–90 | 0.257–0.300 | US |
| Hallam et al. (2001) | Alfalfa | 78–83 | 0.260–0.278 | Iowa |
| Hallam et al. (2001) | Reed canarygrass | 65–98 | 0.217–0.327 | Iowa |
| Haque and Epplin (2010) | Switchgrass | 55–60 | 0.182–0.199 | US |
| Aravindhakshan et al. (2010) | Switchgrass | 43 | 0.144 | Oklahoma |
| Aravindhakshan et al. (2010) | Miscanthus | 51 | 0.169 | Oklahoma |

[a] Inflation adjusted to 2008. Yields of 300 L of ethanol per tonne of feedstock were used.
[b] These numbers are for a plant producing 50 million gallons a year. Costs between $55 and $93 per ton were obtained by varying the plant size and the harvesting method.
[c] Originally reported in 2002 euros/GJ, converted using 21.1 MJ/L of ethanol (LHV) a yield of 300 L/tonne of forest residues, an exchange rate of 1.08 euros/dollar, and updated to 2008 dollars using the GDP deflator (multiplied by 1.175).
[d] Under conditions in Italy; originally in euros/tonne, converted with an exchange rate of 0.68 euros/dollar and 300 L of ethanol per tonne of biomass.
[e] Does not include transportation costs to the biorefinery.

Laboratory (NREL) (1998) (which are for US forest products industry residues) vary greatly with local conditions.

An aggregate US 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 $42 to $47 per dry tonne (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 $47 per dry tonne. 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 ($44–$51 per tonne) would also bring forth significant supplies of forestland feedstocks (including logging residues, removal residues, thinning from timberlands, primary mill residues, etc.) according to analysis performed by the Biomass Research and Development Initiative (BR&Di, 2008).

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 4). 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 tonnes of feedstock. Epplin et al. (2007) used land rent costs in Tennessee of $148 per hectare for long-term leases, and yields of 15.0 tonnes/hectare. For production in Nebraska and South Dakota, Perrin et al. (2008) used land rents ranging from $62 to $222 per hectare, contingent on the field location. For his base case, Duffy (2008) assumed land costs in Iowa of $198 per hectare and yields of 11 tonnes/hectare. Also for the case of Iowa, Babcock et al. (2007) obtained 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 $618 per hectare. These differences across studies, combined with different production and harvesting practices, make for different cost calculations in the literature.

#### 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). Including downstream processing of the seeds, this author placed the costs of producing jatropha oil at 80 and 89 cents/L for Zimbabwe and India, respectively. Again in the context of India, Francis et al. (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.[8] The seeds yield is assumed to stabilize at 1.8 tonnes/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 tonne of jatropha oil ($442 per tonne in 2008 terms).

Perhaps the most detailed estimates were recently provided by Kukrika (2008) for the case of India (see Table 5). This study calculates costs on a per year basis for a project that lasts ten 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.[9]

*3.1.2.2. Microalgae.* The economic viability of some projects dedicated to the production of higher value products has already been demonstrated (Schenk et al., 2008). However, economics are currently the main impediment to large-scale cultivation of microalgae for lower value uses such as biofuels. For microalgal biodiesel to be commercially viable, production costs need to be sharply reduced from current levels.

Recent detailed and reliable estimates on costs of production are hard to obtain. Current knowledge is bound to the commercial sector, as industries are still in an R&D phase (Kovacevic and Wesseler, 2010). Assessing the current costs of producing algal oil is therefore a challenge, mainly because of existing uncertainty as to potential yields and evolving technologies. Some estimates in the literature (Benemann and Oswald, 1996) placed achievable cost for open ponds in the $51–$90[10] per barrel range, for two different yield levels and $CO_2$ supply methods. A summary of their calculations is presented in Table 6. The second option would obviously have higher operating costs as compared with the first one because of the purification and transportation costs. In each production system, two different biomass yield levels (109 tonnes/ha/yr and 218 tonnes/ha/yr) 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).

More recently, and with the renewed interest in microalgae production, several widely diverging estimates of the cost of production have emerged. Unfortunately, and as previously mentioned, many of the details in the calculations are not provided, making it extremely difficult to assess the sources of the differences across studies. Interestingly, almost all of the recent estimates are much higher than the numbers in Table 6, despite the fact that this study serves as a starting point for many of the ensuing work. A large proportion of the differences is due to the difficulty of attaining the large yields assumed by Benemann and Oswald (1996). A summary of several of the most recent estimates is presented in Fig. 1.

The study conducted by Kovacevic and Wesseler (2010) closely followed the cost structure used by Benemann and Oswald (1996). The cost estimates are presented in euros per gigajoule or per hectare for both 2008 and 2010, without reference to the exchange rate between the euro and the US dollar. However, using an exchange rate of 0.73 euros/dollar, per hectare capital and operating costs estimated by Kovacevic and Wesseler (2010) are comparable to those of Benemann and Oswald (1996). A major difference in terms of cost per liter of oil results from large differences in the assumed oil yields per hectare. In particular, the older study is still considered quite aggressive in terms of the assumption regarding achievable yields. Huntley and Redalje (2007), while not providing as many details, also base their operating and capital costs on Benemann and Oswald (1996).

The average and standard deviation of cost across the studies presented in Fig. 1 are $25/L and $72/L, respectively.[11] However, this is strongly affected by the (large) cost estimates of Molina Grima ($298/L) and NBT Ltd. ($262/L). The median (which is less affected by extreme values) is $4.3/L. The cost uncertainties are largely dominated by capital (facility investments) and operating cost estimation in that order (Pienkos, 2008). It should be noted that most of the lower estimates in the figure (e.g., Benemann and Oswald, 1996, NREL aggressive, NREL maximum, and NMSU High commercial) refer to targets 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. The yield impact indicates that improvements in algal oil yields should be targeted as a cost-reducing strategy. The importance of yields in driving costs can be observed in Fig. 1, along with a breakdown of cost components. Operating costs are the major cost component across the different yield levels included in the figure. Accounting for 30% each, water and the supply of $CO_2$ are the two largest components within this cost category (Pienkos, 2008, not shown). 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 Table 7. The "aggressive" and "maximum" indicate assumptions regarding yields that need to be attained and assume algae oil yields of roughly 73 and 131.4 tonnes per hectare. Clearly, significant breakthroughs are needed to achieve these yield levels on a consistent basis.

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 are bearing fruit. As an example, GreenFuel Technologies Corporation developed a new production system called 3D Matrix

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

[9] Yields are assumed at 1 kilogram per tree for the first harvest year (fourth of the crop), increasing to 3 by year 8. There are 1648 trees per hectare. The oil content is assumed at 25%.

[10] Inflation adjusted to 2008.

[11] A list of the main assumptions behind the disparate results presented in Fig. 1 can be found in Pienkos (2008).

**Table 5**
Estimated costs ($/L[a]) of producing jatropha oil in India.
*Source*: Kukrika (2008).

| | Yr 4 | Yr 5 | Yr 6 | Yr 7 | Yr 8 | Yr 9 | Yr 10 |
|---|---|---|---|---|---|---|---|
| **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** |

[a] The original figures are in 2007 Rs/L, and were converted to $/L using an exchange rate of 42.4 Rs/$ as of 2007 and inflation adjusted to 2008.

**Table 6**
Capital and operating costs for a microalgae open pond system.
*Source*: Benemman and Oswald (1996).

| | 30 $g/m^2/d$ 109 tonnes/ha/yr | | 60 $g/m^2/d$ 218 tonnes/ha/yr | |
|---|---|---|---|---|
| | 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 |
| $/tonne-yr biomass | 887 | 835 | 626 | 561 |
| Operating costs ($)[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 |
| $/tonne biomass | 315 | 256 | 193 | 176 |
| $/barrel of algal oil | 90 | 73 | 55 | 51 |
| $/L of algal oil | 0.57 | 0.46 | 0.34 | 0.32 |

*Note*: Inflation adjusted to 2008.

[a] Labor and overhead would amount to about $3915 and $5219 for the low and high productivity cases respectively.

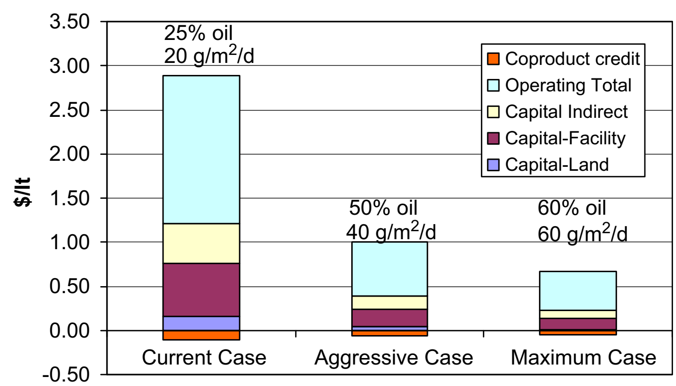


**Fig. 1.** Impacts of productivity on costs of production.
*Source*: Pienkos (2008).

System (3DMS) that achieved productivities of 98 $g/m^2/d$ over a 19-day 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 its research efforts to lower costs of production (F.O. Licht, 2009a). The high capital costs of production facilities (and in particular of photobioreactors) can be expected to decline as engineering expertise develops (Pienkos and Darzins, 2009).

Screening microorganisms for their oil production potential and genetic engineering can increase yields. The latter approach is particularly promising, with efforts being conducted to enhance biomass production, lipid biosynthesis, and to modify lipid composition while limiting competition by other species (Meng et al., 2009; Zeman, 2010). Efforts to increase the value of co-products should improve the economic attractiveness of algal oil production (Meng et al., 2009).

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 Fig. 2.

### 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). 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/L of ethanol annual capacity (Wright and Brown, 2007).

Currently, the operation costs associated with these plants are between $0.35 and $0.45/L depending on assumed feedstocks and corresponding technologies. Anticipated improvements of biofuel conversion technologies are expected to reduce the capital investment needs to $0.95–$1.27/L ethanol annual capacity and to reduce the operating cost to $0.11–$0.25/L of ethanol (Hamelinck et al., 2005). Again, large and risky investments are needed for the technological breakthroughs necessary to achieve these expected cost reductions.

A breakdown of the production costs for lignocellulosic ethanol from four studies is presented in Table 8. Given the variability in feedstock costs reviewed in the previous section, it is to be

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**Table 7**
Recent estimates of costs of production of algal oil (triglyceride).
*Source*: Compiled by the authors.

| Extracted from | Type of facility | Oil content (%) | Biomass product ($g/m^2/d$) | Cost per liter of oil | Comments |
|---|---|---|---|---|---|
| Chisti (2007) | PBR[a] | 30 | N/A | 2.80 | Large-scale facility |
| Chisti (2007) | Ponds[b] | 30 | N/A | 3.21 | |
| Chisti (2007) | PBR | 30–70 | 48 | 5.61–11.2 | Small-scale facility. |
| Chisti (2007) | Ponds | 30–70 | 35 | 6.82–14.0 | Interval reflects different |
| Huntley and Redalje (2007) | Hybrid[c] | 35 | 70.4 | 0.61 | oil yields |
| Benemann and Oswald (1996) | Ponds | 50 | 30 | 0.46–0.57 | Depending on source of |
| Benemann and Oswald (1996) | Ponds | 50 | 60 | 0.32–0.34 | $CO_2$ |
| Pienkos (2008)-NREL maximum | Ponds | 60 | 60 | 0.61 | Maximum, aggressive, and |
| Pienkos (2008)-NREL aggressive | Ponds | 50 | 40 | 0.92 | current labels refer to the |
| Pienkos (2008)-NREL current | Ponds | 25 | 20 | 2.77 | oil yield assumed |
| Pienkos (2008)-NMSU-low yield | Ponds | 35 | 35 | 6.64–10.2 | Interval reflects different |
| Pienkos (2008)-NMSU-high yield | Ponds | 60 | 58 | 2.84–3.64 | scales of production |
| Pienkos (2008)-Solix Phase 2 (projected) | Hybrid | N/A | N/A | 0.22 | Phase 1, Phase 2, and |
| Pienkos (2008)-Solix Phase 1 | Hybrid | 16–47 | 30–40 | 0.66 | current labels refer to the |
| Pienkos (2008)-Solix Current | Hybrid | 16–47 | 0–24.5 | 8.47 | oil yield assumed |
| Pienkos (2008)-NBT Ltd., Israel | Ponds | 35 | 2 | 261.56 | |
| Pienkos (2008)-Seambiotic/IEC Israel | Ponds | 35 | 20 | 6.57 | |
| Pienkos (2008)-Bayer AG | Ponds | 33 | 52 | 3.80 | |
| Pienkos (2008)-General atomics | Hybrid | N/A | N/A | 5.32–8.68 | Interval reflects different |
| Pienkos (2008)-CA Polytechnic Institute | N/A | 25 | 20 | 4.45 | oil yields |
| Pienkos (2008)-Sandia | PBR | 35 | 30 | 8.76 | |
| Pienkos (2008)-Sandia | Ponds | 35 | 30 | 4.16 | |
| Molina Grima et al. (2003) | PBR | 10 | | 297.75 | |

[a] PBR refers to photobioreactor.
[b] Ponds refers to open ponds and raceways.
[c] Hybrid refers to a coupled system of photobioreactors and open ponds and raceways.

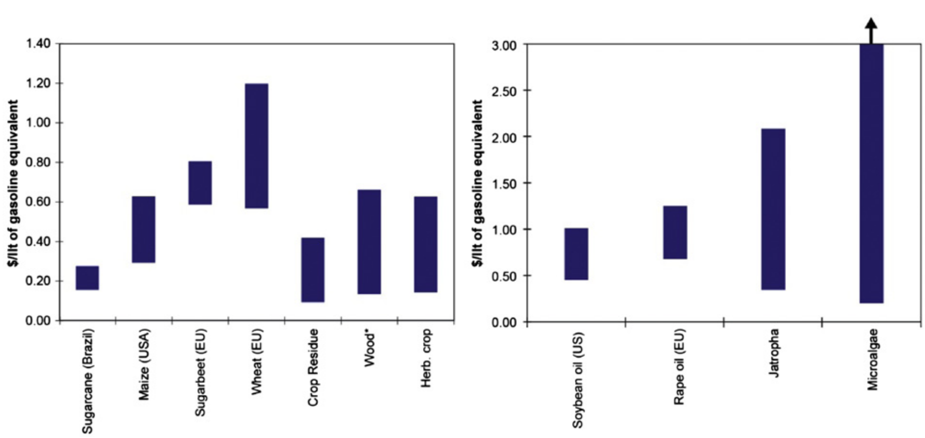


**Fig. 2.** Cost of various feedstocks for first and second generation biofuels.
*Source*: Compiled by the authors. *Note*: For cellulosic ethanol, a yield of 300 L/tonne of feedstock is assumed. A one-to-one conversion was assumed for vegetable oils into biodiesel. *Includes forest residues and dedicated woody energy crops. Feedstock costs for first generation ethanol were obtained from International Energy Agency (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.

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/L range (International Energy Agency (IEA), 2008). Technological advances are expected to drive production costs down to as low as $0.30–$0.40/L by 2020 (International Energy Agency (IEA), 2005; Perlack et al., 2005). More ambitious targets for production cost reductions (achieving costs of $0.28/L by 2012) were included in the US Biofuels Initiative (U.S. Department of Energy (USDOE), 2008).

Despite small differences in the relative weight of some cost categories, estimates are largely consistent with each other in the first three studies, yielding an estimated cost of $0.6/L of ligno-cellulosic ethanol. Capital costs account for roughly 40% of the overall costs in the studies. It should be noted 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

**Table 8**
Production costs for the lignocellulose process ($/L).

| | 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 to −0.16 | −0.1 to −0.12 | −0.09 to −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)[a] | Loblolly pine (2) |
| Feedstock | 0.16 | 0.24 | 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 | 0.40 | 0.45 | 0.65 |

*Note*: Inflation adjusted to 2008.

[a] Two different pretreatments of the biomass are considered here.

**Table 9**
Cost of jatropha-based biodiesel production (inflation adjusted to 2008).

| Item | Costs ($/L) | Country setting and comments |
|---|---|---|
| Gonsalves (2006) | 0.44 | India |
| Francis et al. (2005) | 0.54 | India (feedstock at $441.8/tonne)[a] |
| Peters and Thielmann (2008)[b] | 1.44–2.87 | India-current |
| Peters and Thielmann (2008) | 0.42–1.30 | India-projected |
| Peters and Thielmann (2008) | 2.29–2.45 | Tanzania-current |
| Peters and Thielmann (2008) | 0.72–0.82 | Tanzania-projected |
| Kukrika (2008) | 0.72–1.67 | India—see Table 6 |

[a] Assuming a seed cost of $0.12/kg, an oil extraction rate of 28%, and a processing cost of US$21.2/tonne.
[b] The original ranges are reported in 2004 dollars per 1.09 L 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.

production across all studies. This is in marked contrast to first generation ethanol, where feedstock accounts for roughly 55% to over 70% of the total costs of production (International Energy Agency (IEA), 2008).

For the case of jatropha-based biodiesel, costs of production have been reported in the $0.44–$2.87/L range for developing country settings (see Table 9). Wide ranges are reported even within studies for a given location, which reflects persisting uncertainty about jatropha yields and associated feedstock costs of production (Peters and Thielmann, 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 of these cost projections, since costs may remain high even in large-scale operations (Peters and Thielmann, 2008).

One of the most explicit estimates available for the costs of producing jatropha-based biodiesel in India was provided by Kukrika (2008) (see Table 10). 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).

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 with fossil fuels. The total production costs per unit of energy reported in the literature are summarized in Fig. 3, 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 cost of second generation biodiesel (from either jatropha or algae oil) at similar levels 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 noting 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.

## 4. Challenges and policy implications

Myriad 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

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**Table 10**
Estimated costs ($/L)[a] of producing biodiesel from jatropha trees.
*Source*: Kukrika (2008).

| | Yr 4 | Yr 5 | Yr 6 | Yr 7 | Yr 8 | Yr 9 | Yr 10 |
|---|---|---|---|---|---|---|---|
| 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** |

[a] The original figures are in 2007 Rs/L, and were converted to $/L using an exchange rate of 42.4 Rs/$ as of 2007 and inflation adjusted to 2008.
[b] From Table 5.

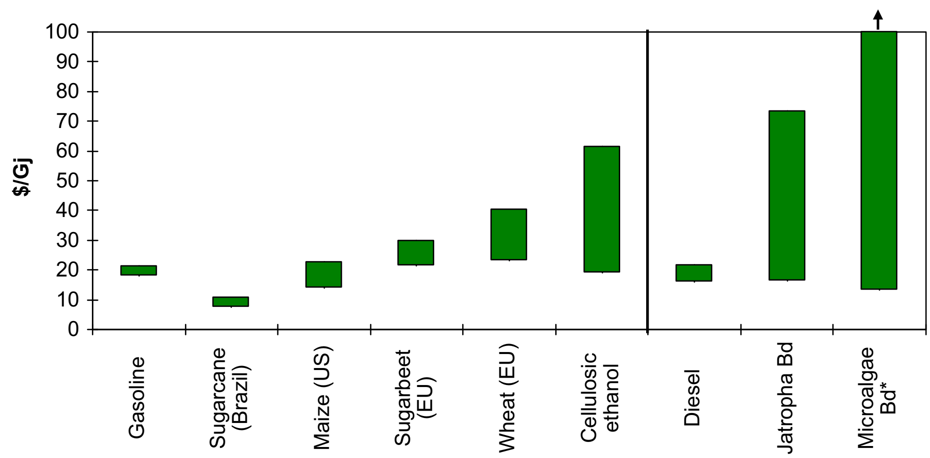


**Fig. 3.** Biofuel production cost ($/GJ) from various feedstocks.
*Source*: International Energy Agency (IEA), (2008). For gasoline and diesel prices, the range is given by wholesale prices (excluding taxes) in years 2007 and 2008 in the US. The assumed energy contents are as follows: ethanol 21.1 MJ/L; gasoline 32 MJ/L; biodiesel 33.3 MJ/L; and diesel 36.4 MJ/L. 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/L (Paulson and Ginder, 2007). First generation ethanol costs are from International Energy Agency (IEA), (2008). *The upper values for feedstock costs would imply costs of production per GJ in the thousands for algae biodiesel.

are being rapidly enacted by different countries, and previous legislation is frequently modified. REN21, the Renewable Energy Policy Network for the 21st Century, reports that 73 countries (many of them developing countries) had bioenergy targets as of early 2009 (REN21, 2009). At least 23 countries were reported as having mandates to blend biofuels into fossil transportation fuels.

A vast majority of these policies would incentivize the supply and utilization of both generations at the same levels, regardless of costs of production 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 those of the US and the EU. The US Energy Independence and Security Act (EISA) of 2007 specifies a mandated volume for advanced biofuels as part of the second Renewable Fuels Standard (RFS2). The minimum size of that market is set at 79.5 billion liters by 2022, of which 60.5 billion liters are reserved for cellulosic biofuels.[12] However, the US Environmental Protection Agency (EPA) is required by the US Congress to make an annual production estimate for cellulosic ethanol and to waive down the cellulosic ethanol portion of the RFS2' mandate if capacity is not available. For example, in December 2010, EPA released the volume requirements for 2011, which include 25.0 million liters of cellulosic ethanol instead of the EISA mandate of 946 million liters.[13]

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 cost differential between these fuels. In a separate piece of legislation, the farm bill of 2007 increased the blender's tax credit for cellulosic ethanol to $0.27/L ($1.01/gallon), while reducing that of conventional (corn) ethanol to $0.12/L ($0.45/gallon).[14]

[12] Additionally, it provides for funds in the form of grants and loans for R&D, and for development and construction of advanced biorefineries.

[13] http://www.epa.gov/otaq/fuels/renewablefuels/420f10056.pdf

[14] 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.

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The EU also provides additional benefits for second generation biofuels, compared with those given to conventional biofuels, but to a lesser extent than does the U.S. Under the draft Directive proposal of 2008, requiring 10% of renewable energy used in 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 the basis of private cost of production (i.e., excluding external costs to society), they are still simply too expensive to produce, relative to the fossil fuels they could replace. Given the public good characteristics of investments in R&D, economic theory would indicate that under-investment 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 as to support the development of the most advantageous biofuels and discourage production of "bad biofuels" (International Energy Agency (IEA), 2008). The International Energy Agency 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 on the order of 30-fold are cited by the World Watch Institute (World Watch Institute (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.[15]

Improvement in feedstock production is another area showing promise for lowering 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 a relatively short amount of time (Smeets et al., 2004; World Watch Institute (WWI), 2007).

One important policy question would be, what is the priority for cost reduction: feedstock, plant cost, conversion, or yield? For the cellulosic biofuels, the conversion cost is the key cost component. In the case of first generation biofuels – algae- and jatropha-based 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.

The limited potential of first generation biofuels to make a significant contribution in displacing fossil fuels and reducing greenhouse gas (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 less competition for prime land with food crops when compared with first generation biofuels. While dedicated energy crops would still be competing for land with food crops, it is envisioned that either by using lower-quality soils (jatropha) or by providing more utilizable biomass per unit of land (e.g., switch-grass 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 the type of biofuels, feedstock prices and conversion costs, the cost of cellulosic ethanol is found to be two to three times higher than 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. As compared with 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 (30–50%) 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 would 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, policy-makers should offer different levels of support to different biofuels. The capacity of biofuels that simultaneously advance multiple policy goals should be considered when designing incentive mechanisms. As such, an integrated approach combining rural development, climate change, and energy provision is warranted when formulating the policy framework for second generation biofuels. That framework should also consider trends in regional and international developments (in both policies and trade) to exploit synergies and maximize the potential benefits achievable through the policies implemented. As an example, support of biofuels that do not comply with international standards (e.g., on quality or sustainability criteria) would hardly result in the deployment of an industry able to expand beyond some local or domestic markets.

Policy instruments, such as tax credits or exemptions, could also be used to differentially incentivize the production pathways according to their contribution to pre-established goals. For example, if a valued objective is the reduction of GHG emissions, higher incentives (e.g., subsidies) could be provided to biofuels with a higher level of GHG reductions. Additional goals such as the enhancement of the livelihoods of small farmers in developing countries could also be pursued by providing incentives to processors that procure their raw material from them. The US, for instance, provides a higher tax credit for second generation biofuels than for corn ethanol. In Brazil, biodiesel plants that procure certain feedstock from family farms in some regions of the country (among other requirements) can claim a "social seal" that qualifies them for government-provided tax benefits.[16]

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[15] The U.S. is by far the country with the largest investments in bioenergy R&D. As an example, the U.S. Department of Energy will invest over $600 million over the next four or five years in several joint demonstration projects with private players. In addition, almost $800 million in funding was announced under the American Recovery and Reinvestment Act to accelerate the research and commercialization of biofuels (U.S. Department of Energy (USDOE), 2009).

[16] 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 about whether it will achieve the desired goals (Gordon, 2008).

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