TOPIC PAPER #8

BIOMASS

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

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Potential Biomass Energy Supply in 2030 to 2050 Time Frame

Bioenergy Cross-Cutting Team

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Date submitted: Jan 30, 2007

I. Executive Summary

Given current trends world energy demand is expected to increase by 50 percent by 2030.[1] There are expectations that renewable resources will be able to play a significant role satisfying this future energy demand. Others have a more pessimistic view and forecast that it will not make up even 2% of the total energy mix by 2030.[1] In 2001 global primary-energy consumption was 418 EJ (an exajoule (EJ) is 10^{18} joules; for comparison, 1.055 EJ is roughly equivalent to one quadrillion BTU or 172 million barrels of oil equivalent.). Of this, biomass supplied 45 EJ. This is significantly more than the 2% predicted to be used by 2030,[1] but is probably overlooked because about 39 EJ of this was in the form of traditional uses for heating and cooking, which do not enter world trade and are mostly beyond governmental control and taxation. Global biomass production on the earth's land surface is equal to 4,560 EJ (the gross primary production) of which half is lost by autotrophic respiration and decomposition, leaving 2,280 EJ (net primary production or NPP).[2] The availability of the NPP for use in food and energy production is restricted by many factors, such as logistics, economics, or legal restraints. Without intervention this NPP is in balance with natural decomposition. Because of its large value, usage of even a portion of the NPP would indicate that there is considerable potential for biomass to play a role of some type in global energy production beyond heating a cookstove.

Numerous studies have been carried out to determine the percentage of the global biomass production that could be used to supply some of the world's energy needs.[2-15] All of these studies have had to deal with the variety of paths that biomass takes in the modern world and have had to deal with estimates of global population, changing diets, and changes in crop yields. A recent report by FAO has estimated population, food needs and agricultural development for the time frame of 2015 to 2030.[16] This report covers many of the pertinent factors that will determine if there will be sufficient agricultural output available for providing food, fiber, and fuel in the future.

According to the FAO, agricultural production of food and feed will continue to grow at a pace to meet the needs of the world population thru 2030. Population growth will continue to decrease during this time period and on into the next century. Over the last 40 years, food production has been controlled by demand rather than supply. This has led to a decline of almost 50% in the value of commodity crops in constant dollars over this time period. This decline has led to the fact that only in countries with farm support programs in place have crop yields and production reached the highest levels, while third world production has lagged.

Over the last 20 years, a variety of studies have been carried out looking at what the potential of agriculture could be to produce both energy and food for the world if such production was optimized. While these have had varying final conclusions, most have estimated between 250 and 500 EJ of biomass energy could be produced while still feeding a growing population in the world. These studies have in general not looked at expanding current agricultural acreage significantly. The most optimistic studies require that global agricultural food production per hectare, under equivalent environmental conditions, reach optimal levels. This would allow large areas of land to become available for energy crop production. If only waste biomass and dung were used from our current agricultural production, an energy supply of ~100 EJ could be expected.

Biotechnology is expected to increase crop production in the next few decades at a higher than historic rate. This increase is being brought about by marker-assisted breeding that can increase trait development by a tenfold rate over conventional breeding. Along with this increased rate, the ability to engineer specific new traits into crops will bring about remarkable changes in crop production. This increase could be expected to double the average yield of crops such as corn by 2030.[20] Such an increase in the U.S. corn crop would allow the corn production in the USA to reach 25 billion bushels. A corn crop of this size would make it possible to produce 54 billion gallons of ethanol by conventional means, 6 billion gallons of biodiesel from the corn oil, and 18 billion gallons of ethanol from the excess stover (e.g. stalks). On top of this, 154 million metric tons of distillers' dried grain would more than fill the demand for animal feed that is currently met by corn and soybean production.

Many of these predictions require that some pressure be brought upon agriculture to spur production globally. The energy market could provide this new opportunity for agriculture by speeding investment in production. The development of new energy crops has the potential to produce even more bioenergy per hectare with less inputs and more environmentally friendly production means. This will not happen without the development of local conversion methods and logistics for efficiently handling the low energy-density of most biomass feedstocks.

II. Potential Biomass Energy Supply in 2030

A. Framing Questions

- Biofuel key drivers
- Critical land and resource issues for large-scale production
- Biofuels pathways from multiple feedstocks
- Constraints to first generation biofuels
- Next-generation biofuels
- Quantification of largest CO_2 impact from biofuels—biomass to electricity, cellulose to liquids, conventional to biodiesel or ethanol
- Scale, cost, and technological issues associated with cellulosic ethanol.

III. Overview of Methodology

This study is a review of the published literature on the topic of bioenergy and food production. While not a comprehensive review we have tried to cover the most current and applicable published art.

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IV. Bioenergy Roadmap

A. Background

Given current trends, world energy demand is expected to increase by 50 percent by 2030.[1] There are expectations that renewable resources will be able to play a significant role in satisfying this future energy demand. Others have a more pessimistic view and forecast that it will not make up even 2% of the total energy mix by 2030.[1] The issue is whether agriculture and forestry can supply food, fiber and significant energy needs for a growing population.

In 2001 global primary energy consumption was 418 EJ. Of this biomass supplied 45 EJ. This is significantly more than the 2% predicted to be used by 2030 but is probably overlooked because about 39 EJ of this was in the form of traditional uses for heating and cooking, which do not enter world trade and are mostly beyond governmental control and taxation. Global biomass production on the earth's land surface is equal to 4,560 EJ (the gross primary production) of which half is lost by autotrophic respiration and decomposition, leaving 2,280 EJ(net primary production or NPP).[2] The availability of the NPP for use in food and energy production is restricted by many factors, such as logistics, economics, or legal restraints. Without intervention, this NPP is in balance with natural decomposition. Because of its large value, usage of even a portion of the NPP would indicate that there is considerable potential for biomass to play a role of some type in global energy production beyond heating a cookstove.

V. Overview

Use of renewable energy from biomass will affect a variety of flows in the biosphere, as shown in Figure V.1.

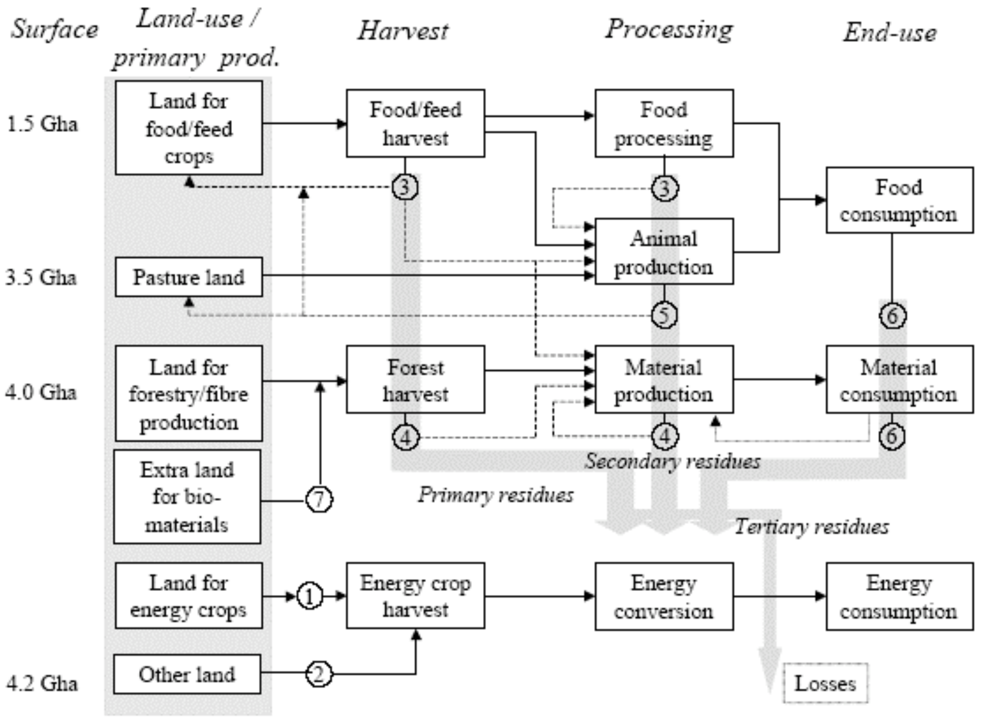


Fig. 1. Overview of various types of biomass flows and the global land surface (Based on: [1,22]). The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The gray arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

Figure V.1. Overview of various types of biomass flows and the global land surface. [3]

Providing both food and fuel is a global issue rather than one that just can be addressed in North America. It will require the development of better food crops for all the arable land in current use, fostering best agricultural practices, development of bioenergy crops (preferably perennial) for excess agricultural land and marginally arable land, development of suitable harvesting and storage of energy crops, and the development of an efficient conversion system.

In order to assure a food supply for the global population, the world needs to produce an excess amount of food each year in to make up for potential shortfalls in any one year. This has been standard practice for the last several decades. While this is a very necessary insurance system, it has led to large reserves of crops that have decreased the value of agricultural production and stagnated production in areas of the world without price support systems. See Figures V.2, V.3 and V.4 and Table V.1.

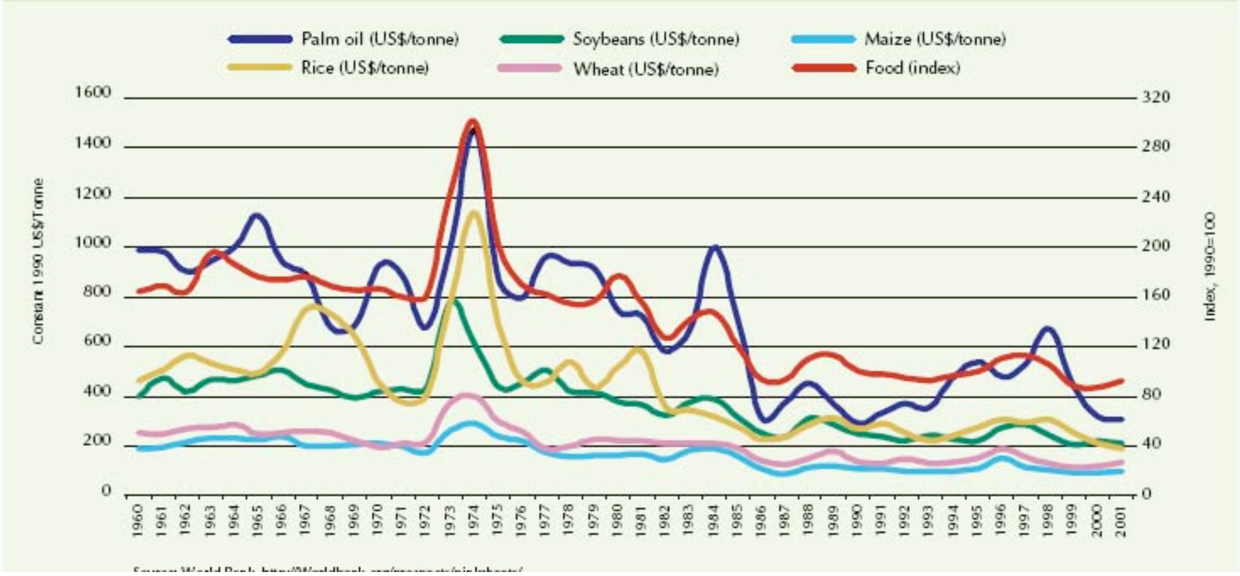
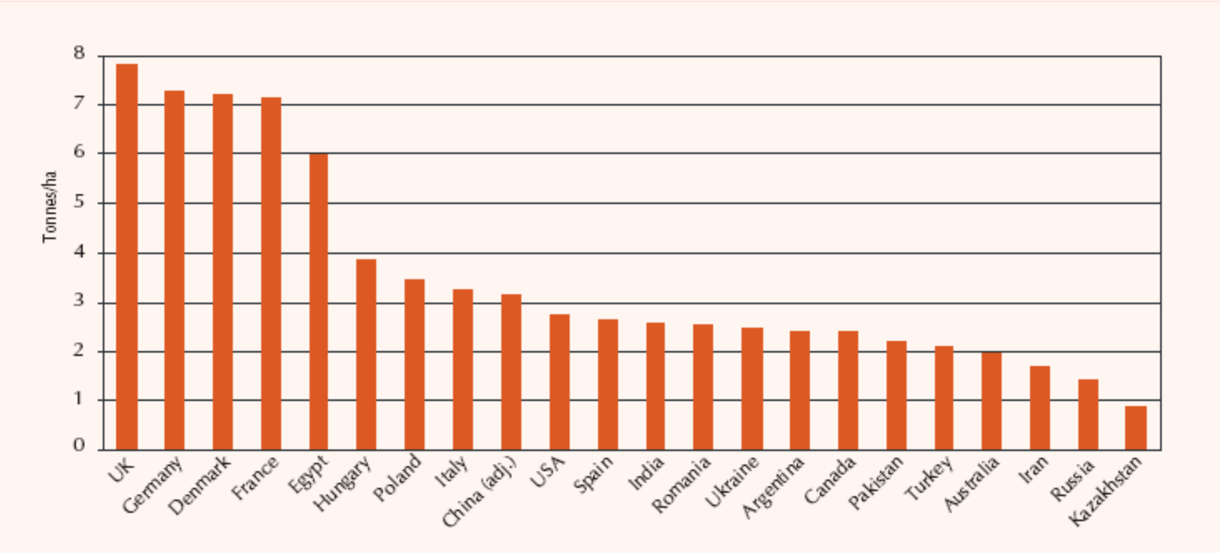
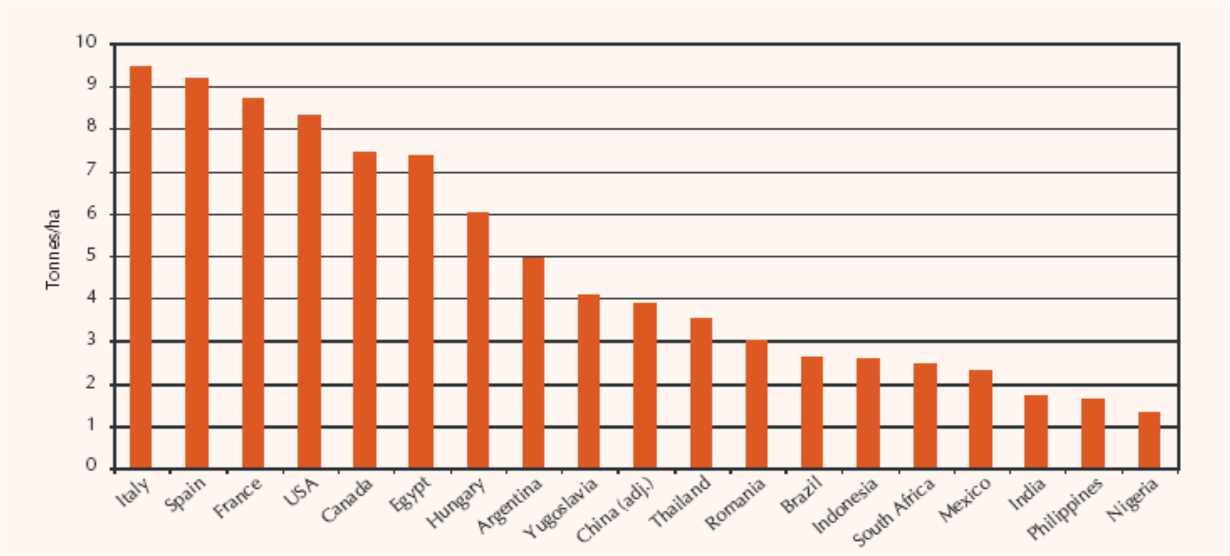


Figure V.2 Cost of selected crops over time. [4]



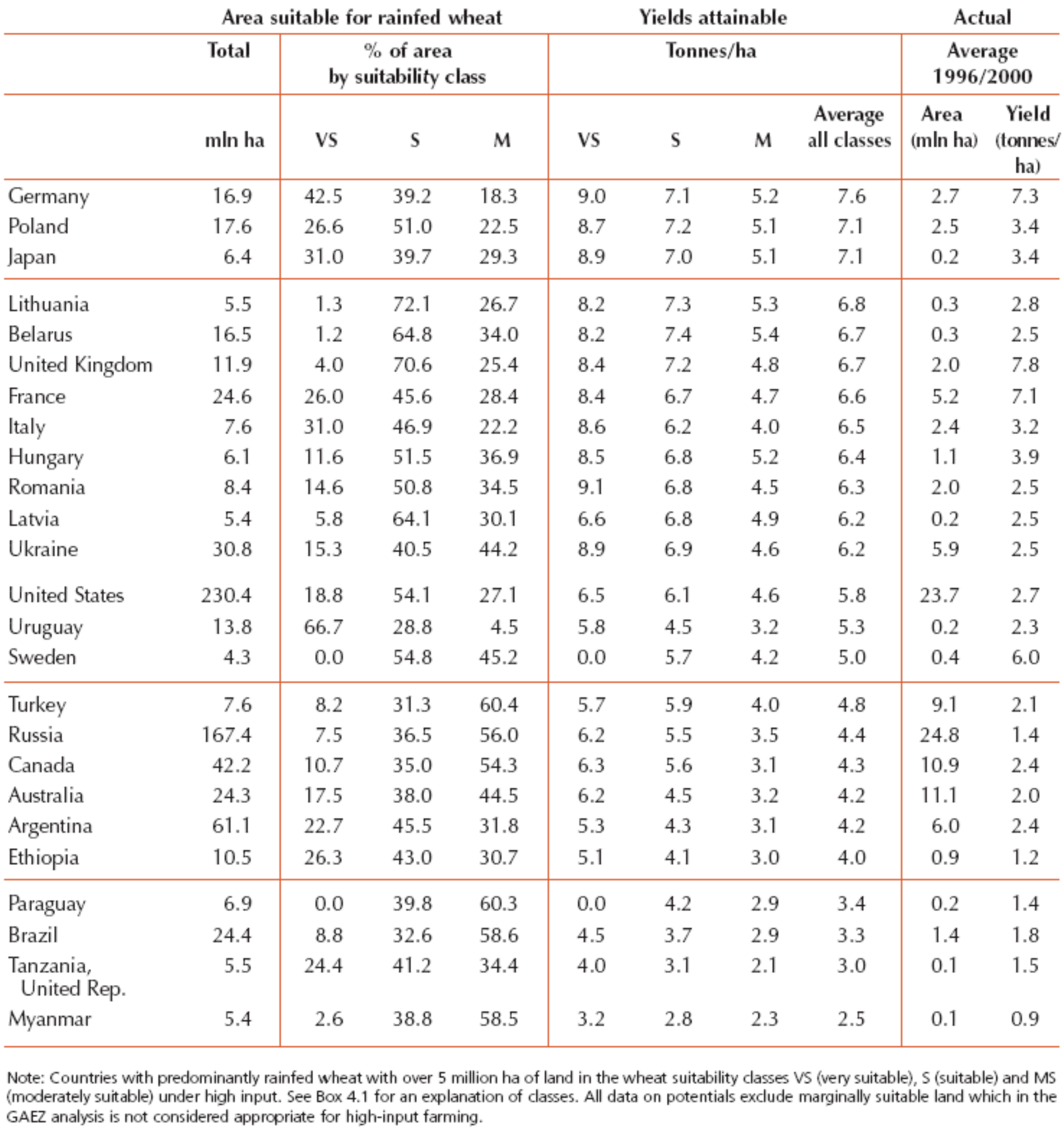
Note: Twenty-two countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world wheat output in 1996/2000

Figure V.3. Output of wheat in selected countries.[4]



Note: Nineteen countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world maize output in 1996/2000

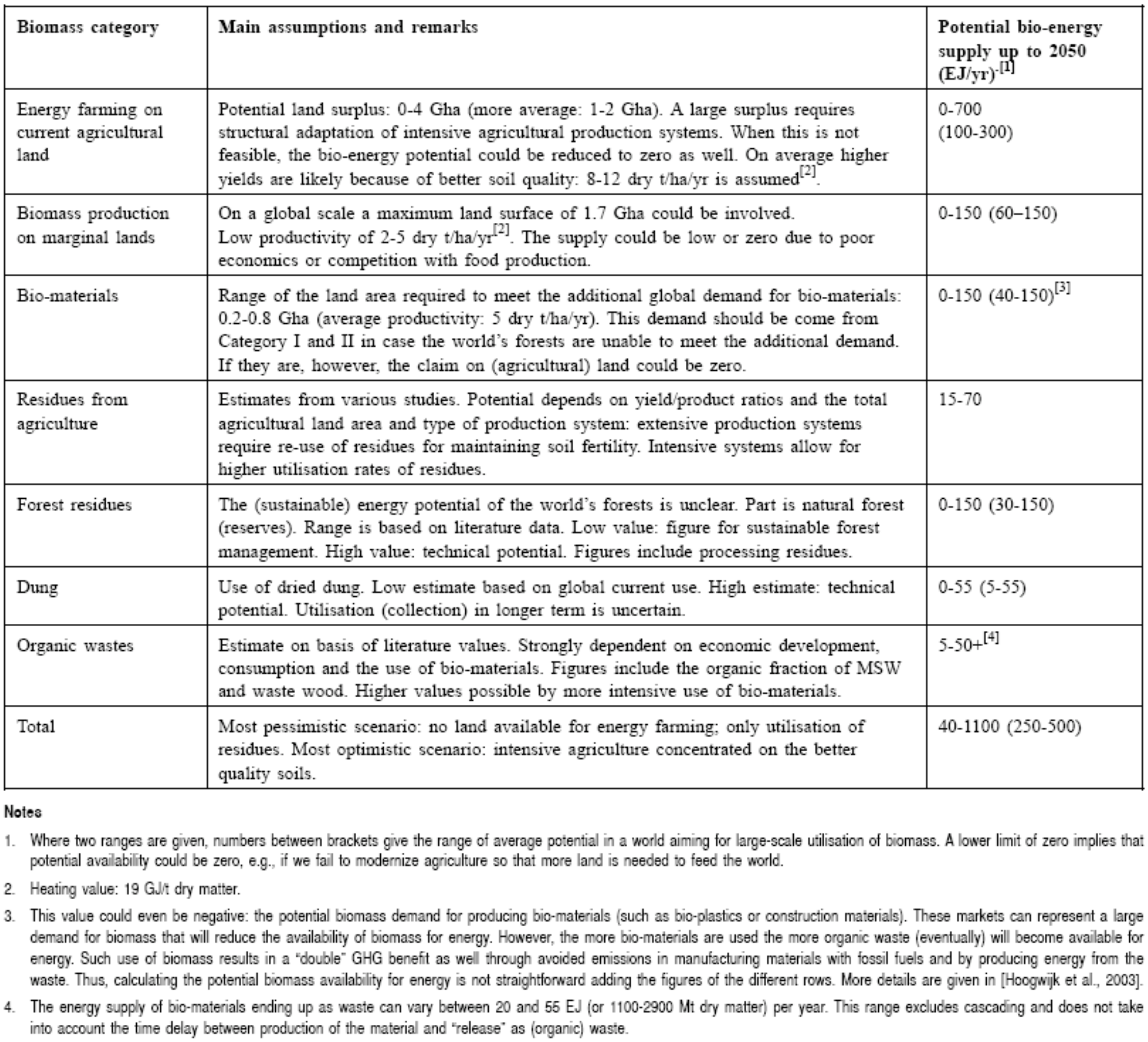
Figure V.4. Output of maize in selected countries.[4]



	Area suitable for rainfed wheat				Yields attainable				Actual	
	Total	% of area by suitability class			Tonnes/ha				Average 1996/2000	
	mln ha	VS	S	M	VS	S	M	Average all classes	Area (mln ha)	Yield (tonnes/ ha)
Germany	16.9	42.5	39.2	18.3	9.0	7.1	5.2	7.6	2.7	7.3
Poland	17.6	26.6	51.0	22.5	8.7	7.2	5.1	7.1	2.5	3.4
Japan	6.4	31.0	39.7	29.3	8.9	7.0	5.1	7.1	0.2	3.4
Lithuania	5.5	1.3	72.1	26.7	8.2	7.3	5.3	6.8	0.3	2.8
Belarus	16.5	1.2	64.8	34.0	8.2	7.4	5.4	6.7	0.3	2.5
United Kingdom	11.9	4.0	70.6	25.4	8.4	7.2	4.8	6.7	2.0	7.8
France	24.6	26.0	45.6	28.4	8.4	6.7	4.7	6.6	5.2	7.1
Italy	7.6	31.0	46.9	22.2	8.6	6.2	4.0	6.5	2.4	3.2
Hungary	6.1	11.6	51.5	36.9	8.5	6.8	5.2	6.4	1.1	3.9
Romania	8.4	14.6	50.8	34.5	9.1	6.8	4.5	6.3	2.0	2.5
Latvia	5.4	5.8	64.1	30.1	6.6	6.8	4.9	6.2	0.2	2.5
Ukraine	30.8	15.3	40.5	44.2	8.9	6.9	4.6	6.2	5.9	2.5
United States	230.4	18.8	54.1	27.1	6.5	6.1	4.6	5.8	23.7	2.7
Uruguay	13.8	66.7	28.8	4.5	5.8	4.5	3.2	5.3	0.2	2.3
Sweden	4.3	0.0	54.8	45.2	0.0	5.7	4.2	5.0	0.4	6.0
Turkey	7.6	8.2	31.3	60.4	5.7	5.9	4.0	4.8	9.1	2.1
Russia	167.4	7.5	36.5	56.0	6.2	5.5	3.5	4.4	24.8	1.4
Canada	42.2	10.7	35.0	54.3	6.3	5.6	3.1	4.3	10.9	2.4
Australia	24.3	17.5	38.0	44.5	6.2	4.5	3.2	4.2	11.1	2.0
Argentina	61.1	22.7	45.5	31.8	5.3	4.3	3.1	4.2	6.0	2.4
Ethiopia	10.5	26.3	43.0	30.7	5.1	4.1	3.0	4.0	0.9	1.2
Paraguay	6.9	0.0	39.8	60.3	0.0	4.2	2.9	3.4	0.2	1.4
Brazil	24.4	8.8	32.6	58.6	4.5	3.7	2.9	3.3	1.4	1.8
Tanzania, United Rep.	5.5	24.4	41.2	34.4	4.0	3.1	2.1	3.0	0.1	1.5
Myanmar	5.4	2.6	38.8	58.5	3.2	2.8	2.3	2.5	0.1	0.9

Note: Countries with predominantly rainfed wheat with over 5 million ha of land in the wheat suitability classes VS (very suitable), S (suitable) and MS (moderately suitable) under high input. See Box 4.1 for an explanation of classes. All data on potentials exclude marginally suitable land which in the GAEZ analysis is not considered appropriate for high-input farming.

Table V.1. Yield of predominantly rainfed wheat in selected countries.[4]



Biomass category	Main assumptions and remarks	Potential bio-energy supply up to 2050 (EJ/yr)[1]
Energy farming on current agricultural land	Potential land surplus: 0-4 Gha (more average: 1-2 Gha). A large surplus requires structural adaptation of intensive agricultural production systems. When this is not feasible, the bio-energy potential could be reduced to zero as well. On average higher yields are likely because of better soil quality: 8-12 dry t/ha/yr is assumed[2].	0-700 (100-300)
Biomass production on marginal lands	On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2-5 dry t/ha/yr[2]. The supply could be low or zero due to poor economics or competition with food production.	0-150 (60–150)
Bio-materials	Range of the land area required to meet the additional global demand for bio-materials: 0.2-0.8 Gha (average productivity: 5 dry t/ha/yr). This demand should be come from Category I and II in case the world's forests are unable to meet the additional demand. If they are, however, the claim on (agricultural) land could be zero.	0-150 (40-150)[3]
Residues from agriculture	Estimates from various studies. Potential depends on yield/product ratios and the total agricultural land area and type of production system: extensive production systems require re-use of residues for maintaining soil fertility. Intensive systems allow for higher utilisation rates of residues.	15-70
Forest residues	The (sustainable) energy potential of the world's forests is unclear. Part is natural forest (reserves). Range is based on literature data. Low value: figure for sustainable forest management. High value: technical potential. Figures include processing residues.	0-150 (30-150)
Dung	Use of dried dung. Low estimate based on global current use. High estimate: technical potential. Utilisation (collection) in longer term is uncertain.	0-55 (5-55)
Organic wastes	Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of bio-materials. Figures include the organic fraction of MSW and waste wood. Higher values possible by more intensive use of bio-materials.	5-50+[4]
Total	Most pessimistic scenario: no land available for energy farming; only utilisation of residues. Most optimistic scenario: intensive agriculture concentrated on the better quality soils.	40-1100 (250-500)

Notes

1. Where two ranges are given, numbers between brackets give the range of average potential in a world aiming for large-scale utilisation of biomass. A lower limit of zero implies that potential availability could be zero, e.g., if we fail to modernize agriculture so that more land is needed to feed the world.
2. Heating value: 19 GJ/t dry matter.
3. This value could even be negative: the potential biomass demand for producing bio-materials (such as bio-plastics or construction materials). These markets can represent a large demand for biomass that will reduce the availability of biomass for energy. However, the more bio-materials are used the more organic waste (eventually) will become available for energy. Such use of biomass results in a "double" GHG benefit as well through avoided emissions in manufacturing materials with fossil fuels and by producing energy from the waste. Thus, calculating the potential biomass availability for energy is not straightforward adding the figures of the different rows. More details are given in [Hoogwijk et al., 2003].
4. The energy supply of bio-materials ending up as waste can vary between 20 and 55 EJ (or 1100-2900 Mt dry matter) per year. This range excludes cascading and does not take into account the time delay between production of the material and "release" as (organic) waste.

Table V.2. Biomass categories. [5]

As can be seen by the above figures and tables, considerable improvement in yields per hectare could be achieved globally for food production, but with decreasing real value for agricultural products there is no reason for such investments.

If production could be improved globally for food crops, large areas of land currently used for food production could be utilized for bioenergy production, and some marginal land that is currently used for crop production could be converted to more suitable bioenergy crop production.

One scenario for achieving this while feeding a growing population is described in the following. In 1999, the total consumption of crops was 666.5 kg/person/yr, while meat and dairy consumption was 114 kg (36 kg meat and 78 kg dairy) annually per person. Of the meat consumed, 27% was bovine, 40% pork, 28% poultry, and 5% from goats and sheep. By 2030, meat and dairy consumption is expected to increase to 135 kg/person/yr (45 kg meat and 90 kg dairy) with non-meat consumption rising to 709.5 kg. The ratios will change considerably with rapid growth in poultry relative to the other meats. The percentages will be 23% bovine, 33% pork, 38% poultry and 5.3% goats and sheep.[4]

The increase in meat consumption and the ratios will have significant effects on the needs for total crop production. In the world, it currently requires on average 45 kg of grain equivalents to make one kg of bovine meat, 1.6 kg grain/kg milk, 79 kg grain/kg mutton, 6.7 kg grain/kg pork and 3.6 kg grain/kg poultry.[2] This means that at the current ratios in the diet, meat production requires on average 28 kg of grain equivalents per kg of meat produced. If no changes occur in meat product by 2030, the ratios of meat in the diet will mean that for every kg of meat produced it will require 18.2 kg of grain equivalents.

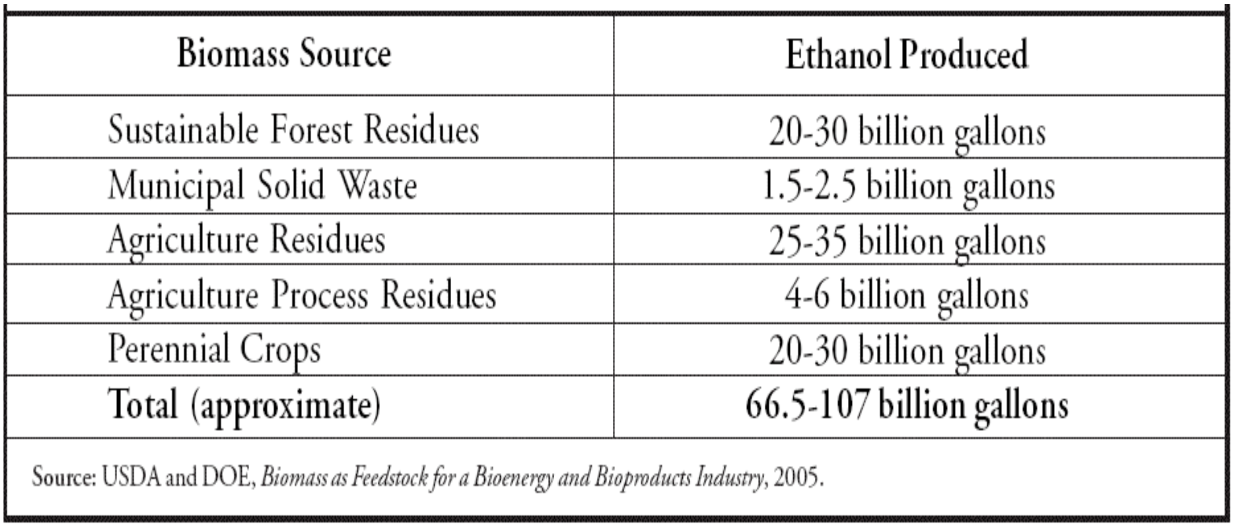
There are more optimal ways of producing meat, and if such methods are adopted globally, then this would significantly reduce the amount of grain equivalents required. Optimally, in a landless system of meat production, a kg of bovine meat would require 15 grain equivalents, mutton 46 grain equivalents, pork 6.2 and poultry 3.1 and 1 grain equivalent for dairy.[2] If such practices were adopted, because of economic factors or policy, the grain equivalents required per kg of meat would change to 9.1 kg in 2030.

The current diet therefore requires a total of 665 kg directly from plants + 36 kg meat times 28 kg grain/kg meat + 78 kg dairy times 1.6 kg grain/kg milk = 1,798 kg of grain equivalents per person. If modern practices are adopted for meat and dairy production by 2030 this could change to 709.5 directly from plants + 1 times 90 kg dairy + 9.1 times 45 kg meat = 1,209 kg of grain equivalents per person. Such a decrease will make it much easier to meet food demand and some of our future energy demands.

In concert with improving the status of agriculture globally, energy crop and energy crop conversion technologies need to be developed to make use of the large potential of biomass that could be available in the future. The most likely estimate of this potential is 250 to 500 exajoules.[5] The world currently uses ~500 exajoules in all energy forms. For comparison, 1.055 exajoules is roughly equivalent to one quadrillion BTU or 172 million barrels of oil equivalent.

A. U.S. Production Potential

Several different options have been looked at for the production of biofuels in the USA. The DOE funded a study on the potential for energy crop and residue collection. This study found that there is the potential to produce 1.3 billion dry tons of biomass in the first half of this century annually from forestry and crop production.[7] The table below summarizes the ethanol production potential.[8]



Biomass Source	Ethanol Produced
Sustainable Forest Residues	20-30 billion gallons
Municipal Solid Waste	1.5-2.5 billion gallons
Agriculture Residues	25-35 billion gallons
Agriculture Process Residues	4-6 billion gallons
Perennial Crops	20-30 billion gallons
Total (approximate)	**66.5-107 billion gallons**

Source: USDA and DOE, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry*, 2005.

Table VA.1. Potential ethanol production from various biomass sources.[8]

Another possibility discussed is the potential of biotechnology to radically speed the development of the current corn crops. Monsanto has indicated that based on current trends the average yield of corn in the USA will reach 300 bushels per acre by 2030, up from the current 150 bushels. This increase would provide up to 20 billion bushels of corn for ethanol production. Production of ethanol from the available starch could potentially reach 54 billion gallons. Beyond this, 6 billion gallons of biodiesel could be made from the recoverable corn oil, with enough corn stover production to either supply energy for the ethanol plants or produce another 21 billion gallons of ethanol.[9]

Another study based on the current economics of ethanol production estimated its effect on the U.S. corn crop and global corn production. The study estimates that at $4.05/bushel of corn and $60/bbl of crude oil, corn-based ethanol production would reach 31.5 billion gallons per year in 2015. Supporting this level of production would require 95.6 million acres of corn to be planted. This increase in acreage would occur because of economic drivers preferring corn over other crops. Also the corn export market would be lost because non-domestic corn production would also increase to fill those markets. Total corn production in the USA would be approximately 15.6 billion bushels, compared to 11.0 billion bushels today.[10]

B. Logistics of Production

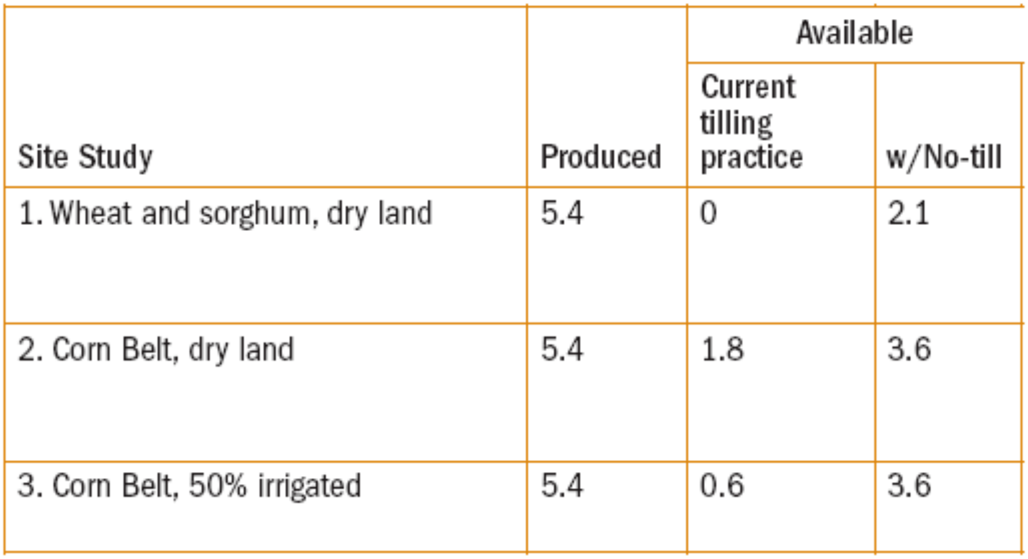
Biomass is produced in a much more distributed manner than oil and gas, which makes its collection and conversion problematic. This will have ramifications on the types of technology deployed to convert it into a usable fuel and also getting it to urban markets. Table VB.1 below shows the size of plants and the needed acreage to supply that plant with feedstock.

	Land required within a given radius to feed plant of given size,[a] %				
Feedstock collection radius, miles	**Plant size at 90% capacity, tons/day**				
	500	**1000**	**5000**	**10000**	**20000**
10	6.5	13.1	65.5	-	-
20	1.6	3.3	16.4	32.7	65
30	0.7	1.5	7.3	14.6	29
40	0.4	0.8	4.1	8.2	16.4
50	0.3	0.5	2.6	5.2	10.5
60	0.2	0.4	1.8	3.6	7.3
70	0.1	0.3	1.3	2.7	5.3
Ethanol production,[b] million gal/yr	12	24	122	244	488

[a] 12.5 tons/acre of switchgrass
[b] 70 gallons of ethanol/ton

Table VB.1. Percent of land required within a given radius to feed several plant sizes.[11]

The most likely first plants deployed will use crop residues for feedstock. Since this will only allow a sustainable harvest of 1 to 3 ton/acre, the size of plants will need to be much smaller to take in to consideration the cost of transportation of the feedstock.



Site Study	Produced	Available	
		Current tilling practice	w/No-till
1. Wheat and sorghum, dry land	5.4	0	2.1
2. Corn Belt, dry land	5.4	1.8	3.6
3. Corn Belt, 50% irrigated	5.4	0.6	3.6

Table VB.2. Feedstock production and availability in a 50 mile radius (million dry tons).[12]

C. Conversion Technologies

Table VC.1 outlines a variety of technologies that are proposed for converting biomass to modern bioenergy production. The currently deployed technologies are starch- and sugar-to-ethanol, biodiesel production, and direct co-firing. There are currently a variety of technologies that are at the pilot plant or demonstrations stage. These will be deployed as they find applications with different feedstocks and logistics.[13]

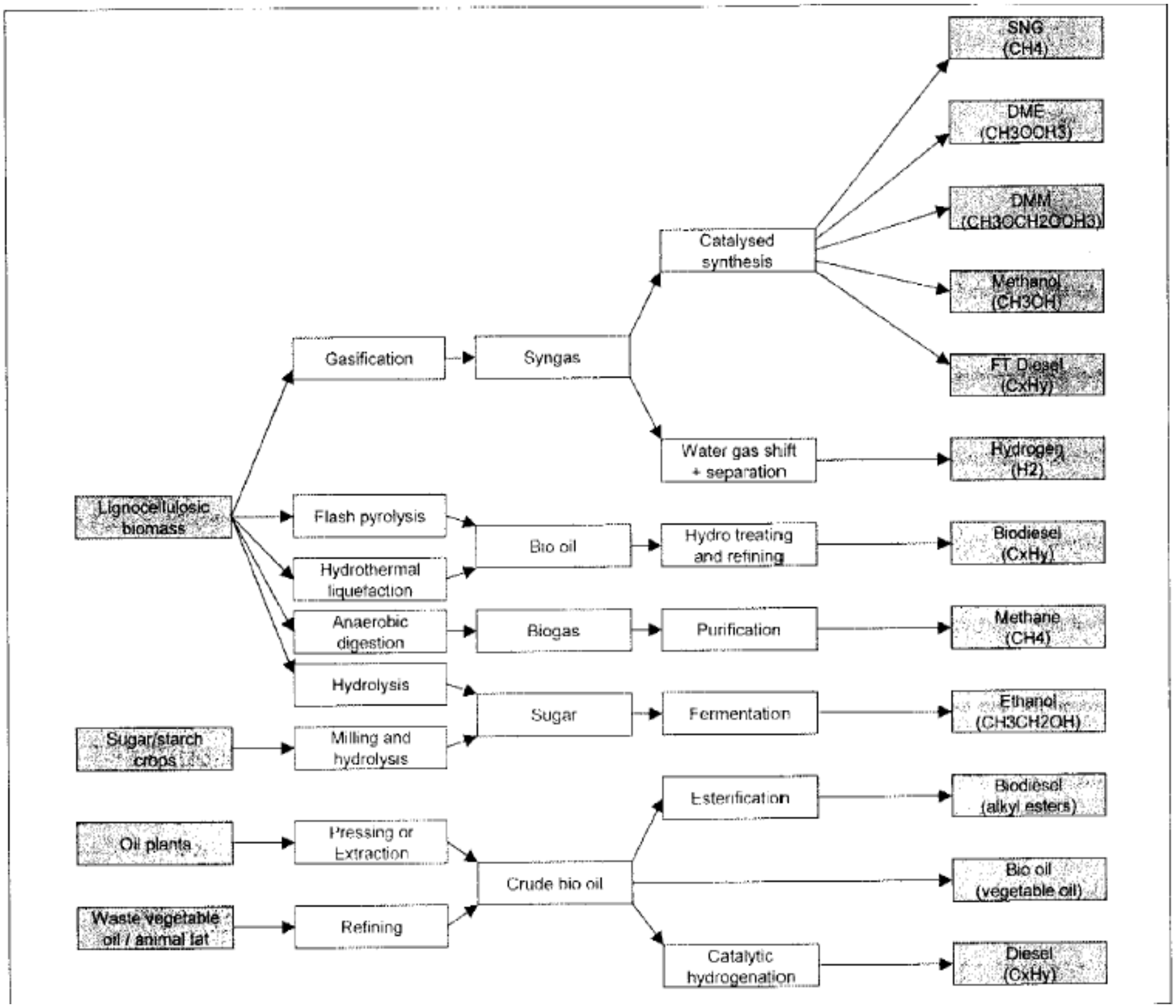


Figure VC.1. Technologies to convert biomass to products.[13]

VI. Proposed Recommendations

The primary driver, to ensure that both food and fuel production needs are met, is to develop a robust food and energy market based on current food crops that are suitable for such production. This will bring the value of these crops up to a point where there is incentive to use best practices in crop production, storage, and transportation of these products. This should make more land and crop volumes available for energy production. This will not happen overnight but definitely could be developed over the next 10 years.

The second step is to continue to develop high-yielding crops, both for food and energy. The non-food energy crops should be perennial crops developed for either very high oil yield or lignocellulose yield with minimal protein components. Such crops would require less fertilizer and be suitable for more marginal arable lands.

The third need is to develop efficient use of agricultural production waste, such as straw, stover, dung, municipal solid waste, and woody residues from forestry. While these sources are not as large as the potential for bioenergy crops, they still globally account for over 100 EJ of energy, more than the current use of transportation fuel. These must be gathered in a sustainable fashion and agricultural practices may have to be developed in order to do this.

The fourth step is to develop suitable harvesting, storage, and transportation systems for energy crops to conversion sites. Since most crops are of low density and are produced over large areas, efficient transportation systems are a requirement. This would indicate that there should be some focus on rail and water transportation systems.

A fifth need is to develop suitable high-yielding conversion systems for turning the primary energy of the crops into suitable secondary-energy fuel sources. Several technologies can be developed: fermentation, gasification, and pyrolysis. All three have positive characteristics and may be suitable with the different crops and the logistics required.

A final step would be to develop technologies to efficiently use biomass fuels in various systems including co-firing and internal combustion systems.

VII. Issues Overview

While agriculture and forestry look like environmentally sound future energy sources, this will only be true if done sustainably. This will require a systems approach that will ensure that the natural resources at our disposal are not depleted. Closed-loop systems with energy production linked to meat production from the process wastes and methane production from the animal wastes generated are attempts at such systems. Much must be done to truly understand what the consequences will be of these different options.

Policies should be put into place that will encourage sustainable agricultural production globally. Food production should be encouraged locally to ensure that food is available where needed, and excess arable land can be used either for export food or fuel production. This will ensure the most energy-efficient use of agriculture. Education and demonstration projects for sustainable high-yielding crop production should be developed around the world and crop development for these varying environments should be carried out.

Good economic modeling should be done on the effect of bioenergy production. This would establish what the price for commodity crops will need to be to drive investment in modern agricultural production practices globally. It would also give a good assessment of the logistical issues around various crop production and conversion technologies as well as those involved in getting the final fuel to the consumer. This would narrow the research priorities and ensure that there are no major surprises in following a bioenergy policy.

Energy crop development for production on marginal and surplus agricultural land should be carried out. Most current crops were developed for food and feed use or for fiber production. Crops specifically for energy production will have different characteristics and will need to be developed for a wide variety of environments. Preferably they would have low water and external-nutrient requirements. For both food and fuel, developing higher photosynthetic efficiencies will have major benefits.

Local conversion technologies need to be developed to manage the low density of biomass and its disperse nature of production. Compaction, torrefaction (a mild pyrolysis process), or conversion to a bio-oil are all technologies to be explored.

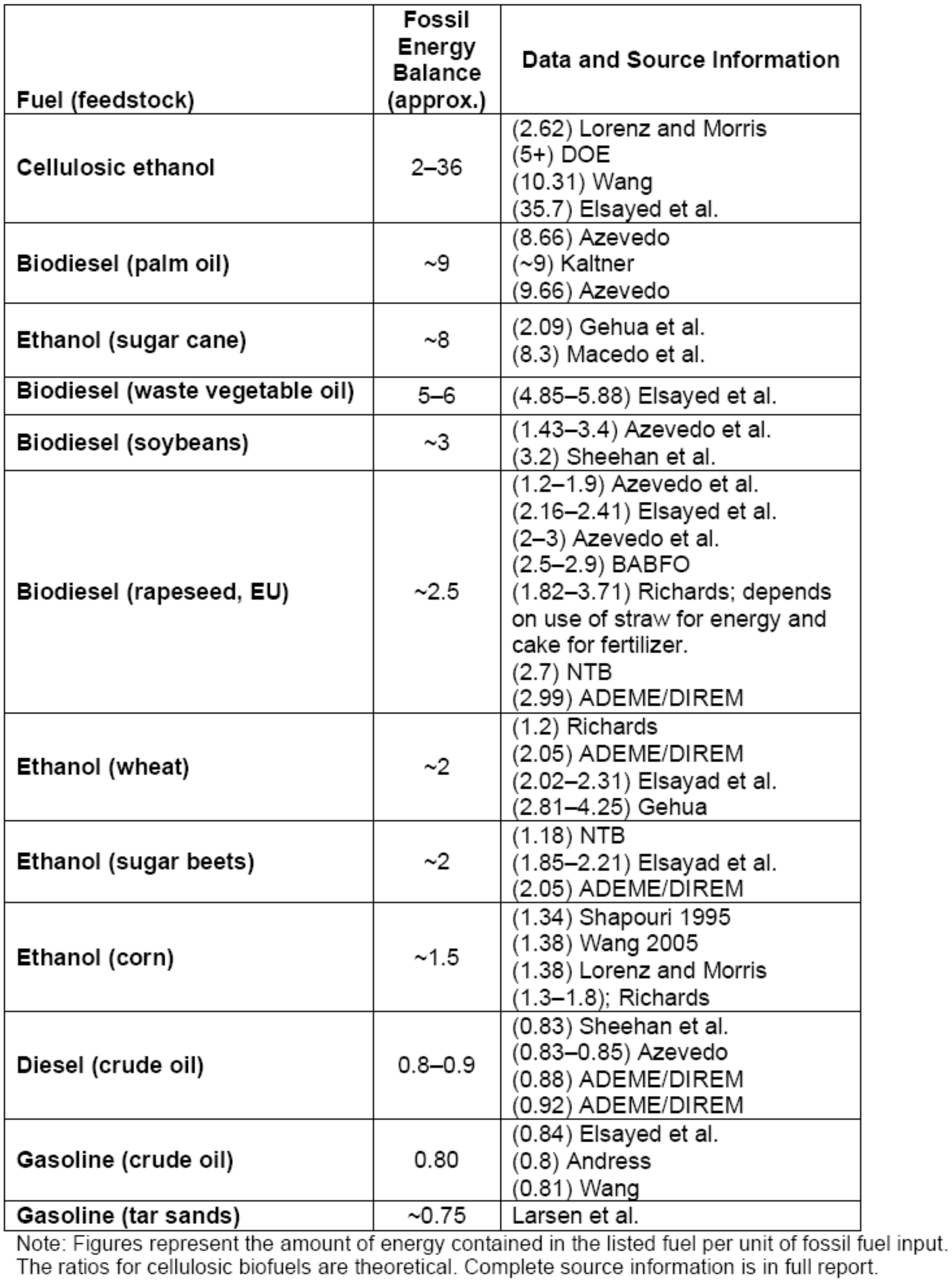
Logistics of biofuel transportation is a key hurdle. Investment in rail, waterway, and pipeline transportation will be needed to get the fuel from the producing regions to the consuming regions.

Most biomass conversion technologies also have the potential to produce electricity. Developing technologies and means to capture this potential will be important.

Many current bioenergy feedstocks have just as much or more potential in consumer products displacing non-renewable feedstocks. Developing these markets where they have positive energy balances should be supported.

If there is to be a policy on carbon dioxide emissions, doing this sooner rather than later will have positive impacts on deployment of technologies, whether they be coal-based or biofuel-based.

Development of clean biomass conversion and energy utilization is necessary for co-firing and transportation fuels. Table VII.1 shows energy balance for various current biofuels.[6]



Fuel (feedstock)	Fossil Energy Balance (approx.)	Data and Source Information
Cellulosic ethanol	2–36	(2.62) Lorenz and Morris (5+) DOE (10.31) Wang (35.7) Elsayed et al.
Biodiesel (palm oil)	~9	(8.66) Azevedo (~9) Kaltner (9.66) Azevedo
Ethanol (sugar cane)	~8	(2.09) Gehua et al. (8.3) Macedo et al.
Biodiesel (waste vegetable oil)	5–6	(4.85–5.88) Elsayed et al.
Biodiesel (soybeans)	~3	(1.43–3.4) Azevedo et al. (3.2) Sheehan et al.
Biodiesel (rapeseed, EU)	~2.5	(1.2–1.9) Azevedo et al. (2.16–2.41) Elsayed et al. (2–3) Azevedo et al. (2.5–2.9) BABFO (1.82–3.71) Richards; depends on use of straw for energy and cake for fertilizer. (2.7) NTB (2.99) ADEME/DIREM
Ethanol (wheat)	~2	(1.2) Richards (2.05) ADEME/DIREM (2.02–2.31) Elsayad et al. (2.81–4.25) Gehua
Ethanol (sugar beets)	~2	(1.18) NTB (1.85–2.21) Elsayad et al. (2.05) ADEME/DIREM
Ethanol (corn)	~1.5	(1.34) Shapouri 1995 (1.38) Wang 2005 (1.38) Lorenz and Morris (1.3–1.8); Richards
Diesel (crude oil)	0.8–0.9	(0.83) Sheehan et al. (0.83–0.85) Azevedo (0.88) ADEME/DIREM (0.92) ADEME/DIREM
Gasoline (crude oil)	0.80	(0.84) Elsayed et al. (0.8) Andress (0.81) Wang
Gasoline (tar sands)	~0.75	Larsen et al.

Note: Figures represent the amount of energy contained in the listed fuel per unit of fossil fuel input. The ratios for cellulosic biofuels are theoretical. Complete source information is in full report.

Table VII.1. Fossil energy balance of current biofuels [6]

Table VII.2. Energy conversion factors.[14]

This is a quick-reference list of conversion factors used by the Bioenergy Feedstock Development Programs at ORNL.[13] It was compiled from a wide range of sources, and is designed to be concise and convenient rather than all-inclusive. Most conversion factors and data are given to only 3 significant figures. Users are encouraged to consult other original sources for independent verification of these numbers. The following are links to Web sites we have found useful (many universities worldwide maintain good guides and conversion calculator pages):

- **U.S. National Institute of Standards and Technology (NIST)**
- **Centre for Innovation in Mathematics Teaching, University of Exeter, U.K.**
- **Department of Geological Sciences, University of Michigan**
- **Convertit.com Measurement Converter**

Energy contents are expressed here as lower heating value (LHV) unless otherwise stated (this is closest to the actual energy yield in most cases). Higher heating value (HHV, including condensation of combustion products) is greater by between 5% (in the case of coal) and 10% (for natural gas), depending mainly on the hydrogen content of the fuel. For most biomass feedstocks this difference appears to be 6–7%. The appropriateness of using LHV or HHV when comparing fuels, calculating thermal efficiencies, etc. really depends upon the application. For stationary combustion where exhaust gases are cooled before discharging (e.g. power stations), HHV is more appropriate. Where no attempt is made to extract useful work from hot exhaust gases (e.g. motor vehicles), the LHV is more suitable. In practice, many European publications report LHV, whereas North American publications use HHV.

Energy units

Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2).
- 1.0 joule = 0.239 calories (cal)
- 1.0 calorie = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 joules = 0.948 million Btu = 239 million calories = 278 kWh
- 1.0 British thermal unit (Btu) = 1,055 joules (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (BOE)
- 1,000 Btu/lb = 2.33 gigajoules per tonne (GJ/t)
- 1,000 Btu/U.S. gallon = 0.279 megajoules per liter (MJ/l)

Power

- 1.0 watt = 1.0 joule/second = 3.413 Btu/hr
- 1.0 kilowatt (kW) = 3,413 Btu/hr = 1.341 horsepower
- 1.0 kilowatt-hour (kWh) = 3.6 MJ = 3,413 Btu
- 1.0 horsepower (hp) = 550 foot-pounds per second = 2,545 Btu per hour = 745.7 watts = 0.746 kW

Energy Costs

- $1.00 per million Btu = $0.948/GJ
- $1.00/GJ = $1.055 per million Btu

Some common units of measure

- 1.0 U.S. ton (short ton) = 2,000 pounds
- 1.0 imperial ton (long ton or shipping ton) = 2,240 pounds
- 1.0 metric tonne (tonne) = 1,000 kilograms = 2,205 pounds
- 1.0 U.S. gallon = 3.79 liter = 0.833 Imperial gallon
- 1.0 imperial gallon = 4.55 liter = 1.20 U.S. gallon
- 1.0 liter = 0.264 U.S. gallon = 0.220 imperial gallon
- 1.0 U.S. bushel = 0.0352 m^3 = 0.97 UK bushel = 56 lb, 25 kg (corn or sorghum) = 60 lb, 27 kg (wheat or soybeans) = 40 lb, 18 kg (barley)

Areas and crop yields

- 1.0 hectare = 10,000 m^2 (an area 100 m x 100 m, or 328 x 328 ft) = 2.47 acres
- 1.0 km^2 = 100 hectares = 247 acres
- 1.0 acre = 0.405 hectares
- 1.0 U.S. ton/acre = 2.24 t/ha
- 1 metric tonne/hectare = 0.446 ton/acre
- 100 g/m^2 = 1.0 tonne/hectare = 892 lb/acre
  - for example, a "target" bioenergy crop yield might be: 5.0 U.S. tons/acre (10,000 lb/acre) = 11.2 tonnes/hectare (1120 g/m^2)

Biomass energy

- Cord: a stack of wood comprising 128 cubic feet (3.62 m^3); standard dimensions are 4 x 4 x 8 feet, including air space and bark. One cord contains approx. 1.2 U.S. tons (oven-dry) = 2,400 pounds = 1,089 kg
  - 1.0 metric tonne wood = 1.4 cubic meters (solid wood, not stacked)
  - Energy content of wood fuel (HHV, bone dry) = 18–22 GJ/t (7,600–9,600 Btu/lb)
  - Energy content of wood fuel (air dry, 20% moisture) = about 15 GJ/t (6,400 Btu/lb)
- Energy content of agricultural residues (range due to moisture content) = 10–17 GJ/t (4,300–7,300 Btu/lb)
- Metric tonne charcoal = 30 GJ (= 12,800 Btu/lb) (but usually derived from 6–12 t air-dry wood, i.e. 90–180 GJ original energy content)
- Metric tonne ethanol = 7.94 petroleum barrels = 1,262 liters
  - ethanol energy content (LHV) = 11,500 Btu/lb = 75,700 Btu/gallon = 26.7 GJ/t = 21.1 MJ/liter. HHV for ethanol = 84,000 Btu/gallon = 89 MJ/gallon = 23.4 MJ/liter
  - ethanol density (average) = 0.79 g/ml (= metric tonnes/m^3)
- Metric tonne biodiesel = 37.8 GJ (33.3 - 35.7 MJ/liter)

  - biodiesel density (average) = 0.88 g/ml (= metric tonnes/m^3)

Fossil fuels

- Barrel of oil equivalent (BOE) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh. “Petroleum barrel” is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 liters); about 7.2 barrels oil are equivalent to one tonne of oil (metric) = 42–45 GJ.
- Gasoline: U.S. gallon = 115,000 Btu = 121 MJ = 32 MJ/liter (LHV). HHV = 125,000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
  - Metric tonne gasoline = 8.53 barrels = 1356 liter = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
  - gasoline density (average) = 0.73 g/ml (= metric tonnes/m^3)
- Petro-diesel = 130,500 Btu/gallon (36.4 MJ/liter or 42.8 GJ/t)
  - petro-diesel density (average) = 0.84 g/ml (= metric tonnes/m^3)
- Note that the energy content (heating value) of petroleum products per unit mass is fairly constant, but their density differs significantly—hence the energy content of a liter, gallon, etc. varies between gasoline, diesel, kerosene.
- Metric tonne coal = 27–30 GJ (bituminous/anthracite); 15–19 GJ (lignite/sub-bituminous) (the above ranges are equivalent to 11,500–13,000 Btu/lb and 6,500–8,200 Btu/lb).
  - Note that the energy content (heating value) per unit mass varies greatly between different “ranks” of coal. “Typical” coal (rank not specified) usually means bituminous coal, the most common fuel for power plants (27 GJ/t).
- Natural gas: HHV = 1,027 Btu/ft3 = 38.3 MJ/m^3; LHV = 930 Btu/ft3 = 34.6 MJ/m^3
  - Therm (used for natural gas, methane) = 100,000 Btu (= 105.5 MJ)

Carbon content of fossil fuels and bioenergy feedstocks

- coal (average) = 25.4 metric tonnes carbon per terajoule (TJ)
    - 1.0 metric tonne coal = 746 kg carbon
- oil (average) = 19.9 metric tonnes carbon/TJ
- 1.0 U.S. gallon gasoline (0.833 Imperial gallon, 3.79 liter) = 2.42 kg carbon
- 1.0 U.S. gallon diesel/fuel oil (0.833 Imperial gallon, 3.79 liter) = 2.77 kg carbon
- natural gas (methane) = 14.4 metric tonnes carbon / TJ
- 1.0 cubic meter natural gas (methane) = 0.49 kg carbon
- carbon content of bioenergy feedstocks: approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues

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The Potential of Biomass Supply in the 2030 to 2050 Time Frame

Full Report

IX. Global agricultural production

Given current trends world energy demand is expected to increase by 50 percent by 2030.[1] There are expectations that renewable resources will be able to play a significant role satisfying this future energy demand. Others have a more pessimistic view and forecast that it will not make up even 2% of the total energy mix by 2030.[1]

In 2001 global primary energy consumption was 418 EJ. Of this biomass supplied 45 EJ. This is significantly more than the 2% predicted to be used by 2030 but is probably overlooked because about 39 EJ of this was in the form of traditional uses for heating and cooking, which do not enter world trade and are mostly beyond governmental control and taxation. Global biomass production on the earth's land surface is equal to 4,560 EJ (the gross primary production) of which half is lost by autotrophic respiration and decomposition, leaving 2,280 EJ(net primary production or NPP).[2] The availability of the NPP for use in food and energy production is restricted by many factors such as logistics, economics or legal restraints. Without intervention this NPP is in balance with natural decomposition. Because of its large value, usage of even a portion of the NPP would indicate that there is considerable potential for biomass to play a role of some type in global energy production beyond heating a cookstove.

Numerous studies have been carried out to determine the percentage of the global biomass production that could be used to supply some of the world's energy needs.[2-15] All of these studies have taken into consideration the variety of paths that biomass takes in the modern world (Figure I.1) as well as estimates of changing global population, diets, and crop yields.[10] A recent report by FAO has estimated population, food needs and agricultural development for the period of 2015 to 2030.[16] This report covers many of the pertinent factors that will determine whether there will be sufficient agricultural output available for providing food, fiber and fuel in the future.

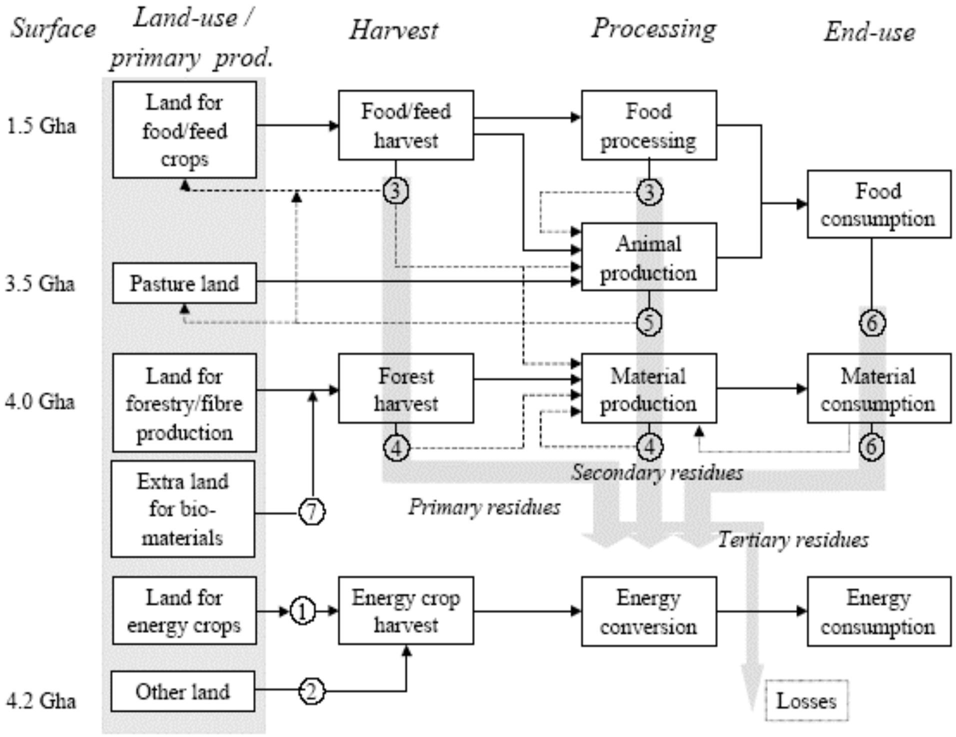
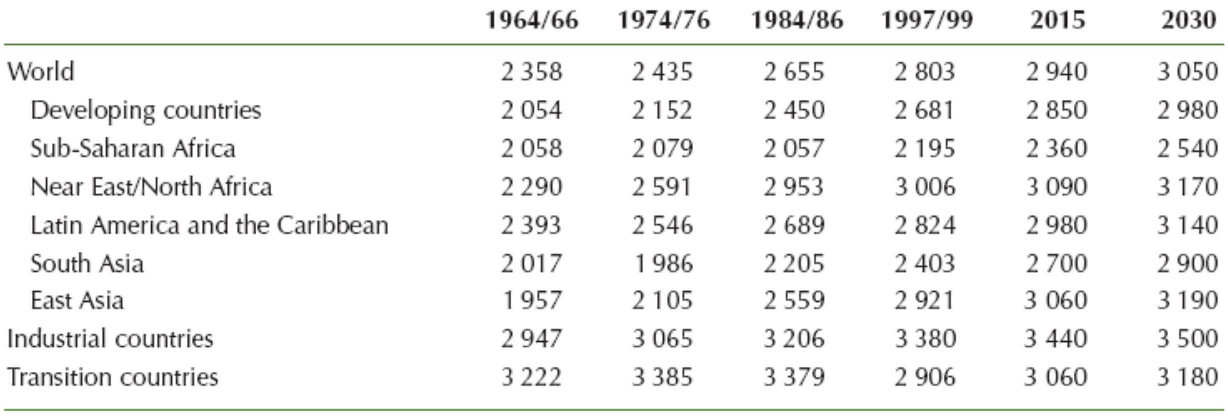


Fig. 1. Overview of various types of biomass flows and the global land surface (Based on: [1,22]). The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The gray arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

Figure I.1. Overview of various types of biomass flows and the global land surface. [10]

Food consumption in Kcal/d per person has been rising globally. It has increased from 2,360 Kcal/d in the mid 1960s to 2800 Kcal/d in 2000. Table I.1 summarizes these data.



	1964/66	1974/76	1984/86	1997/99	2015	2030
World	2 358	2 435	2 655	2 803	2 940	3 050
Developing countries	2 054	2 152	2 450	2 681	2 850	2 980
Sub-Saharan Africa	2 058	2 079	2 057	2 195	2 360	2 540
Near East/North Africa	2 290	2 591	2 953	3 006	3 090	3 170
Latin America and the Caribbean	2 393	2 546	2 689	2 824	2 980	3 140
South Asia	2 017	1 986	2 205	2 403	2 700	2 900
East Asia	1 957	2 105	2 559	2 921	3 060	3 190
Industrial countries	2 947	3 065	3 206	3 380	3 440	3 500
Transition countries	3 222	3 385	3 379	2 906	3 060	3 180

Table I.1. Per capita food consumption (Kcal/person/day).[16]

This gradual rise in food consumption is expected to continue while the world's population increases as well. The world population was 5.9 billion in the period of 1997–1999, will grow to 7.2 billion by 2015, 8.3 billion in 2030, and 9.3 billion by 2050. Population growth peaked in the 1960s at 2.04% and is expected to drop to 1.1% in the next decade and continue to decline to 0.5% by 2045–2050.[16] Practically all of these increases will be in developing countries, with sub-Saharan Africa experiencing the highest growth rate. Compounded by the growth rate in sub-Saharan Africa, the absolute numbers of people in poverty are also predicted to increase there until 2015, although the poverty percentage will decline globally.

While the total calories consumed are expected to increase, the consumption of meat is also expected to change. In 1999 the total consumption of crops consumed was 666.5 kg/person/yr, while meat and dairy consumption was 114 kg (36 kg meat and 78 kg dairy) annually per person. Of the meat consumed, 27% was bovine, 40% pork, 28% poultry and 5% from goats and sheep. By 2030, meat and dairy consumption is expected to increase to 135 kg/person/yr (45 kg meat and 90 kg dairy) with non-meat rising to 709.5 kg. The ratios will change considerably with rapid growth in poultry relative to the other meats. The percentages will be 23% bovine, 33% pork, 38% poultry and 5.3% goats and sheep.[16]

The increase in meat consumption and the ratios will have significant effects on the needs for total crop production. Worldwide, it currently requires on average 45 kg of grain equivalents to make one kg of bovine meat, 1.6 kg grain/kg milk, 79 kg grain/kg mutton, 6.7 kg grain/kg pork and 3.6 kg grain/kg poultry.[2] This means that at the current ratios in the diet, meat production requires on average 28 kg of grain equivalents per kg of meat produced. If no changes occur in meat product by 2030, the ratios of meat in the diet will mean that for every kg of meat produced it will require 18.2 kg of grain equivalents.

There are more optimal ways of producing meat, and if such methods are adopted globally, then this would significantly reduce the amount of grain equivalents required. Optimally in a landless system of meat production a kg of bovine meat would require 15 grain equivalents, mutton 46 grain equivalents, pork 6.2 and poultry 3.1 and 1 grain equivalent for dairy.[2] If such practices were adopted, because of economic factors or policy, the grain equivalents required per kg of meat would change to 9.1 kg in 2030.

The current diet therefore requires a total of 665 kg directly from plants + 36 kg meat times 28 kg grain/kg meat + 78 kg dairy times 1.6 kg grain/kg milk = 1,798 kg of grain equivalents per person. If modern practices are adopted for meat and dairy production by 2030 this could change to 709.5 directly from plants + 1 times 90 kg dairy + 9.1 times 45 kg meat = 1,209 kg of grain equivalents per person. Such a decrease will make it much easier to meet food demand and some of our future energy demands.

Globally this means with 5.9 billion people the total crop production in grain equivalents needs to be 5.9 billion people times 1,798 kg/capita = 10,608 billion kg grain equivalents. By 2030 if meat and dairy production would be optimized it would require 8.3 billion people times 1,209 kg grain equivalents per capita = 10,034.7 billion grain equivalents. This would actually mean that no increased food production would be needed and land use patterns could be changed as crop production improved. While such dramatic changes are not likely, higher commodity crop prices would probably drive food production in this direction.

Larger population and higher per capita food consumption will put growing demands on agriculture. Developing countries will play a major role in the growing demand for agricultural production in an attempt to lessen malnutrition. Countries that have been able to raise their daily per capita food consumption all have several commonalities. They had a fairly high dependence on agriculture, take advantage of rapid growth in food production, and, for the most part, decrease their net imports.[16]

An increase in per capita food consumption is also accompanied by a change in diet as countries develop. There is usually a rapid rise in vegetable oil, sugar, meat, milk, and egg consumption. Cereal crops are by far the most important source of total food consumption and their use has been increasing (see Table I.2).[16]

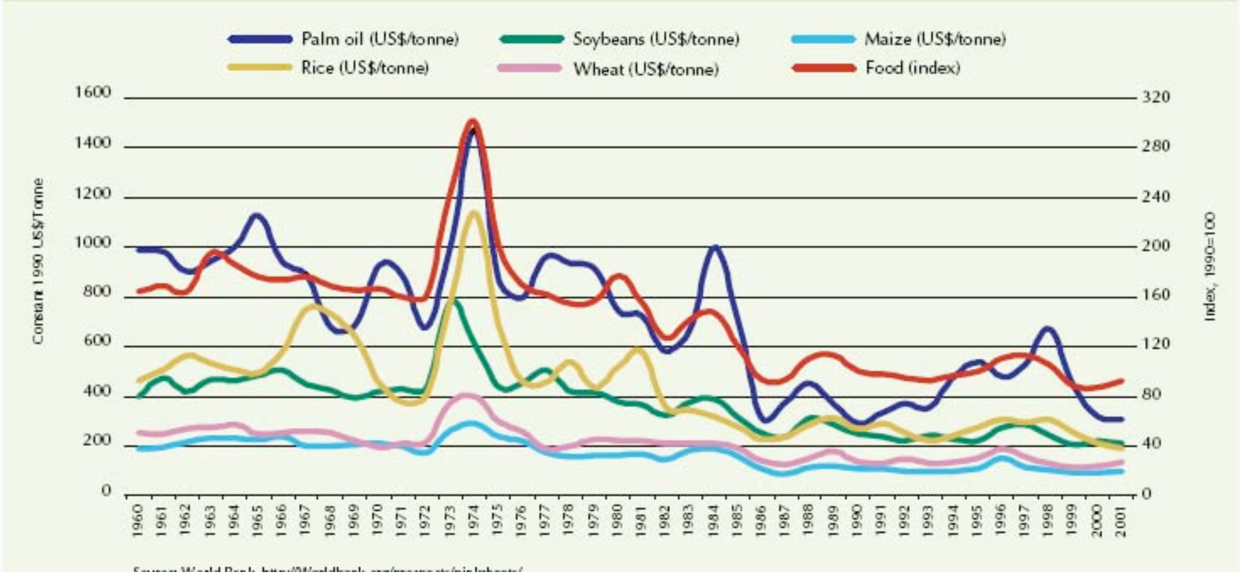
Kg/person/year	1964/66	1974/76	1984/86	1997/99	2015	2030
			World			
Cereals, food	147	151	168	171	171	171
Cereals, all uses	283	304	335	317	332	344
Roots and tubers	83	80	68	69	71	74
Sugar (raw sugar equivalent)	21	23	24	24	25	26
Pulses, dry	9	7	6	6	6	6
Vegetable oils, oilseeds and products (oil eq.)	6	7	9	11	14	16
Meat (carcass weight)	24	27	31	36	41	45
Milk and dairy, excl. butter (fresh milk eq.)	74	75	79	78	83	90
Other food (kcal/person/day)	208	217	237	274	280	290
Total food (kcal/person/day)	2 358	2 435	2 655	2 803	2 940	3 050
			Developing countries			
Cereals, food	141	150	172	173	173	172
Cereals, all uses	183	201	234	247	265	279
Roots and tubers	75	77	62	67	71	75
(Developing minus China)	62	61	57	63	69	75
Sugar (raw sugar equivalent)	14	16	19	21	23	25
Pulses, dry	11	8	8	7	7	7
Vegetable oils, oilseeds and products (oil eq.)	5	5	8	10	13	15
Meat (carcass weight)	10	11	16	26	32	37
Milk and dairy, excl. butter (fresh milk eq.)	28	30	37	45	55	66
Other food (kcal/person/day)	122	129	155	224	240	250
Total food (kcal/person/day)	2 054	2 152	2 450	2 681	2 850	2 980
			Industrial countries			
Cereals, food	136	136	147	159	158	159
Cereals, all uses	483	504	569	588	630	667
Roots and tubers	77	68	69	66	63	61
Sugar (raw sugar equivalent)	37	39	33	33	32	32
Pulses, dry	3	3	3	4	4	4
Vegetable oils, oilseeds and products (oil eq.)	11	15	17	20	22	23
Meat (carcass weight)	62	74	81	88	96	100
Milk and dairy, excl. butter (fresh milk eq.)	186	192	212	212	217	221
Other food (kcal/person/day)	461	485	510	516	540	550
Total food (kcal/person/day)	2 947	3 065	3 206	3 380	3 440	3 500
			Transition countries			
Cereals, food	211	191	183	173	176	173
Cereals, all uses	556	719	766	510	596	685
Roots and tubers	148	132	114	104	102	100
Sugar (raw sugar equivalent)	37	45	46	34	35	36
Pulses, dry	5	4	3	1	1	1
Vegetable oils, oilseeds and products (oil eq.)	7	8	10	9	12	14
Meat (carcass weight)	43	60	66	46	54	61
Milk and dairy, excl. butter (fresh milk eq.)	157	192	181	159	169	179
Other food (kcal/person/day)	288	356	384	306	330	350
Total food (kcal/person/day)	3 223	3 386	3 379	2 906	3 060	3 180

Note: Cereal food consumption includes the grain equivalent of beer consumption and of corn sweeteners.

Table I.2. Changes in the commodity composition of food consumption, major country groups.[16]

In conclusion, there will be a growing population over the next three decades with the growth rate declining to 0.8%. The average per capita food consumption will rise to 3,050 Kcal/day from a current level of 2,800. These two factors translate to an average growth in food demand of 1.8% annually until 2030.

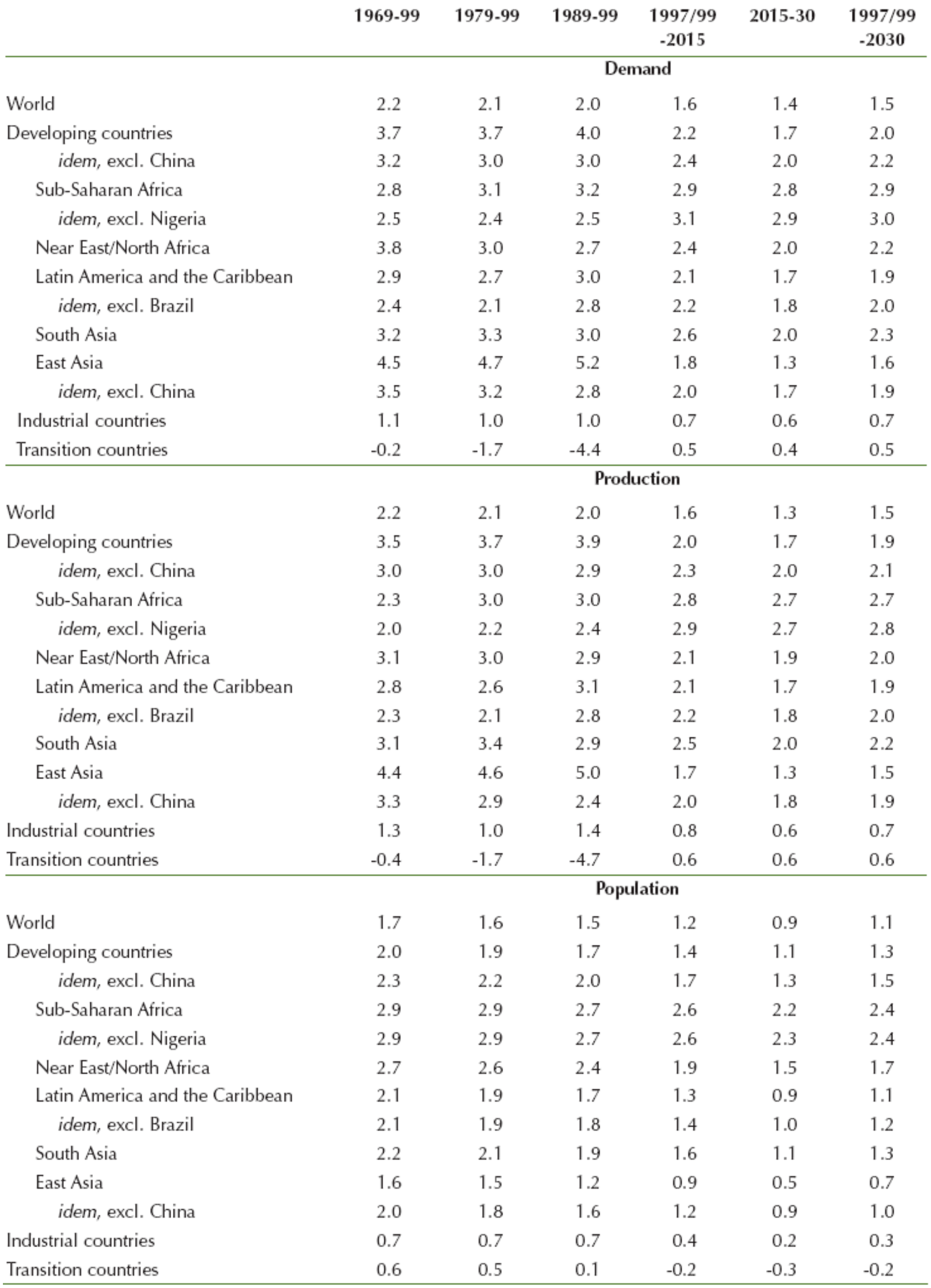
Will agricultural production be able to keep pace with this growth rate? Historical evidence suggests that food production growth has been more than sufficient to meet the expected demand (see Figure I.2 and Table I.3).[16]



Source: World Bank: http://Worldbank.com/prospects/pinkbook/

Figure I.2. Commodity crop prices in constant 1990 US$/ton.[16]

Figure I.2 and Table I.3 show a declining world market price and a production rate that has stayed ahead of the demand rate. Food production has been limited by effective demand rates rather than any shortage of supply. The past trends of decelerating growth of demand will probably continue, since the population growth rate continues to decline in spite of continued growth of consumption. However, even though agricultural production has been able to keep pace, there is no guarantee that this will continue in the future. Much will depend on whether advances in technology, education, and improved farm management that underpinned past growth continue.



	1969-99	1979-99	1989-99	1997/99 -2015	2015-30	1997/99 -2030
			Demand			
World	2.2	2.1	2.0	1.6	1.4	1.5
Developing countries	3.7	3.7	4.0	2.2	1.7	2.0
idem, excl. China	3.2	3.0	3.0	2.4	2.0	2.2
Sub-Saharan Africa	2.8	3.1	3.2	2.9	2.8	2.9
idem, excl. Nigeria	2.5	2.4	2.5	3.1	2.9	3.0
Near East/North Africa	3.8	3.0	2.7	2.4	2.0	2.2
Latin America and the Caribbean	2.9	2.7	3.0	2.1	1.7	1.9
idem, excl. Brazil	2.4	2.1	2.8	2.2	1.8	2.0
South Asia	3.2	3.3	3.0	2.6	2.0	2.3
East Asia	4.5	4.7	5.2	1.8	1.3	1.6
idem, excl. China	3.5	3.2	2.8	2.0	1.7	1.9
Industrial countries	1.1	1.0	1.0	0.7	0.6	0.7
Transition countries	-0.2	-1.7	-4.4	0.5	0.4	0.5
			Production			
World	2.2	2.1	2.0	1.6	1.3	1.5
Developing countries	3.5	3.7	3.9	2.0	1.7	1.9
idem, excl. China	3.0	3.0	2.9	2.3	2.0	2.1
Sub-Saharan Africa	2.3	3.0	3.0	2.8	2.7	2.7
idem, excl. Nigeria	2.0	2.2	2.4	2.9	2.7	2.8
Near East/North Africa	3.1	3.0	2.9	2.1	1.9	2.0
Latin America and the Caribbean	2.8	2.6	3.1	2.1	1.7	1.9
idem, excl. Brazil	2.3	2.1	2.8	2.2	1.8	2.0
South Asia	3.1	3.4	2.9	2.5	2.0	2.2
East Asia	4.4	4.6	5.0	1.7	1.3	1.5
idem, excl. China	3.3	2.9	2.4	2.0	1.8	1.9
Industrial countries	1.3	1.0	1.4	0.8	0.6	0.7
Transition countries	-0.4	-1.7	-4.7	0.6	0.6	0.6
			Population			
World	1.7	1.6	1.5	1.2	0.9	1.1
Developing countries	2.0	1.9	1.7	1.4	1.1	1.3
idem, excl. China	2.3	2.2	2.0	1.7	1.3	1.5
Sub-Saharan Africa	2.9	2.9	2.7	2.6	2.2	2.4
idem, excl. Nigeria	2.9	2.9	2.7	2.6	2.3	2.4
Near East/North Africa	2.7	2.6	2.4	1.9	1.5	1.7
Latin America and the Caribbean	2.1	1.9	1.7	1.3	0.9	1.1
idem, excl. Brazil	2.1	1.9	1.8	1.4	1.0	1.2
South Asia	2.2	2.1	1.9	1.6	1.1	1.3
East Asia	1.6	1.5	1.2	0.9	0.5	0.7
idem, excl. China	2.0	1.8	1.6	1.2	0.9	1.0
Industrial countries	0.7	0.7	0.7	0.4	0.2	0.3
Transition countries	0.6	0.5	0.1	-0.2	-0.3	-0.2

Table I.3. Growth rates of aggregate demand and production (percentage/yr). [16]

At the world level, production equals consumption since crops cannot be stored indefinitely. The downward pressure in world market prices has put pressure on production for export in countries without policies supporting production. The drastic decline in many developing countries' traditional net trade surplus in agricultural goods has been speeded by domestic support and trade protection in countries that previously had been traditional markets. If the demand for agricultural products grows and favors policies globally that support agricultural production, there is good evidence that the resource potential and productivity gains needed to meet this demand are more than available.[16] Figures I.4 and I.5 show the per capita consumption of cereals for all uses.[16]

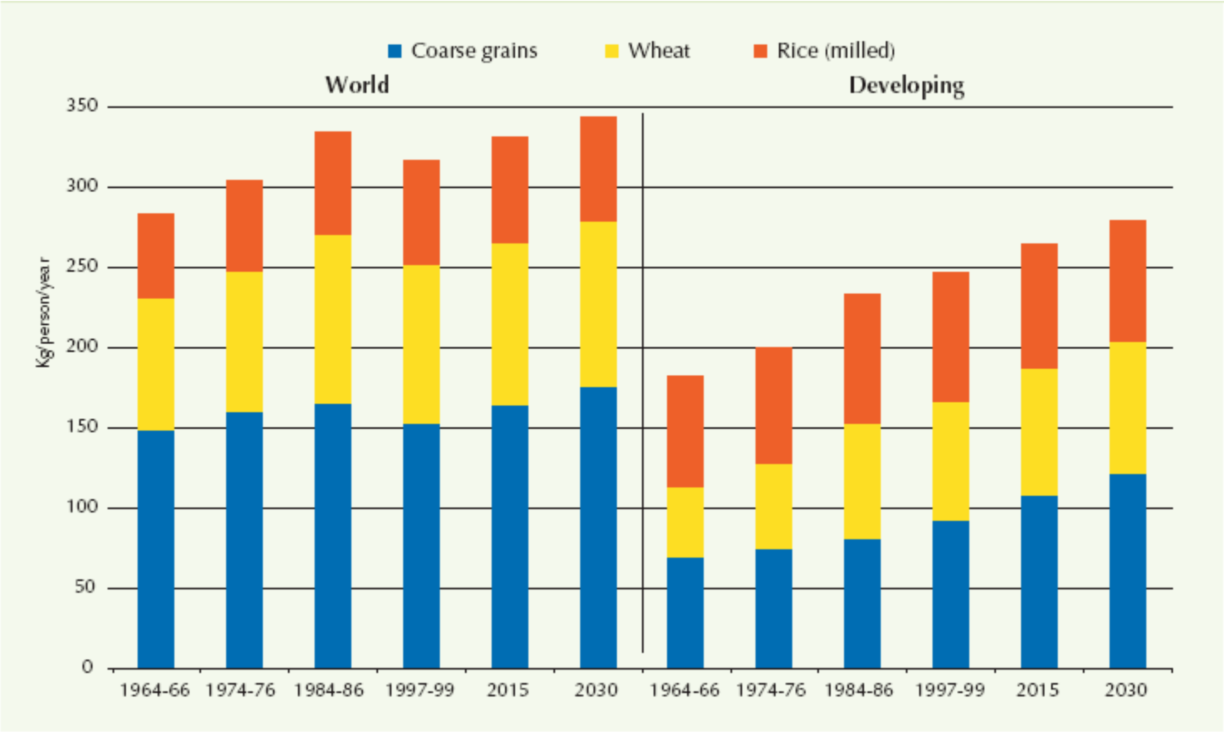


Figure I.4. Per-capita consumption of all cereals.[16]

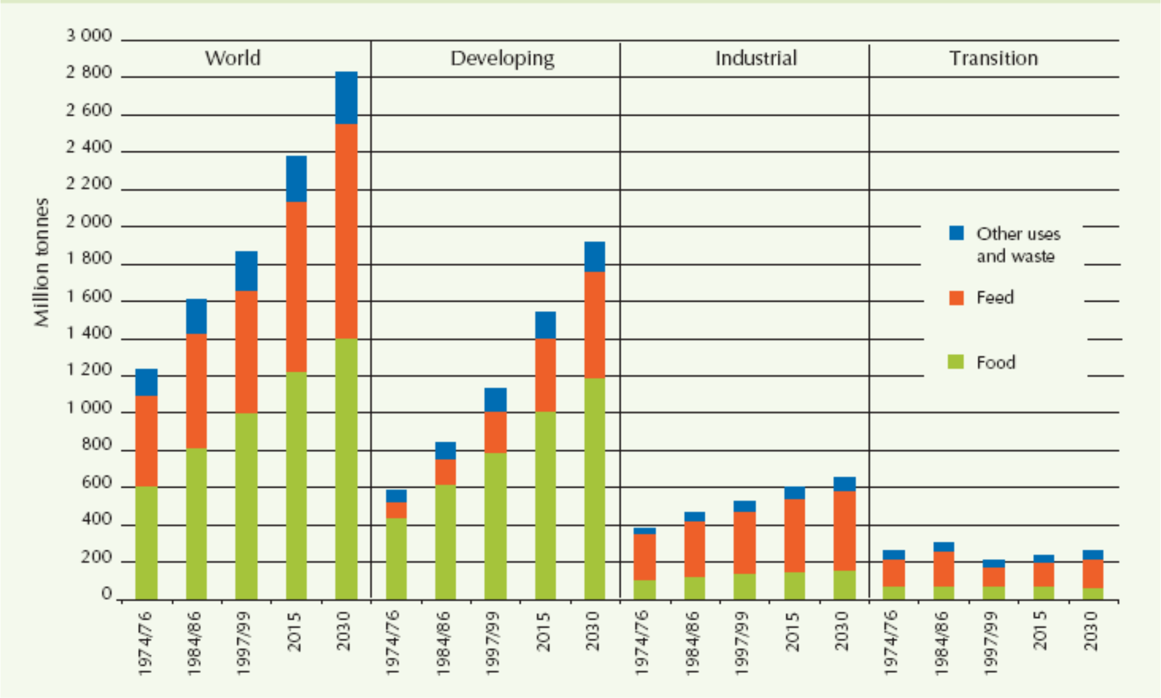
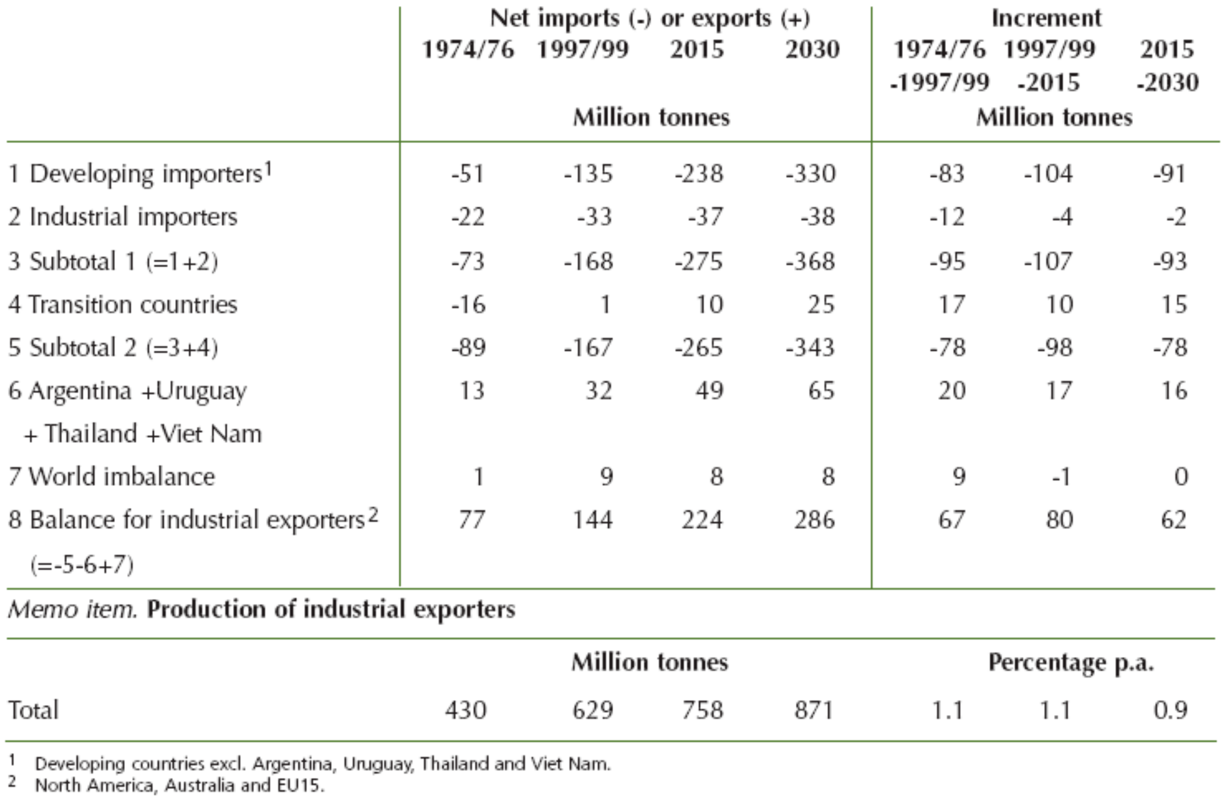


Figure I.5. Categories of cereal consumption.[16]

To meet the decelerating demand for grains there will have to be some growth in production (about 1% per annum, see Table I.4).[16]



	Net imports (-) or exports (+)				Increment		
	1974/76	1997/99	2015	2030	1974/76 -1997/99	1997/99 -2015	2015 -2030
	Million tonnes				Million tonnes		
1 Developing importers[1]	-51	-135	-238	-330	-83	-104	-91
2 Industrial importers	-22	-33	-37	-38	-12	-4	-2
3 Subtotal 1 (=1+2)	-73	-168	-275	-368	-95	-107	-93
4 Transition countries	-16	1	10	25	17	10	15
5 Subtotal 2 (=3+4)	-89	-167	-265	-343	-78	-98	-78
6 Argentina +Uruguay + Thailand +Viet Nam	13	32	49	65	20	17	16
7 World imbalance	1	9	8	8	9	-1	0
8 Balance for industrial exporters[2] (=-5-6+7)	77	144	224	286	67	80	62
Memo item. **Production of industrial exporters**							
	Million tonnes				Percentage p.a.		
Total	430	629	758	871	1.1	1.1	0.9

[1] Developing countries excl. Argentina, Uruguay, Thailand and Viet Nam.

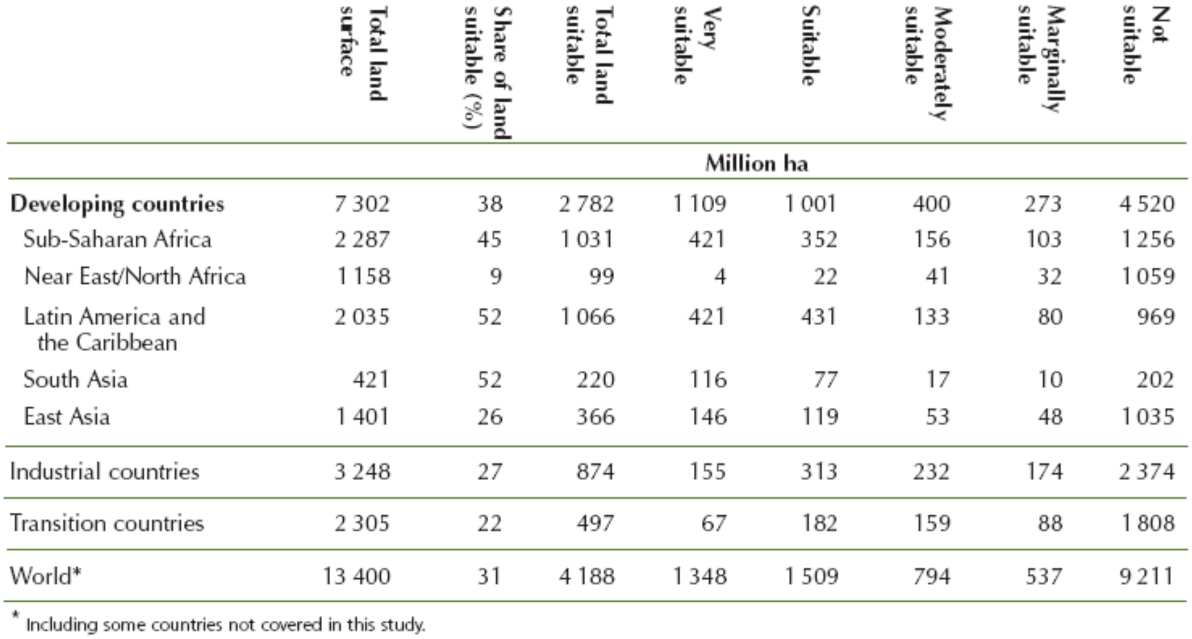
[2] North America, Australia and EU15.

Table I.4.Incremental growth in grain cereal demand.[16]

To meet these challenges, traditional exporting countries and developing exporting countries will have to increase their production from 629 million tons to 871 million tons by 2030. This production increase requires an annual growth rate of 1.1% thru 2015 and 0.9%/yr for the next 15 years. This is lower than the average growth rate of 1.6% seen in the past 32 years.[16]

What will be the actual growth rates in aggregate crop production? The FAO report indicates that this growth rate will be 1.4%, which is down from the 2.1% for the previous 30 years. The projected increase in crop production from 1997–2030 is 55%. The projected faster growth in developing countries will increase their share of world production from 67% to 72%.[16]

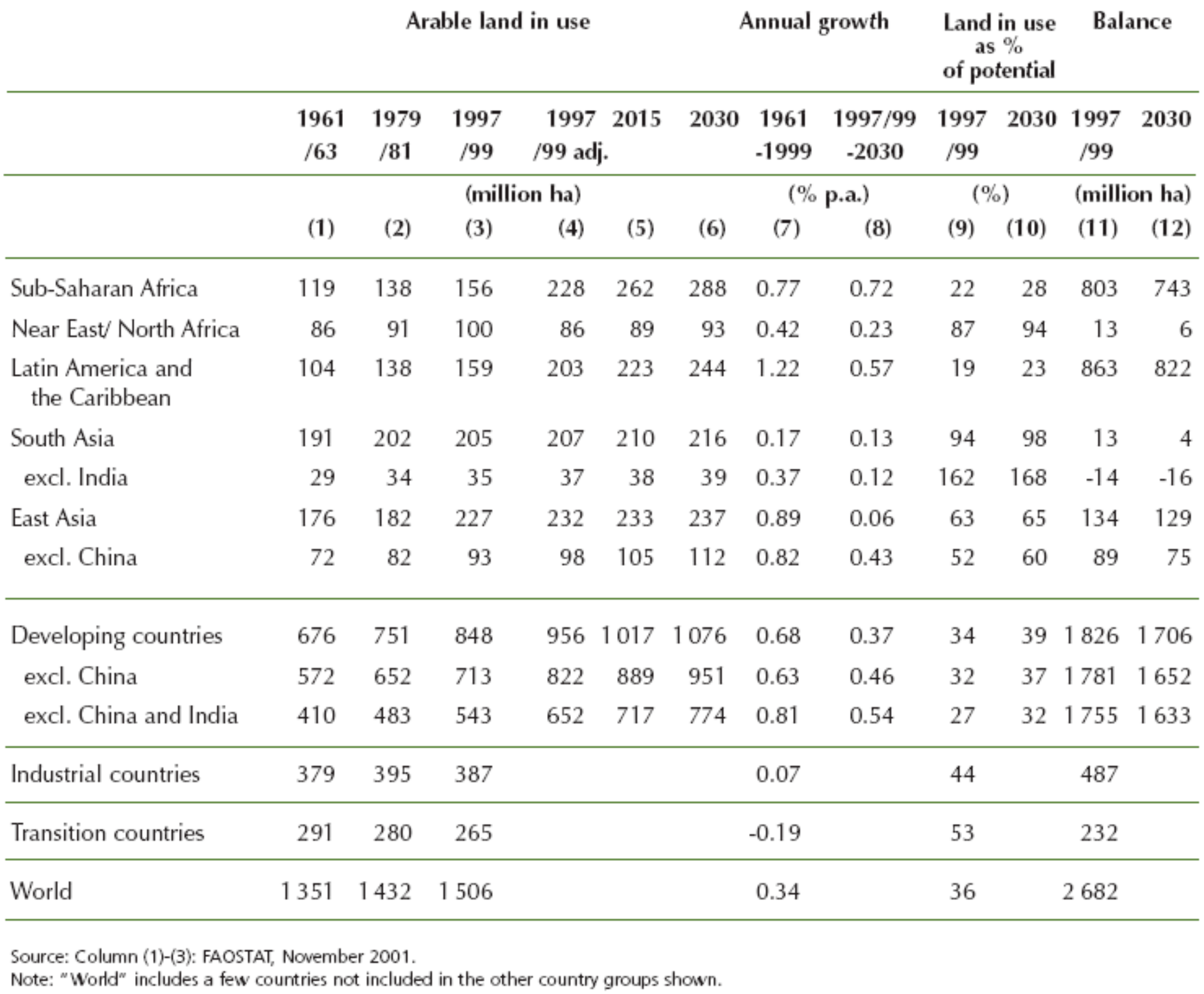
At present, 11% (1.5 billion hectares) of the globe's land surface is used for crop production. This area represents 36% of the land estimated to be suitable for some type of agricultural production. About 4.2 billion hectares globally have some potential for cultivation. The developing countries have about 2.8 billion hectares and of this, about 960 million are in cultivation. Ninety percent of this unutilized land is in Latin America and sub-Saharan Africa. More than half is concentrated in Brazil, Democratic Republic of Congo, Sudan, Angola, Argentina, Colombia, and Bolivia. There is virtually no land available in South Asia and the Near East or North Africa. Most of this land is also constrained by fragility, low fertility, disease or lack of infrastructure (see Tables I.5 and I.6).[16]



	Total land surface	Share of land suitable (%)	Total land suitable	Very suitable	Suitable	Moderately suitable	Marginally suitable	Not suitable
	Million ha							
Developing countries	7 302	38	2 782	1 109	1 001	400	273	4 520
Sub-Saharan Africa	2 287	45	1 031	421	352	156	103	1 256
Near East/North Africa	1 158	9	99	4	22	41	32	1 059
Latin America and the Caribbean	2 035	52	1 066	421	431	133	80	969
South Asia	421	52	220	116	77	17	10	202
East Asia	1 401	26	366	146	119	53	48	1 035
Industrial countries	3 248	27	874	155	313	232	174	2 374
Transition countries	2 305	22	497	67	182	159	88	1 808
World*	13 400	31	4 188	1 348	1 509	794	537	9 211

* Including some countries not covered in this study.

Table I.5. Land with rain-fed crop potential.16



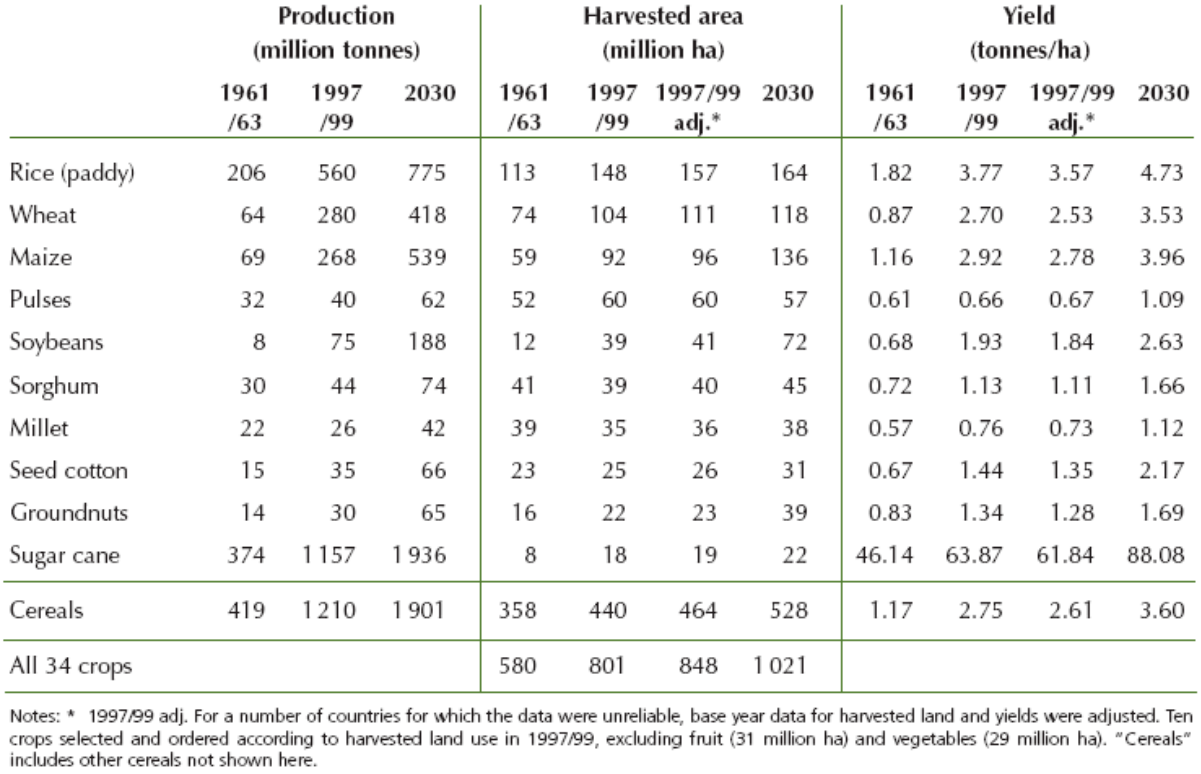
	Arable land in use						Annual growth		Land in use as % of potential		Balance	
	1961 /63	1979 /81	1997 /99	1997 /99 adj.	2015	2030	1961 -1999	1997/99 -2030	1997 /99	2030	1997 /99	2030
			(million ha)				(% p.a.)		(%)		(million ha)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Sub-Saharan Africa	119	138	156	228	262	288	0.77	0.72	22	28	803	743
Near East/ North Africa	86	91	100	86	89	93	0.42	0.23	87	94	13	6
Latin America and the Caribbean	104	138	159	203	223	244	1.22	0.57	19	23	863	822
South Asia	191	202	205	207	210	216	0.17	0.13	94	98	13	4
excl. India	29	34	35	37	38	39	0.37	0.12	162	168	-14	-16
East Asia	176	182	227	232	233	237	0.89	0.06	63	65	134	129
excl. China	72	82	93	98	105	112	0.82	0.43	52	60	89	75
Developing countries	676	751	848	956	1 017	1 076	0.68	0.37	34	39	1 826	1 706
excl. China	572	652	713	822	889	951	0.63	0.46	32	37	1 781	1 652
excl. China and India	410	483	543	652	717	774	0.81	0.54	27	32	1 755	1 633
Industrial countries	379	395	387				0.07		44		487	
Transition countries	291	280	265				-0.19		53		232	
World	1 351	1 432	1 506				0.34		36		2 682	

Source: Column (1)-(3): FAOSTAT, November 2001.
Note: "World" includes a few countries not included in the other country groups shown.

Figure I.6. Total arable land: past and projected.[16]

Overall, developing countries' arable area will increase by 120 million hectares by 2030. Developed countries' land area under production has actually decreased in the past, and this trend may continue. It has become increasingly easier over the past decades to extract additional units of food from arable land, and this has been reflected in the decline in the real price of food. This trend may continue in the future unless new demands call for increases in agricultural production.

Technology has a major role to play in determining the amount of land needed for food production. Are we reaching the ceiling of the green revolution? Will we only be seeing incremental increases in the developed world, while areas of the developing world where full use of modern agricultural practices have not been implemented will see somewhat higher growth? Table I.6 estimates global area and yields for a variety of crops assuming that there will be a slow down in this growth rate to 1% per annum to 2030.[16]

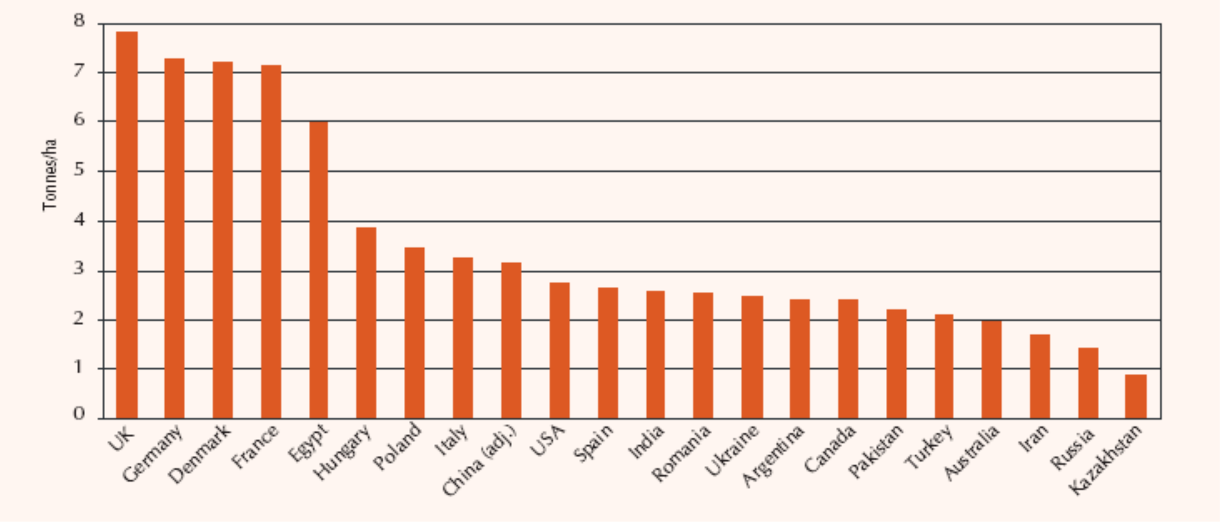


	Production (million tonnes)			Harvested area (million ha)				Yield (tonnes/ha)			
	1961 /63	1997 /99	2030	1961 /63	1997 /99	1997/99 adj.*	2030	1961 /63	1997 /99	1997/99 adj.*	2030
Rice (paddy)	206	560	775	113	148	157	164	1.82	3.77	3.57	4.73
Wheat	64	280	418	74	104	111	118	0.87	2.70	2.53	3.53
Maize	69	268	539	59	92	96	136	1.16	2.92	2.78	3.96
Pulses	32	40	62	52	60	60	57	0.61	0.66	0.67	1.09
Soybeans	8	75	188	12	39	41	72	0.68	1.93	1.84	2.63
Sorghum	30	44	74	41	39	40	45	0.72	1.13	1.11	1.66
Millet	22	26	42	39	35	36	38	0.57	0.76	0.73	1.12
Seed cotton	15	35	66	23	25	26	31	0.67	1.44	1.35	2.17
Groundnuts	14	30	65	16	22	23	39	0.83	1.34	1.28	1.69
Sugar cane	374	1 157	1 936	8	18	19	22	46.14	63.87	61.84	88.08
Cereals	419	1 210	1 901	358	440	464	528	1.17	2.75	2.61	3.60
All 34 crops				580	801	848	1 021				

Notes: * 1997/99 adj. For a number of countries for which the data were unreliable, base year data for harvested land and yields were adjusted. Ten crops selected and ordered according to harvested land use in 1997/99, excluding fruit (31 million ha) and vegetables (29 million ha). "Cereals" includes other cereals not shown here.

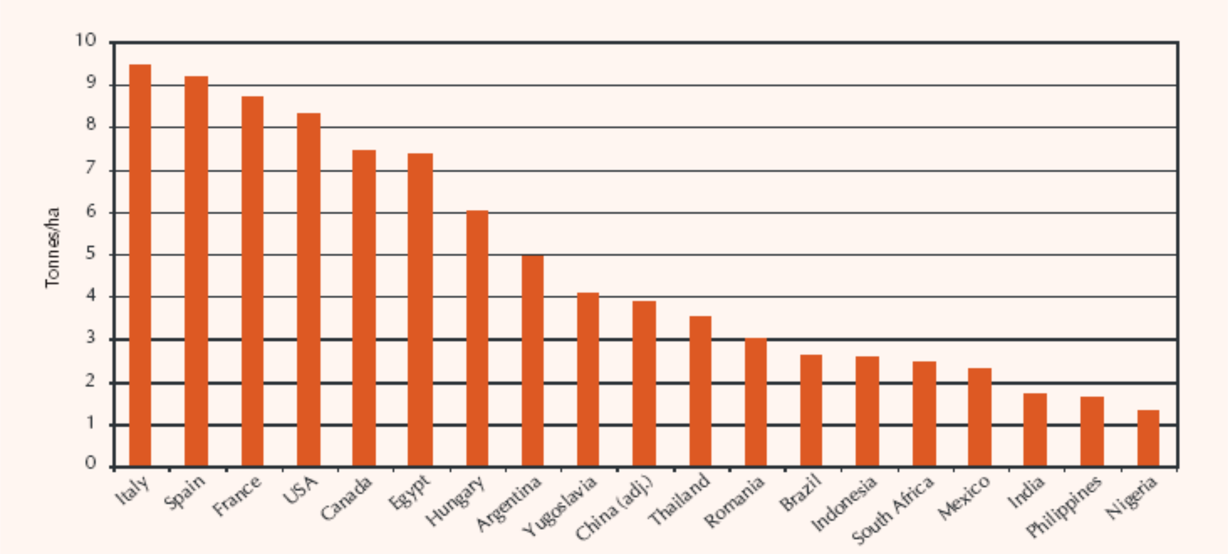
Table I.6. Area and yields for ten major crops in developing countries.[16]

World agricultural production in past 4 decades has grown mostly from increased intensive use of land already under cultivation rather than from expansion of acreage, and even with some decrease in acreage in developed countries. Can this continue, and what is the potential for increased production? Figure I.6 and I.7 indicate the wide variance in wheat and corn productivity in different countries.[16]



Note: Twenty-two countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world wheat output in 1996/2000

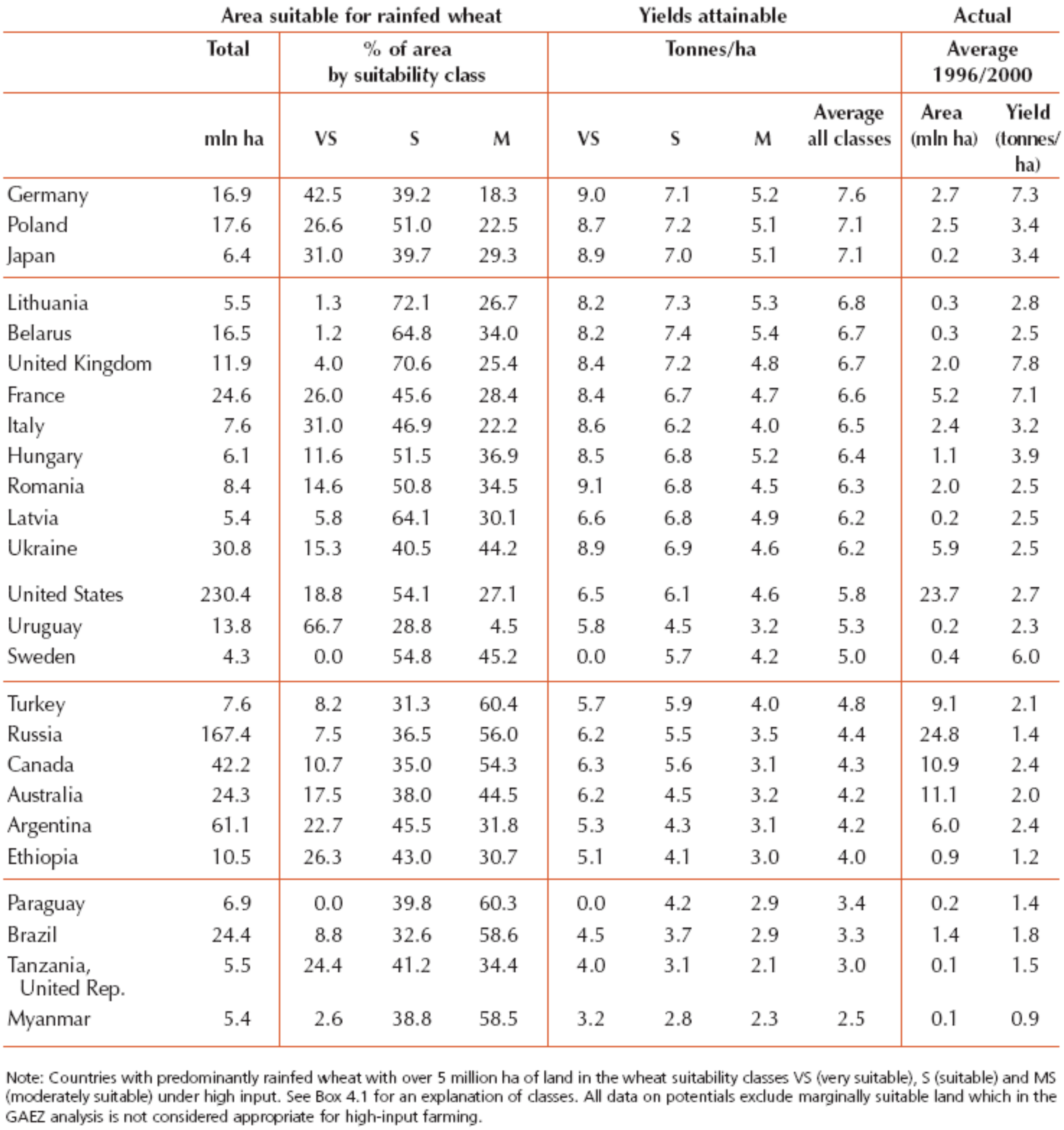
Figure I.6. Wheat yields (average 1996–2000).[16]



Note: Nineteen countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world maize output in 1996/2000

Figure I.7. Maize yields (average 1996–2000). [16]

Table I.7 shows the yields in various countries for wheat under similar agro-ecologies.[16]



	Area suitable for rainfed wheat				Yields attainable				Actual	
	Total	% of area by suitability class			Tonnes/ha				Average 1996/2000	
	mln ha	VS	S	M	VS	S	M	Average all classes	Area (mln ha)	Yield (tonnes/ ha)
Germany	16.9	42.5	39.2	18.3	9.0	7.1	5.2	7.6	2.7	7.3
Poland	17.6	26.6	51.0	22.5	8.7	7.2	5.1	7.1	2.5	3.4
Japan	6.4	31.0	39.7	29.3	8.9	7.0	5.1	7.1	0.2	3.4
Lithuania	5.5	1.3	72.1	26.7	8.2	7.3	5.3	6.8	0.3	2.8
Belarus	16.5	1.2	64.8	34.0	8.2	7.4	5.4	6.7	0.3	2.5
United Kingdom	11.9	4.0	70.6	25.4	8.4	7.2	4.8	6.7	2.0	7.8
France	24.6	26.0	45.6	28.4	8.4	6.7	4.7	6.6	5.2	7.1
Italy	7.6	31.0	46.9	22.2	8.6	6.2	4.0	6.5	2.4	3.2
Hungary	6.1	11.6	51.5	36.9	8.5	6.8	5.2	6.4	1.1	3.9
Romania	8.4	14.6	50.8	34.5	9.1	6.8	4.5	6.3	2.0	2.5
Latvia	5.4	5.8	64.1	30.1	6.6	6.8	4.9	6.2	0.2	2.5
Ukraine	30.8	15.3	40.5	44.2	8.9	6.9	4.6	6.2	5.9	2.5
United States	230.4	18.8	54.1	27.1	6.5	6.1	4.6	5.8	23.7	2.7
Uruguay	13.8	66.7	28.8	4.5	5.8	4.5	3.2	5.3	0.2	2.3
Sweden	4.3	0.0	54.8	45.2	0.0	5.7	4.2	5.0	0.4	6.0
Turkey	7.6	8.2	31.3	60.4	5.7	5.9	4.0	4.8	9.1	2.1
Russia	167.4	7.5	36.5	56.0	6.2	5.5	3.5	4.4	24.8	1.4
Canada	42.2	10.7	35.0	54.3	6.3	5.6	3.1	4.3	10.9	2.4
Australia	24.3	17.5	38.0	44.5	6.2	4.5	3.2	4.2	11.1	2.0
Argentina	61.1	22.7	45.5	31.8	5.3	4.3	3.1	4.2	6.0	2.4
Ethiopia	10.5	26.3	43.0	30.7	5.1	4.1	3.0	4.0	0.9	1.2
Paraguay	6.9	0.0	39.8	60.3	0.0	4.2	2.9	3.4	0.2	1.4
Brazil	24.4	8.8	32.6	58.6	4.5	3.7	2.9	3.3	1.4	1.8
Tanzania, United Rep.	5.5	24.4	41.2	34.4	4.0	3.1	2.1	3.0	0.1	1.5
Myanmar	5.4	2.6	38.8	58.5	3.2	2.8	2.3	2.5	0.1	0.9

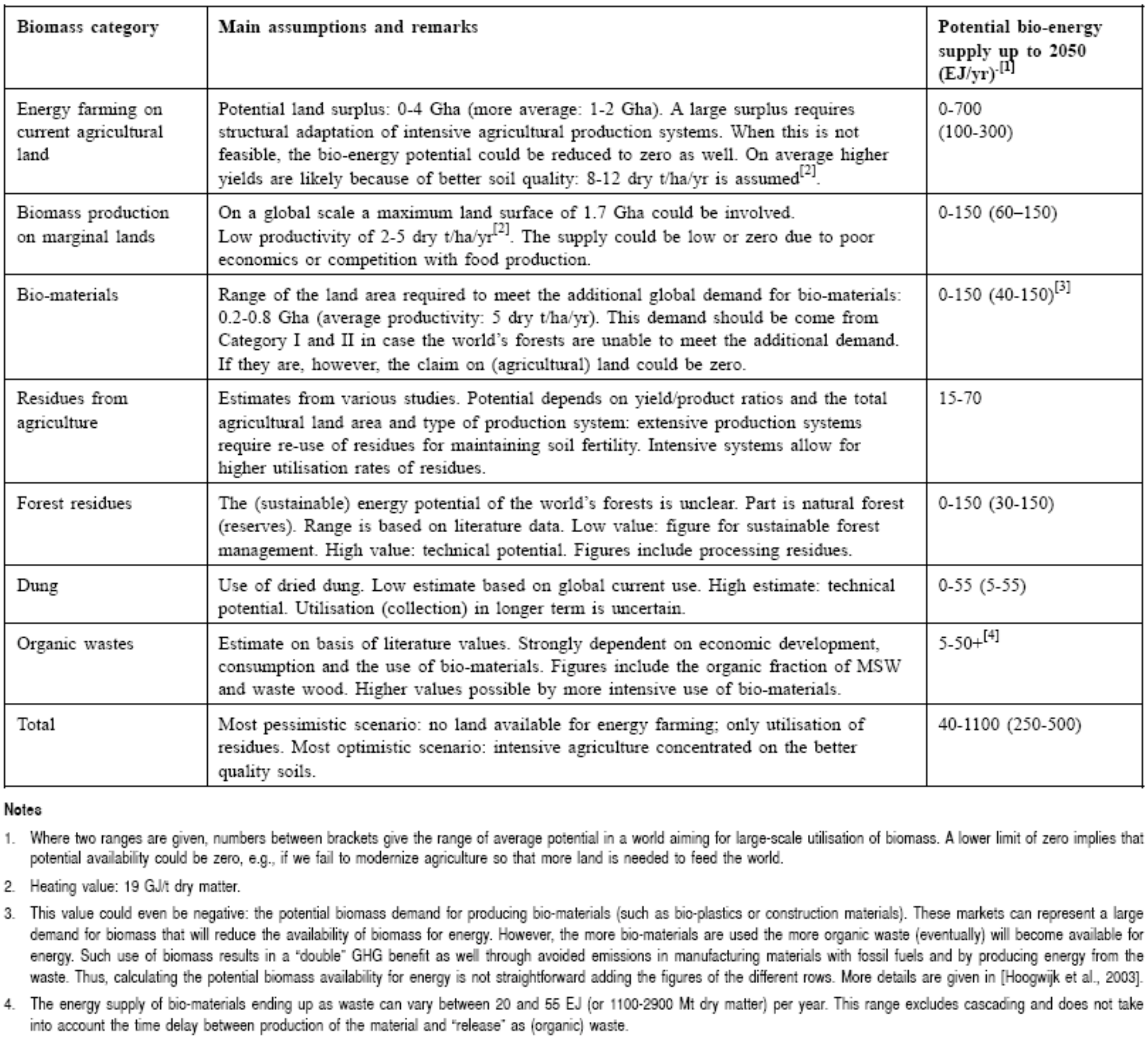
Note: Countries with predominantly rainfed wheat with over 5 million ha of land in the wheat suitability classes VS (very suitable), S (suitable) and MS (moderately suitable) under high input. See Box 4.1 for an explanation of classes. All data on potentials exclude marginally suitable land which in the GAEZ analysis is not considered appropriate for high-input farming.

Table I.7. Agro-ecological similarity for rain-fed wheat production. [16]

These wide variations are a key indication that, depending on the intensity applied for crop production, there is considerable potential for yield increases. This does not mean that under current policy and price structure there is any incentive to change the intensity of production or that such changes are sustainable. The data do indicate that there is considerable production potential that technology may be able to bridge in the future.

Agricultural biotechnology is still in its early stages. Most of the advances seen thus far have been in agronomic traits such as herbicide resistance and pest resistance. In the future, this technology may make it easier to find traits of interest and follow those traits in breeding. Marker-assisted selection helps shorten the cycle of traditional breeding by allowing for more rapid selection. These advances may maintain or accelerate the productivity of agriculture. Hosts of traits are in the pipeline including fungal resistance; tolerance to drought, moisture, soil acidity, temperature extremes, and salt; and changes in starch, protein, or oil content.

The preceding section has been a summary of the key issues surrounding global agricultural production for food and feed as seen in a 2003 FAO summary. It assumed the only demand for growth in production was coming from population and diet changes. The outcome of the report was that global food production would continue to provide for the food demands that are called for. A new demand on agriculture has come about due to higher crude-oil prices in the past few years, as well as from some countries' needs to meet Kyoto Accord goals. This means that new demands will come about for energy crops. These demands will change economic incentives for production because of the imbalance of supply to meet both traditional and new demands. As stated earlier, a variety of studies have looked at the potential for both energy and food production from arable land available globally.[2-15] These studies have not only had to look at the population growth and food-supply needs, but also at the variety of energy outputs that can come from arable land. Table I.8 summarizes the potential global energy supply for 2050 from these various outputs based on most of the published art.[4]



Biomass category	Main assumptions and remarks	Potential bio-energy supply up to 2050 (EJ/yr) [1]
Energy farming on current agricultural land	Potential land surplus: 0-4 Gha (more average: 1-2 Gha). A large surplus requires structural adaptation of intensive agricultural production systems. When this is not feasible, the bio-energy potential could be reduced to zero as well. On average higher yields are likely because of better soil quality: 8-12 dry t/ha/yr is assumed[2].	0-700 (100-300)
Biomass production on marginal lands	On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2-5 dry t/ha/yr[2]. The supply could be low or zero due to poor economics or competition with food production.	0-150 (60–150)
Bio-materials	Range of the land area required to meet the additional global demand for bio-materials: 0.2-0.8 Gha (average productivity: 5 dry t/ha/yr). This demand should be come from Category I and II in case the world's forests are unable to meet the additional demand. If they are, however, the claim on (agricultural) land could be zero.	0-150 (40-150)[3]
Residues from agriculture	Estimates from various studies. Potential depends on yield/product ratios and the total agricultural land area and type of production system: extensive production systems require re-use of residues for maintaining soil fertility. Intensive systems allow for higher utilisation rates of residues.	15-70
Forest residues	The (sustainable) energy potential of the world's forests is unclear. Part is natural forest (reserves). Range is based on literature data. Low value: figure for sustainable forest management. High value: technical potential. Figures include processing residues.	0-150 (30-150)
Dung	Use of dried dung. Low estimate based on global current use. High estimate: technical potential. Utilisation (collection) in longer term is uncertain.	0-55 (5-55)
Organic wastes	Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of bio-materials. Figures include the organic fraction of MSW and waste wood. Higher values possible by more intensive use of bio-materials.	5-50+[4]
Total	Most pessimistic scenario: no land available for energy farming; only utilisation of residues. Most optimistic scenario: intensive agriculture concentrated on the better quality soils.	40-1100 (250-500)

Notes

1. Where two ranges are given, numbers between brackets give the range of average potential in a world aiming for large-scale utilisation of biomass. A lower limit of zero implies that potential availability could be zero, e.g., if we fail to modernize agriculture so that more land is needed to feed the world.
2. Heating value: 19 GJ/t dry matter.
3. This value could even be negative: the potential biomass demand for producing bio-materials (such as bio-plastics or construction materials). These markets can represent a large demand for biomass that will reduce the availability of biomass for energy. However, the more bio-materials are used the more organic waste (eventually) will become available for energy. Such use of biomass results in a "double" GHG benefit as well through avoided emissions in manufacturing materials with fossil fuels and by producing energy from the waste. Thus, calculating the potential biomass availability for energy is not straightforward adding the figures of the different rows. More details are given in [Hoogwijk et al., 2003].
4. The energy supply of bio-materials ending up as waste can vary between 20 and 55 EJ (or 1100-2900 Mt dry matter) per year. This range excludes cascading and does not take into account the time delay between production of the material and "release" as (organic) waste.

Table I.8. Overview of the global potential bioenergy supply in the long term for a number of categories, and the main preconditions and assumptions that determine these potentials.[4]

What is the current situation for bioenergy? The Worldwatch institute has recently published a summary of their report on the global potential of biofuels in the 21st century. Currently the two most prevalent biofuels after traditional bioenergy uses are ethanol and biodiesel. World production of ethanol has more than doubled between 2000 and 2005 while biodiesel has quadrupled (see Figures I.8 and I.9).[17]

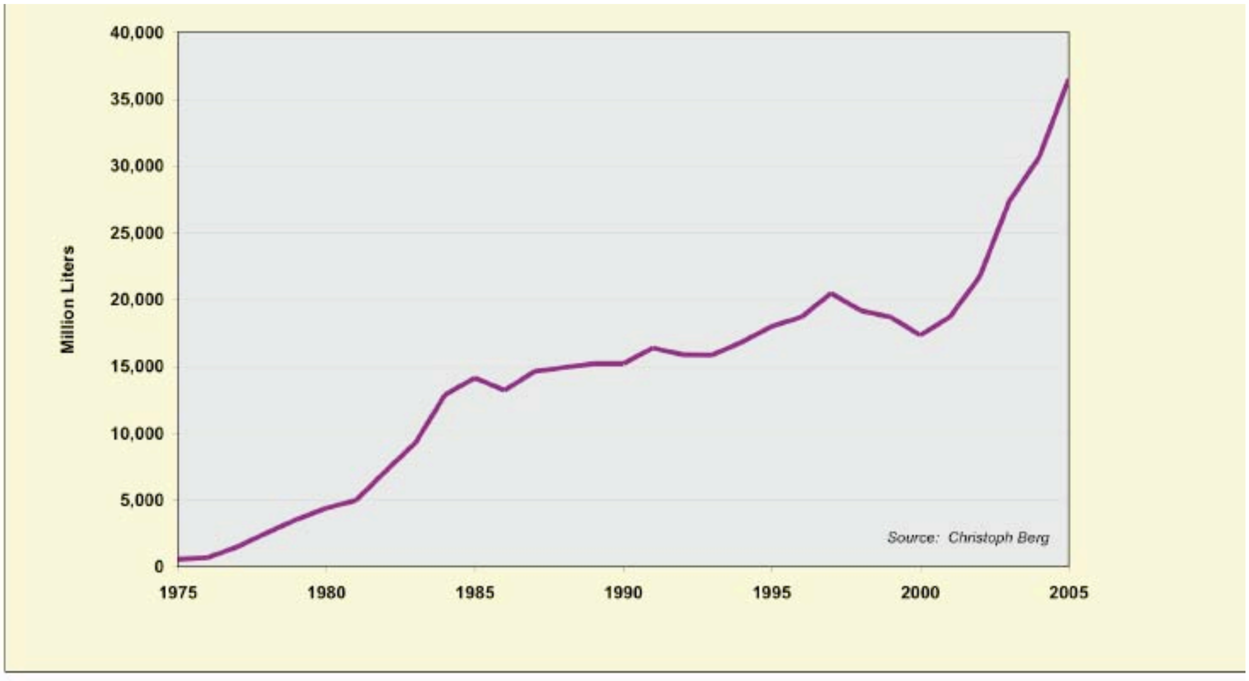


Figure I.8. World fuel-ethanol production, 1975–2005.[17]

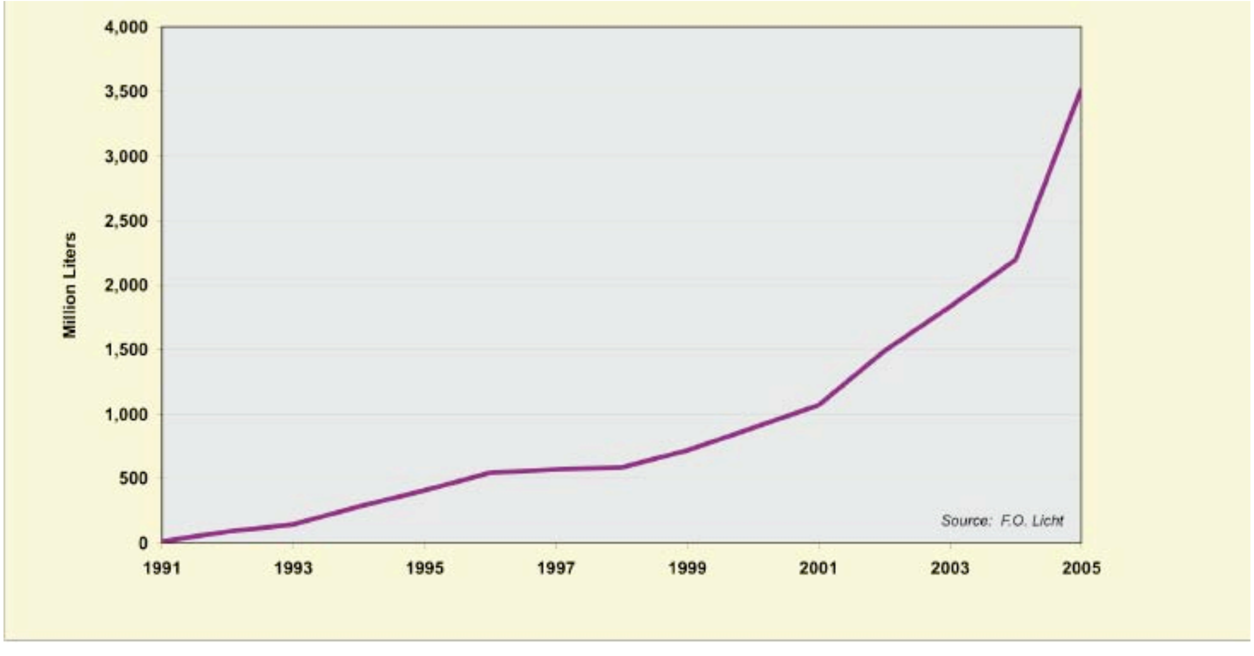


Figure I.9. World fuel-biodiesel production, 1991–2005.[17]

Biofuels investments have risen rapidly with the rise in oil prices and on environmental concerns in Brazil, Europe and the USA. Current production is based on oilseeds, corn, and sugar cane. Built upon the base of these feedstocks, there is expected to be further expansion with energy crops as technology becomes available to convert them cost effectively to biofuels. Current energy crops yields are shown in Figure I.10.[17]

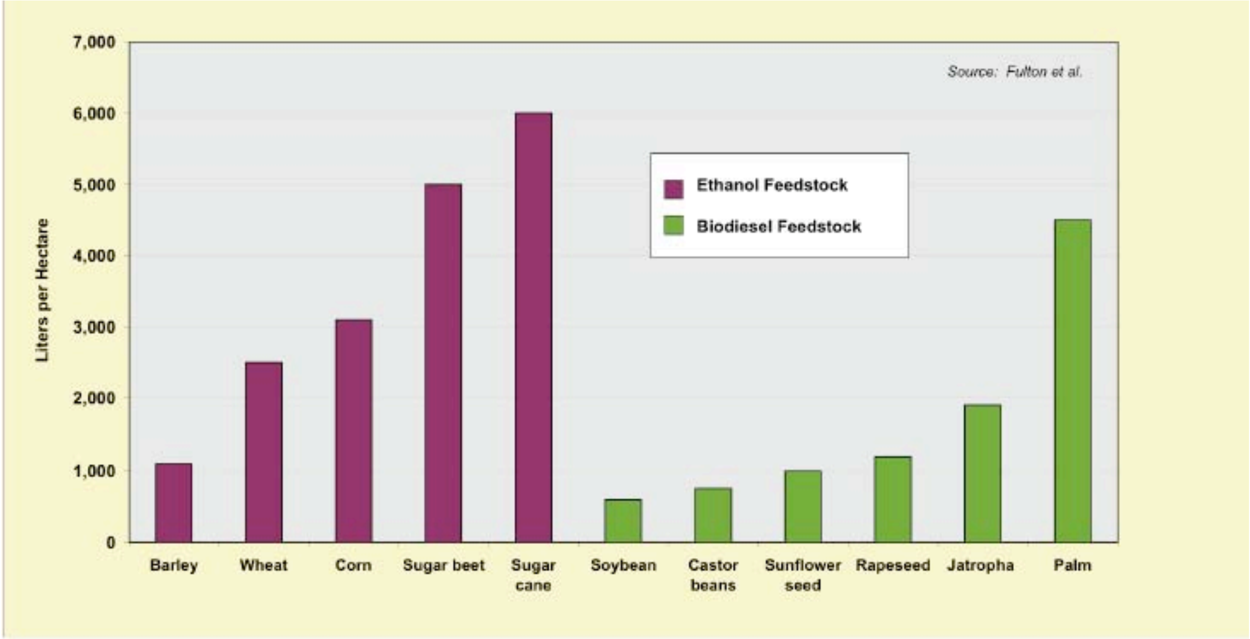
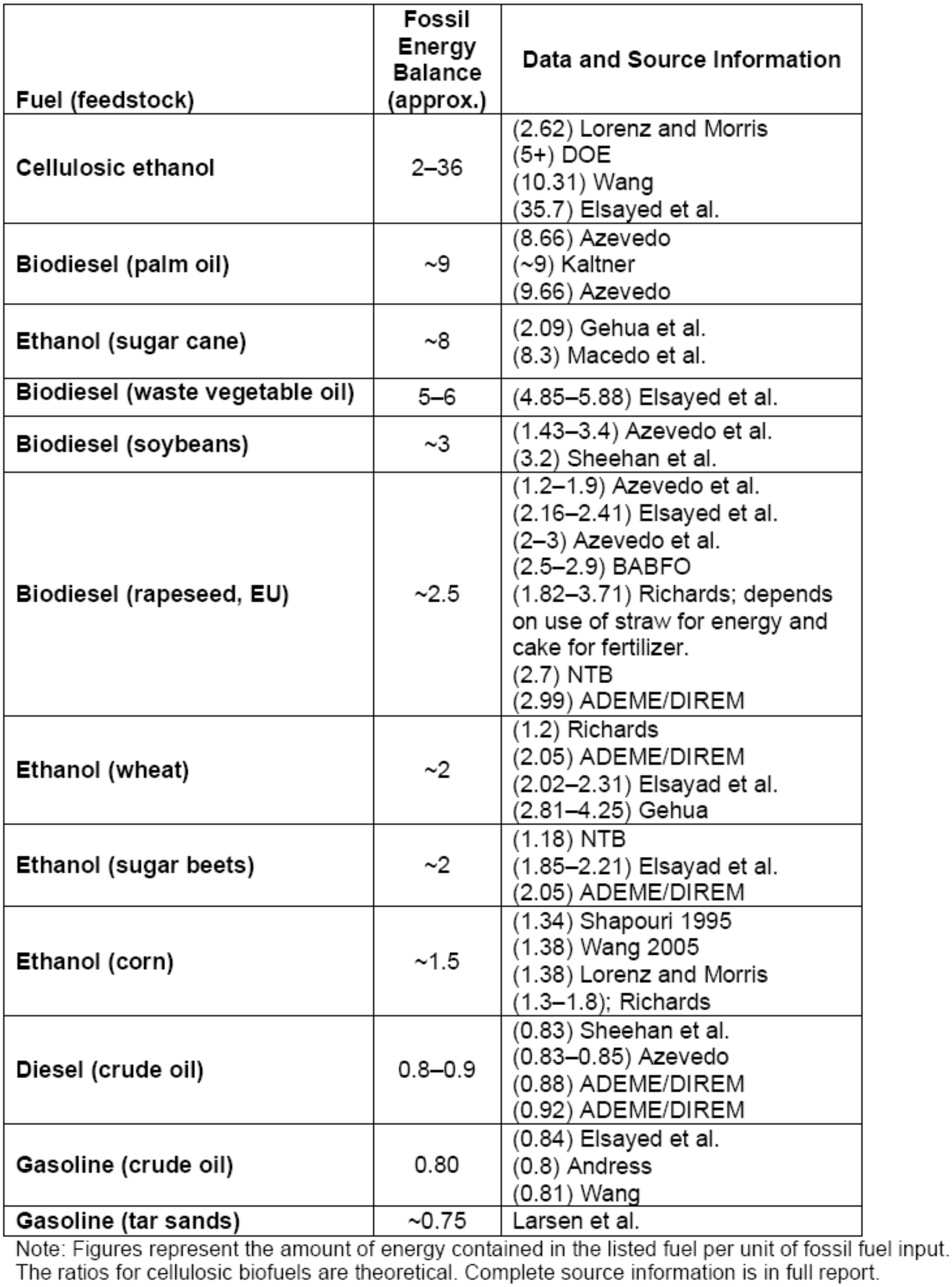


Figure I.10. Biofuel yields of selected crops.[17]

In order to produce many of the current biofuels, energy is used to produce, harvest, transport, and convert the crop to the final fuel. The amount of energy used varies depending on the type of crop, fertilizer needs, whether the co-products of the crop can be used as an energy source, and the type of conversion. The actual cost of production of the fuel will also vary depending on the cost of the feedstock and the value of the co-products of the conversion. Table I.9 is a summary of some fossil-energy usages in current production.[17] One notable comparison is between ethanol produced from corn and sugar cane. Sugarcane production produces a waste co-product, which can be burned to provide energy for the processing plant. This gives its production a high-energy value versus its fossil fuel input of 8:1. Ethanol from corn has a much lower value of 1.5:1. This is mainly because corn production uses more nitrogen fertilizer in its production and the co-product in its processing is a high-value animal feed product: distiller’s dried grain. This co-product could be burned to provide energy for the process but has higher value as a high-protein animal feed. Trade-offs of this nature will probably play a role in choices of whether to use a given feedstock for food or fuel in the future of bioenergy production.

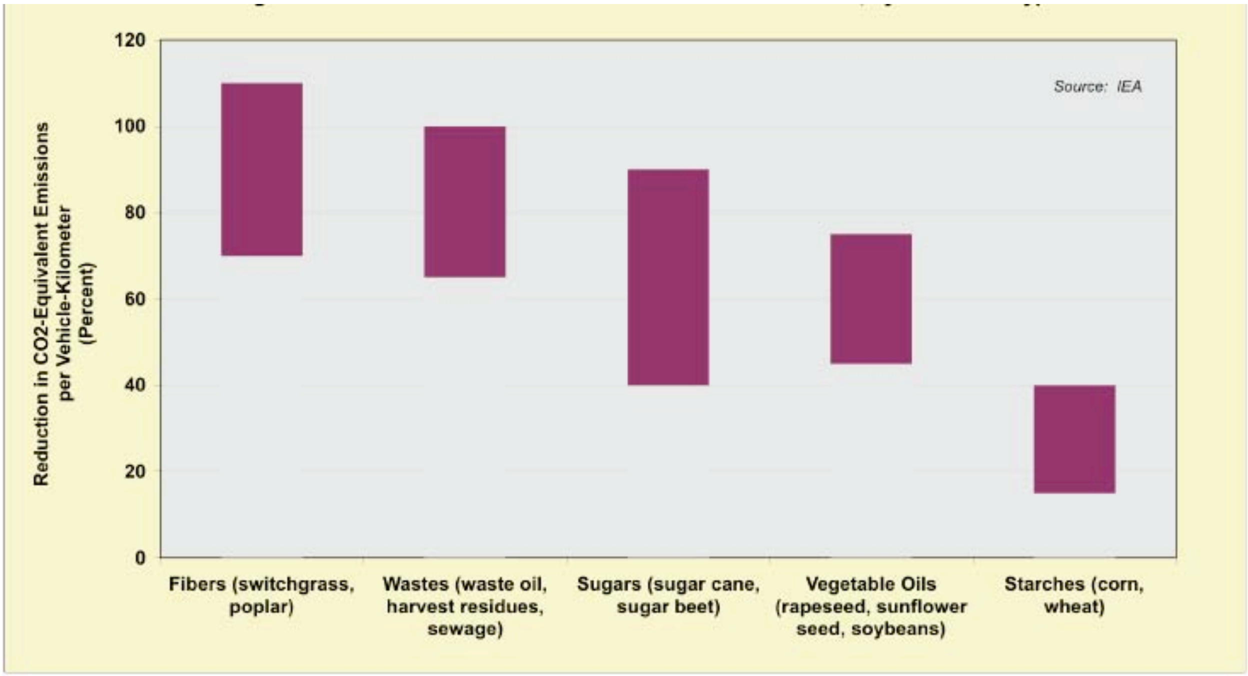


Fuel (feedstock)	Fossil Energy Balance (approx.)	Data and Source Information
Cellulosic ethanol	2–36	(2.62) Lorenz and Morris (5+) DOE (10.31) Wang (35.7) Elsayed et al.
Biodiesel (palm oil)	~9	(8.66) Azevedo (~9) Kaltner (9.66) Azevedo
Ethanol (sugar cane)	~8	(2.09) Gehua et al. (8.3) Macedo et al.
Biodiesel (waste vegetable oil)	5–6	(4.85–5.88) Elsayed et al.
Biodiesel (soybeans)	~3	(1.43–3.4) Azevedo et al. (3.2) Sheehan et al.
Biodiesel (rapeseed, EU)	~2.5	(1.2–1.9) Azevedo et al. (2.16–2.41) Elsayed et al. (2–3) Azevedo et al. (2.5–2.9) BABFO (1.82–3.71) Richards; depends on use of straw for energy and cake for fertilizer. (2.7) NTB (2.99) ADEME/DIREM
Ethanol (wheat)	~2	(1.2) Richards (2.05) ADEME/DIREM (2.02–2.31) Elsayad et al. (2.81–4.25) Gehua
Ethanol (sugar beets)	~2	(1.18) NTB (1.85–2.21) Elsayad et al. (2.05) ADEME/DIREM
Ethanol (corn)	~1.5	(1.34) Shapouri 1995 (1.38) Wang 2005 (1.38) Lorenz and Morris (1.3–1.8); Richards
Diesel (crude oil)	0.8–0.9	(0.83) Sheehan et al. (0.83–0.85) Azevedo (0.88) ADEME/DIREM (0.92) ADEME/DIREM
Gasoline (crude oil)	0.80	(0.84) Elsayed et al. (0.8) Andress (0.81) Wang
Gasoline (tar sands)	~0.75	Larsen et al.

Note: Figures represent the amount of energy contained in the listed fuel per unit of fossil fuel input. The ratios for cellulosic biofuels are theoretical. Complete source information is in full report.

Table I.9. Fossil-energy balances of selected fuel types.[17]

The other major consideration currently driving biofuels growth is the benefit on greenhouse gas emissions. Figures I.11 and I.12 cover some of these considerations.[17]



Source: IEA

Figure I.11. Potential reductions in greenhouse gas emissions by feedstock type.[17]

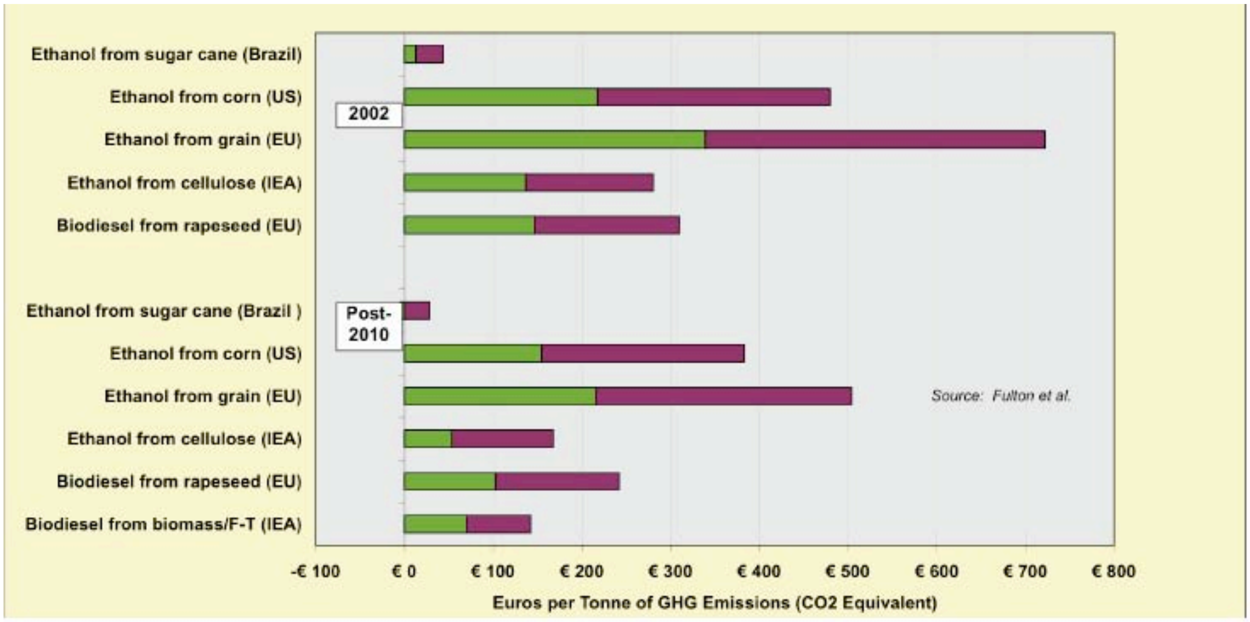
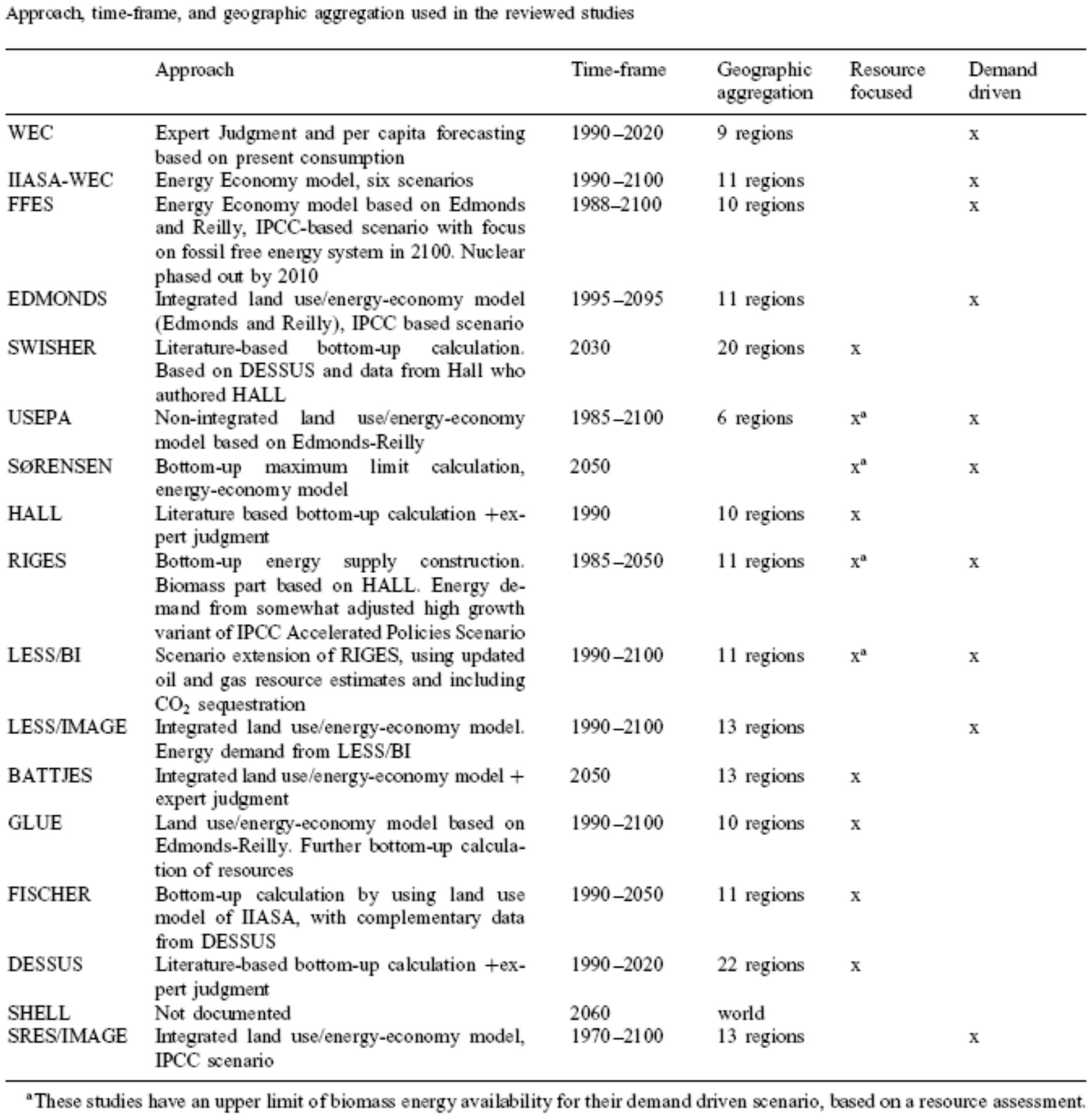


Figure I.12. Biofuel cost per tonne of greenhouse gas (GHG) reduction. [17]
(Note: Low (green) and high (purple) ranges were developed using highest cost–lowest GHG reduction estimate, and lowest cost–highest GHG reduction estimate for each option, then taking the 25% and 75% percentile of this range to represent the low and high estimates in this figure.)

Future growth in production will be driven by increased demand for renewable fuels fed both by the higher cost of conventional fossil fuels and by environmental policy. While this will likely increase the price of agricultural commodities, it has the potential to benefit subsistence agricultural production globally because of the higher value that can be obtained from the products they produce.

As stated earlier, there have been numerous studies on the potential of bioenergy over the past two decades. These have been driven by both environmental concerns and concern that fossil fuels will not last forever. In 2003, a summary of 17 such publications was done.[9] The review divided most of the prior studies into two types. The first were demand driven. These looked at the potential for bioenergy to meet certain targets or demands. The second types were resource-based and determined how those resources could be used to meet the various markets that needed to be supplied (see Table I.10).[9]



Approach, time-frame, and geographic aggregation used in the reviewed studies

	Approach	Time-frame	Geographic aggregation	Resource focused	Demand driven
WEC	Expert Judgment and per capita forecasting based on present consumption	1990–2020	9 regions		x
IIASA-WEC	Energy Economy model, six scenarios	1990–2100	11 regions		x
FFES	Energy Economy model based on Edmonds and Reilly, IPCC-based scenario with focus on fossil free energy system in 2100. Nuclear phased out by 2010	1988–2100	10 regions		x
EDMONDS	Integrated land use/energy-economy model (Edmonds and Reilly), IPCC based scenario	1995–2095	11 regions		x
SWISHER	Literature-based bottom-up calculation. Based on DESSUS and data from Hall who authored HALL	2030	20 regions	x	
USEPA	Non-integrated land use/energy-economy model based on Edmonds-Reilly	1985–2100	6 regions	x[a]	x
SØRENSEN	Bottom-up maximum limit calculation, energy-economy model	2050		x[a]	x
HALL	Literature based bottom-up calculation +expert judgment	1990	10 regions	x	
RIGES	Bottom-up energy supply construction. Biomass part based on HALL. Energy demand from somewhat adjusted high growth variant of IPCC Accelerated Policies Scenario	1985–2050	11 regions	x[a]	x
LESS/BI	Scenario extension of RIGES, using updated oil and gas resource estimates and including CO_2 sequestration	1990–2100	11 regions	x[a]	x
LESS/IMAGE	Integrated land use/energy-economy model. Energy demand from LESS/BI	1990–2100	13 regions		x
BATTJES	Integrated land use/energy-economy model + expert judgment	2050	13 regions	x	
GLUE	Land use/energy-economy model based on Edmonds-Reilly. Further bottom-up calculation of resources	1990–2100	10 regions	x	
FISCHER	Bottom-up calculation by using land use model of IIASA, with complementary data from DESSUS	1990–2050	11 regions	x	
DESSUS	Literature-based bottom-up calculation +expert judgment	1990–2020	22 regions	x	
SHELL	Not documented	2060	world		
SRES/IMAGE	Integrated land use/energy-economy model, IPCC scenario	1970–2100	13 regions		x

[a] These studies have an upper limit of biomass energy availability for their demand driven scenario, based on a resource assessment.

Table I.10. Approaches, time frame, and geographic aggregation used in the reviewed studies.[9]

Figure I.13 graphically displays the results of the various studies.[9] While there is considerable variation in the projections, most indicate that a bioenergy supply of 200 to 400 EJ could be achieved by 2050. This energy is expected to come from a variety of sources including crop residues and bioenergy crops (see Figure I.14). Figure I.14 provides more information about the studies than is shown in Figure I.13. Several of the studies only looked at specific categories of bioenergy supply. Those that looked at the broad spectrum of potential supplies have much larger values for the potential of biomass in the future. Most studies separate food production from bioenergy production so that the food supply is not affected, although these agricultural industries are likely to be highly connected. More plausibly, the economics of producing food and fuel will become more positive as the demand for products increases. These developments will drive increased production of agricultural crops to meet demand.

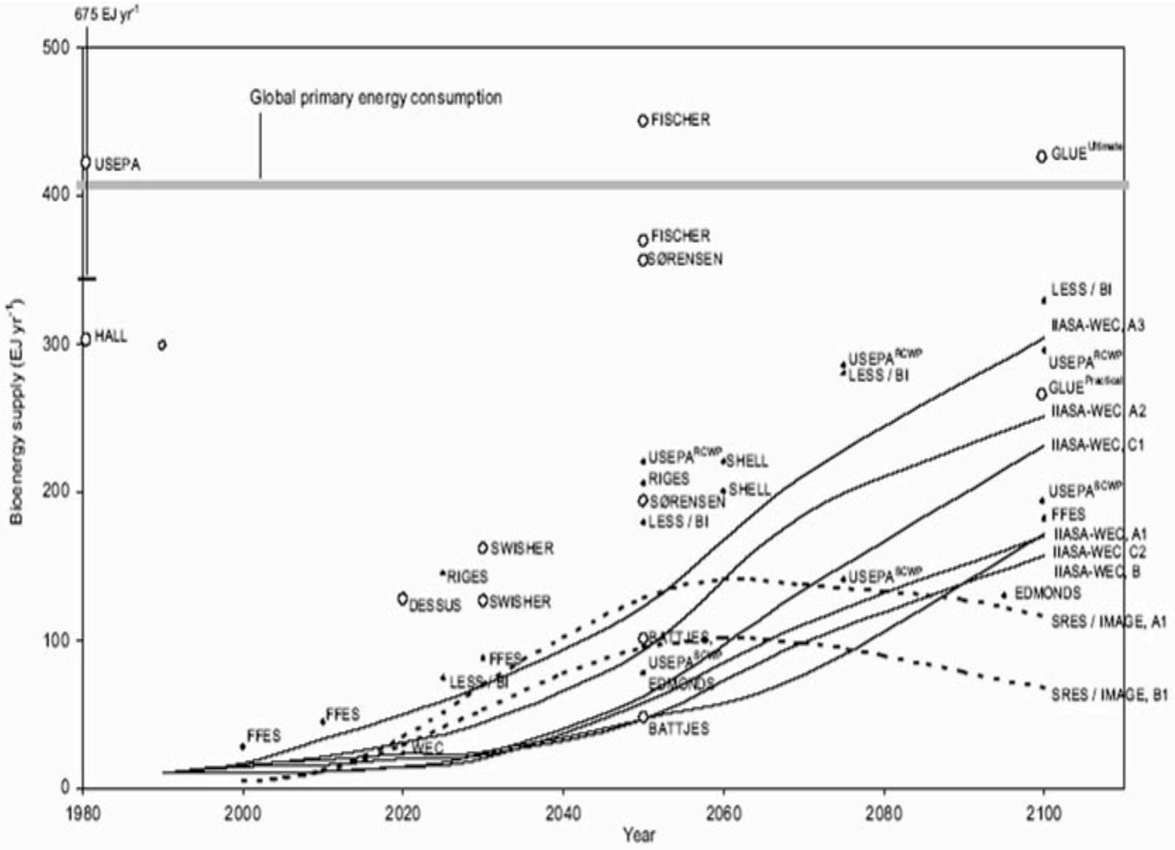


Fig. 2. Potential biomass supply for energy over time. Resource-focused studies are represented by hollow circles and demand-driven studies are represented by filled circles. USEPA and HALL, who do not refer to any specific time, are placed at the left side of the diagram. IIASA-WEC and SRES/IMAGE are represented by solid and dashed lines respectively, with scenario variant names given without brackets at the right end of each line. The present approximate global primary energy consumption is included for comparison. (The global consumption of oil, natural gas, coal, nuclear energy and hydro electricity 1999–2000 was about 365 EJ yr^{-1} [43]. Global biomass consumption for energy is estimated at 35–55 EJ yr^{-1} [44-46].)

Figure I.13. Potential biomass supply for energy over time. [9]

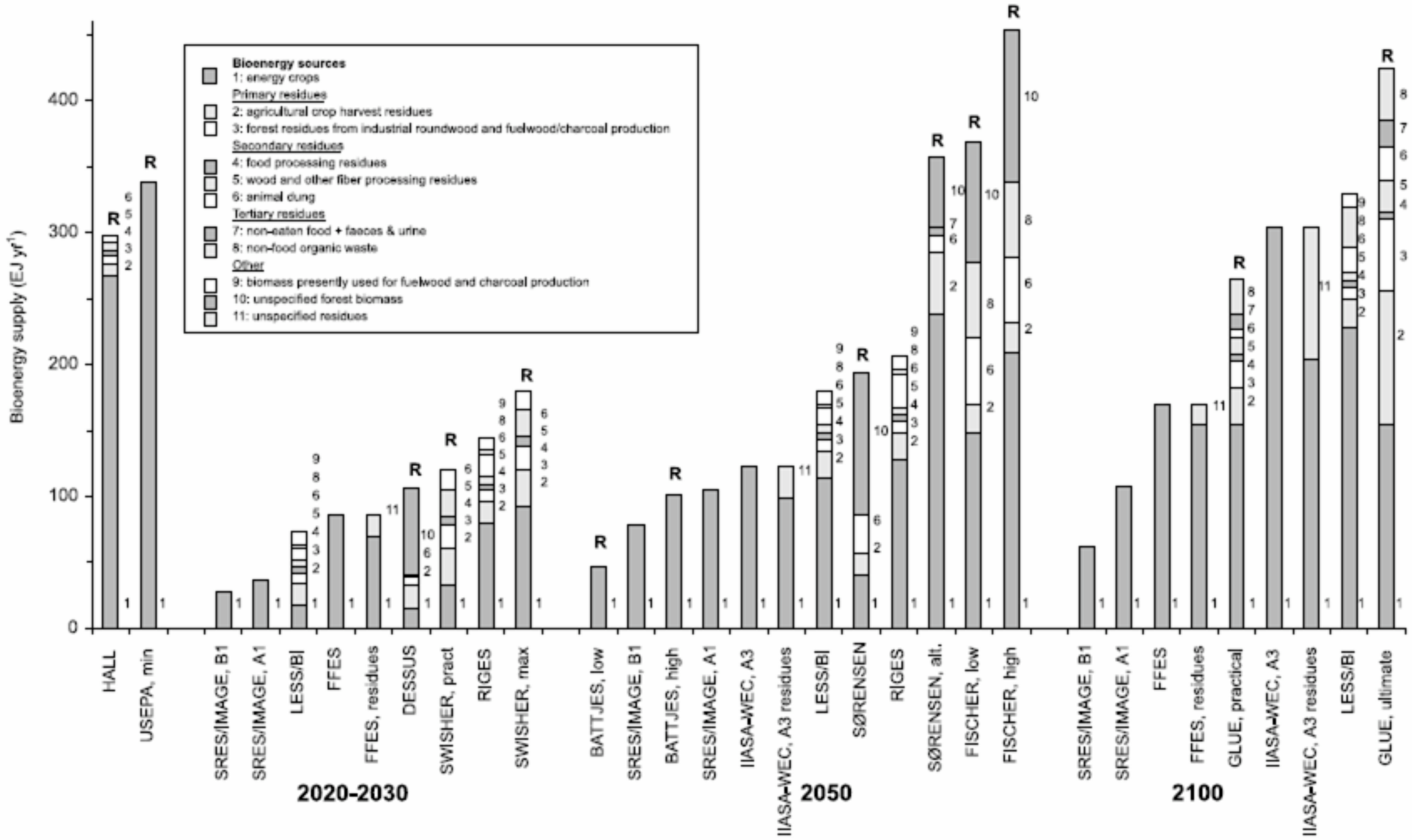


Fig. 5. The contribution of specific sources to the total bioenergy supply. The number sequence to the right of the bars corresponds to the sequence of bioenergy sources in each bar. Studies that are characterized as resource-focused are indicated with R. The IIASA-WEC study is represented by the bioenergy-intensive A3 variant. The non-specified residue potential in SWISHER is distributed between residue categories 2–6 according to HALL, since SWISHER use data from David Hall who also produced the HALL estimate.

Figure I.14. The contribution of specific sources to the total bioenergy supply. [9]

Several studies since the review of Berndes *et al*. in 2003 have further refined the possibilities for biomass production. In 2004, a paper by Parikka considered woody biomass and other residues as potential sources of bioenergy.[11] Table I.11 summarizes their results gathered from the FAO database.[11]

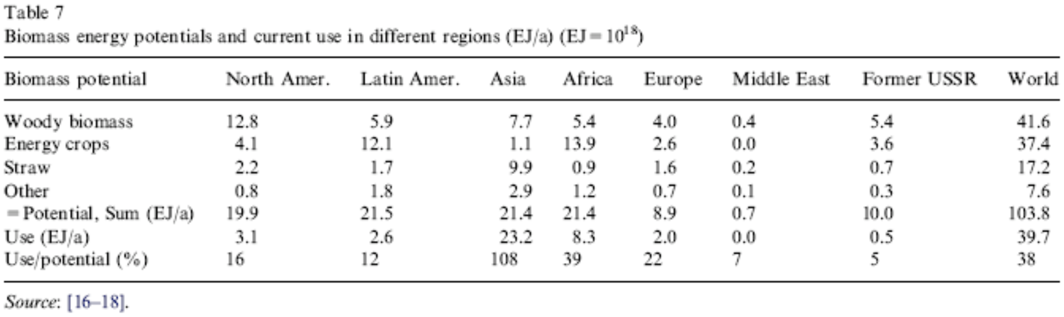


Table 7
Biomass energy potentials and current use in different regions (EJ/a) (EJ = 10^{18})

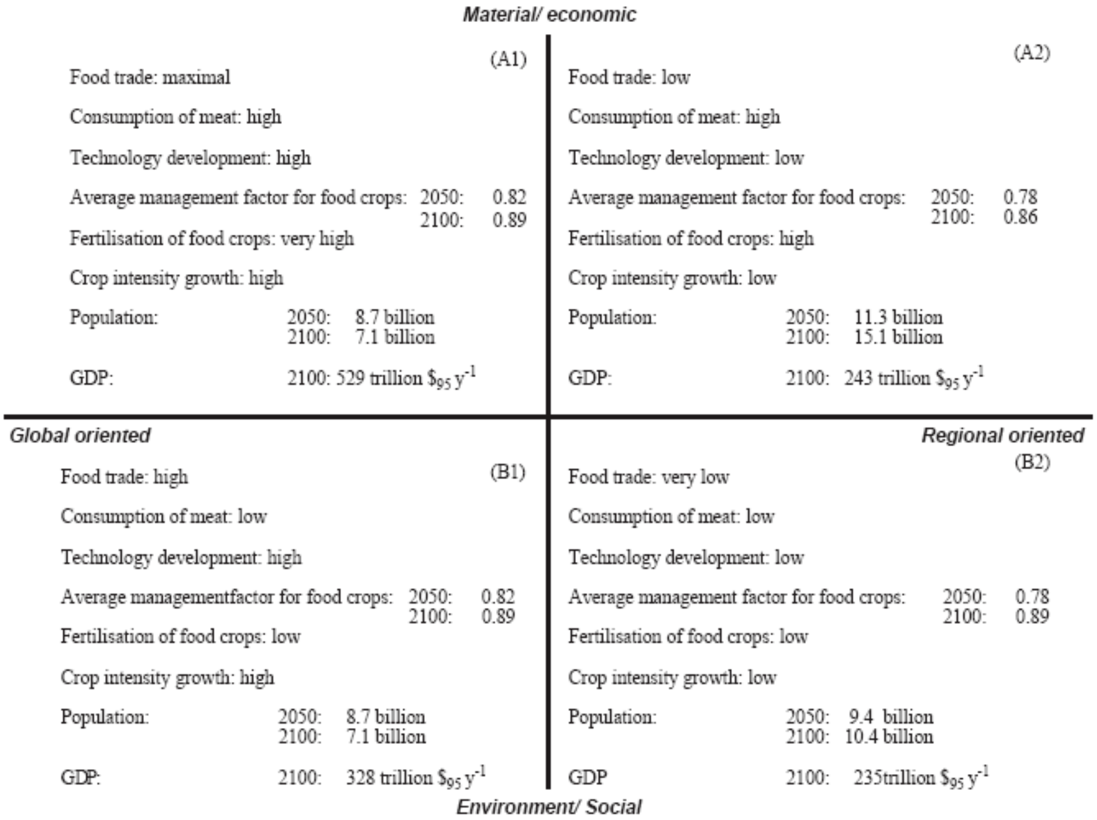
Biomass potential	North Amer.	Latin Amer.	Asia	Africa	Europe	Middle East	Former USSR	World
Woody biomass	12.8	5.9	7.7	5.4	4.0	0.4	5.4	41.6
Energy crops	4.1	12.1	1.1	13.9	2.6	0.0	3.6	37.4
Straw	2.2	1.7	9.9	0.9	1.6	0.2	0.7	17.2
Other	0.8	1.8	2.9	1.2	0.7	0.1	0.3	7.6
= Potential, Sum (EJ/a)	19.9	21.5	21.4	21.4	8.9	0.7	10.0	103.8
Use (EJ/a)	3.1	2.6	23.2	8.3	2.0	0.0	0.5	39.7
Use/potential (%)	16	12	108	39	22	7	5	38

Source: [16–18].

Table I.11. Biomass energy potentials and current use in different regions.[11]

These data indicate that the total sustainable energy potential worldwide is about 100 EJ per annum, with 41% from woody biomass. Additionally, Parrikka concluded that the greatest potential for expanded biomass production exists in North America, Latin America, Europe and the former USSR.

Hoogwijk, *et al.* carried out another refinement of the IMAGE model in 2005.[12] Their study compared four different scenarios and their effects on the potential of bioenergy production. Because of the large potential that energy crops might have in the future, this study emphasized bioenergy crops. Energy-crop production was examined on abandoned agricultural land, low productivity land, and at-rest land. To simplify the study, only woody bioenergy crops were studied, although a wider variety will most likely be utilized in the future. Figure I.15 summarizes the parameters placed on the future world.



(A1)
Food trade: maximal
Consumption of meat: high
Technology development: high
Average management factor for food crops: 2050: 0.82 2100: 0.89
Fertilisation of food crops: very high
Crop intensity growth: high
Population: 2050: 8.7 billion 2100: 7.1 billion
GDP: 2100: 529 trillion $\$_{95}\,y^{-1}$

(A2)
Food trade: low
Consumption of meat: high
Technology development: low
Average management factor for food crops: 2050: 0.78 2100: 0.86
Fertilisation of food crops: high
Crop intensity growth: low
Population: 2050: 11.3 billion 2100: 15.1 billion
GDP: 2100: 243 trillion $\$_{95}\,y^{-1}$

(B1)
Food trade: high
Consumption of meat: low
Technology development: high
Average managementfactor for food crops: 2050: 0.82 2100: 0.89
Fertilisation of food crops: low
Crop intensity growth: high
Population: 2050: 8.7 billion 2100: 7.1 billion
GDP: 2100: 328 trillion $\$_{95}\,y^{-1}$

(B2)
Food trade: very low
Consumption of meat: low
Technology development: low
Average management factor for food crops: 2050: 0.78 2100: 0.89
Fertilisation of food crops: low
Crop intensity growth: low
Population: 2050: 9.4 billion 2100: 10.4 billion
GDP 2100: 235trillion $\$_{95}\,y^{-1}$

Fig. 4. Assumptions related to food demand and supply for the four scenarios considered in this study.

Figure I.15. Assumptions related to food demand and supply for four scenarios.[12]

Different factors are applied to population growth and the level of management of agricultural production. The management factor affects the predicted annual increases in food production. The global average annual increase from 1961 to 2002 for sugar cane, wheat, rice, and coffee are 0.66%, 2.26%, 1.82%, and 0.94%, respectively. For use in the Hoogwijk study, future increases are estimated at 1.1% to 2.6% up to 2020, and 1.2% to 1.6% up to 2050.[12] For reference, the management factor assigned for today's sugarcane production is 0.7 in this study with a future upper limit of 1.5.

Land use patterns are shown in Figure I.16 for the various scenarios. As can be seen, the amount of crop land needed for food production varies widely based on the productivity and population projected in the different future scenarios.

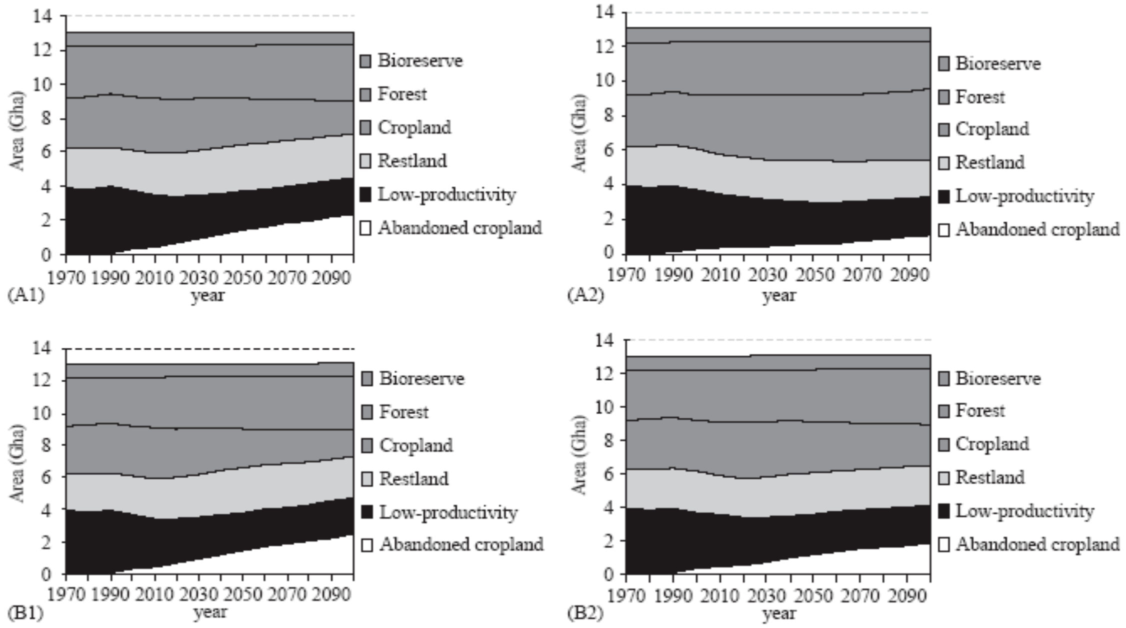


Fig. 7. Simulated distribution of the land-use pattern, excluding the land-claim exclusion factor: agricultural land, forest land, grassland, low-productive land and rest land.

Figure I.16. Simulated distribution of land-use pattern.[12]

Table I.12 outlines the projected bioenergy crop production for each scenario, with estimates for 2050 ranging from 300 to 650 EJ per year. Low productivity land was not a production prime factor in this future. For reference, total primary energy consumption for the world in 2000 was 400-450 EJ/y.

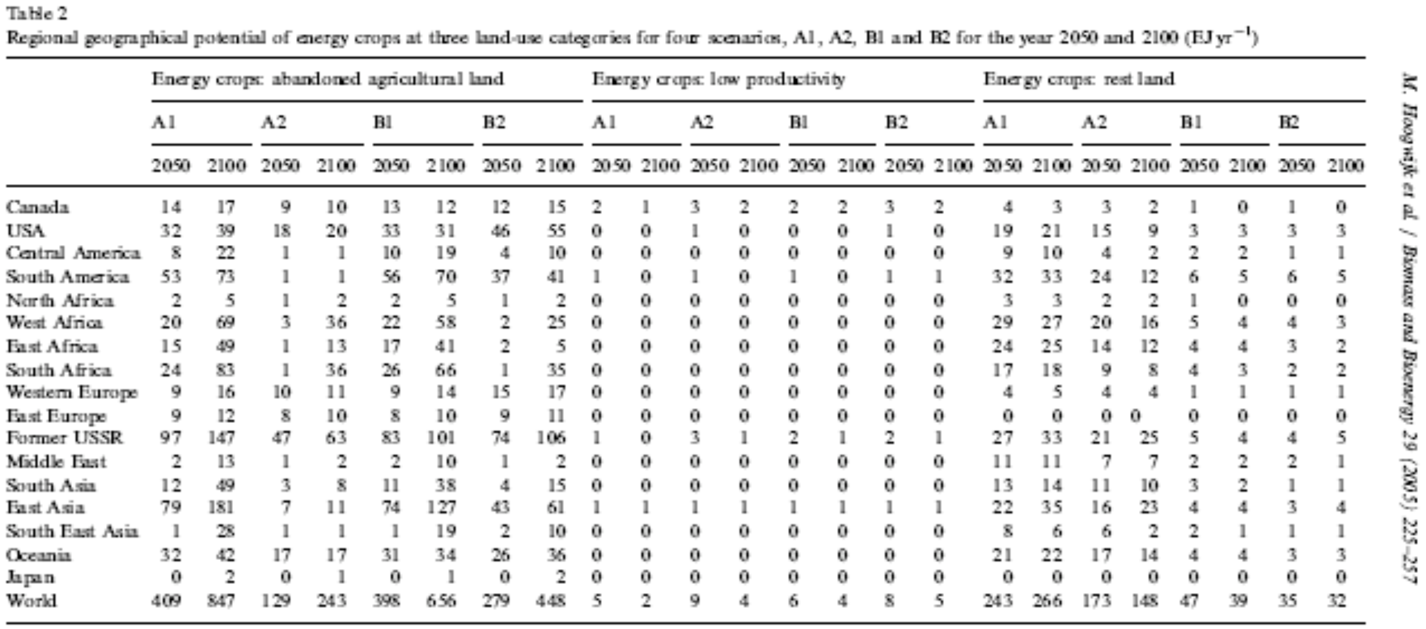


Table 2

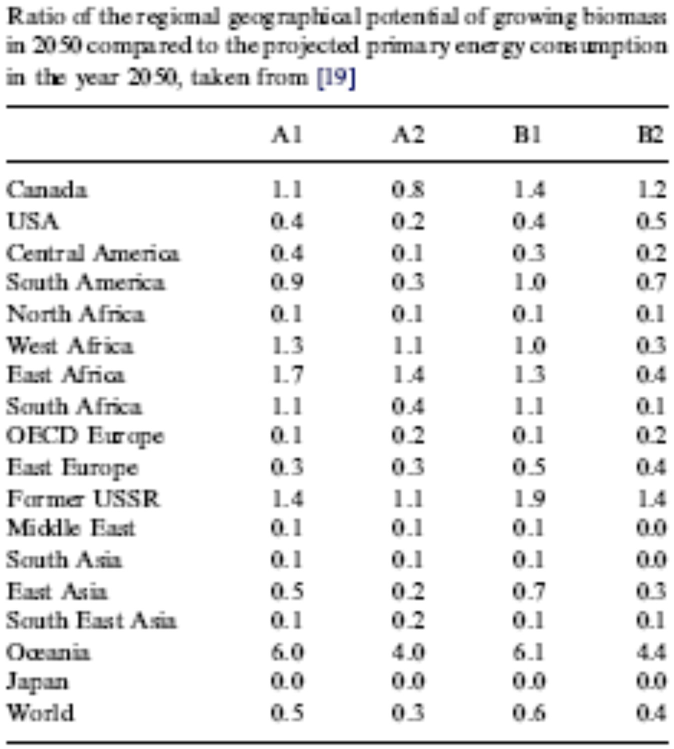
Regional geographical potential of energy crops at three land-use categories for four scenarios, A1, A2, B1 and B2 for the year 2050 and 2100 (EJ yr^{-1})

	Energy crops: abandoned agricultural land								Energy crops: low productivity								Energy crops: rest land							
	A1		A2		B1		B2		A1		A2		B1		B2		A1		A2		B1		B2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Canada	14	17	9	10	13	12	12	15	2	1	3	2	2	2	3	2	4	3	3	2	1	0	1	0
USA	32	39	18	20	33	31	46	55	0	0	1	0	0	0	1	0	19	21	15	9	3	3	3	3
Central America	8	22	1	1	10	19	4	10	0	0	0	0	0	0	0	0	9	10	4	2	2	2	1	1
South America	53	73	1	1	56	70	37	41	1	0	1	0	1	0	1	1	32	33	24	12	6	5	6	5
North Africa	2	5	1	2	2	5	1	2	0	0	0	0	0	0	0	0	3	3	2	2	1	0	0	0
West Africa	20	69	3	36	22	58	2	25	0	0	0	0	0	0	0	0	29	27	20	16	5	4	4	3
East Africa	15	49	1	13	17	41	2	5	0	0	0	0	0	0	0	0	24	25	14	12	4	4	3	2
South Africa	24	83	1	36	26	66	1	35	0	0	0	0	0	0	0	0	17	18	9	8	4	3	2	2
Western Europe	9	16	10	11	9	14	15	17	0	0	0	0	0	0	0	0	4	5	4	4	1	1	1	1
East Europe	9	12	8	10	8	10	9	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Former USSR	97	147	47	63	83	101	74	106	1	0	3	1	2	1	2	1	27	33	21	25	5	4	4	5
Middle East	2	13	1	2	2	10	1	2	0	0	0	0	0	0	0	0	11	11	7	7	2	2	2	1
South Asia	12	49	3	8	11	38	4	15	0	0	0	0	0	0	0	0	13	14	11	10	3	2	1	1
East Asia	79	181	7	11	74	127	43	61	1	1	1	1	1	1	1	1	22	35	16	23	4	4	3	4
South East Asia	1	28	1	1	1	19	2	10	0	0	0	0	0	0	0	0	8	6	6	2	2	1	1	1
Oceania	32	42	17	17	31	34	26	36	0	0	0	0	0	0	0	0	21	22	17	14	4	4	3	3
Japan	0	2	0	1	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
World	409	847	129	243	398	656	279	448	5	2	9	4	6	4	8	5	243	266	173	148	47	39	35	32

M. Hoogwijk et al. / Biomass and Bioenergy 29 (2005) 225–257

Table I.12. Regional energy-crop production projections for Hoogwijk scenarios. [12]

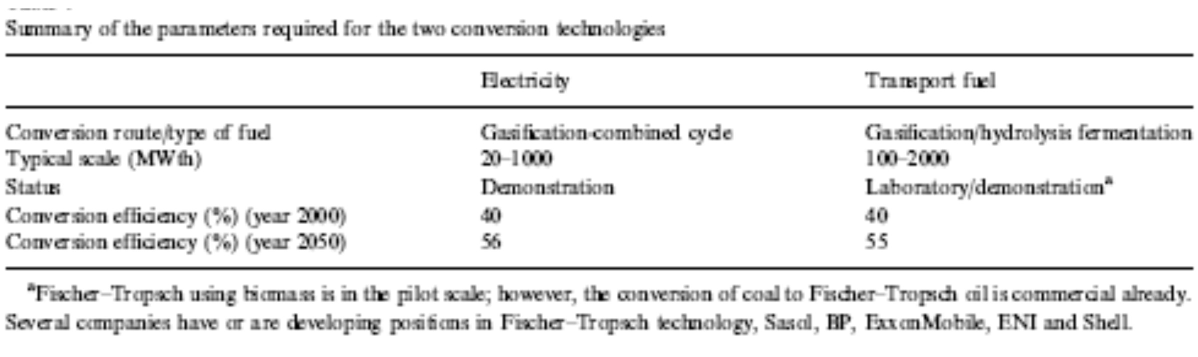
Tables I.13, I.14 and I.15 show ratios of bioenergy production to energy usage, energy conversion factors, and the technical energy production estimated in this study. Table I.13 shows the projected ratio of bioenergy production to total energy consumption for various regions, while Table I.15 displays projected global bioenergy production, as well as the electricity and fuel that could be obtained from it based on the conversion factors shown in Table I.14.



Ratio of the regional geographical potential of growing biomass in 2050 compared to the projected primary energy consumption in the year 2050, taken from [19]

	A1	A2	B1	B2
Canada	1.1	0.8	1.4	1.2
USA	0.4	0.2	0.4	0.5
Central America	0.4	0.1	0.3	0.2
South America	0.9	0.3	1.0	0.7
North Africa	0.1	0.1	0.1	0.1
West Africa	1.3	1.1	1.0	0.3
East Africa	1.7	1.4	1.3	0.4
South Africa	1.1	0.4	1.1	0.1
OECD Europe	0.1	0.2	0.1	0.2
East Europe	0.3	0.3	0.5	0.4
Former USSR	1.4	1.1	1.9	1.4
Middle East	0.1	0.1	0.1	0.0
South Asia	0.1	0.1	0.1	0.0
East Asia	0.5	0.2	0.7	0.3
South East Asia	0.1	0.2	0.1	0.1
Oceania	6.0	4.0	6.1	4.4
Japan	0.0	0.0	0.0	0.0
World	0.5	0.3	0.6	0.4

Table I.13. Ratio of the regional geographical potential of growing biomass in 2050 compared to the projected primary energy consumption in the year 2050.[12]

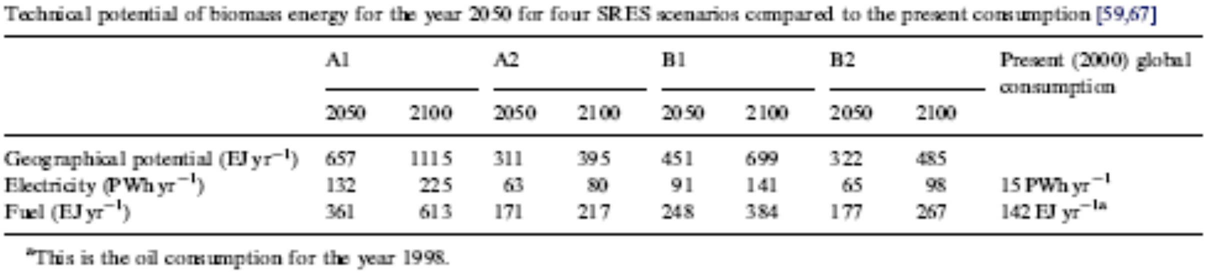


Summary of the parameters required for the two conversion technologies

	Electricity	Transport fuel
Conversion route/type of fuel	Gasification-combined cycle	Gasification/hydrolysis fermentation
Typical scale (MWth)	20–1000	100–2000
Status	Demonstration	Laboratory/demonstration[a]
Conversion efficiency (%) (year 2000)	40	40
Conversion efficiency (%) (year 2050)	56	55

[a] Fischer–Tropsch using biomass is in the pilot scale; however, the conversion of coal to Fischer–Tropsch oil is commercial already. Several companies have or are developing positions in Fischer–Tropsch technology, Sasol, BP, ExxonMobile, ENI and Shell.

Table I.14. Summary of the parameters required for two conversion technologies.[12]



Technical potential of biomass energy for the year 2050 for four SRES scenarios compared to the present consumption [59,67]

	A1		A2		B1		B2		Present (2000) global consumption
	2050	2100	2050	2100	2050	2100	2050	2100	
Geographical potential (EJ yr^{-1})	657	1115	311	395	451	699	322	485	
Electricity (PWh yr^{-1})	132	225	63	80	91	141	65	98	15 PWh yr^{-1}
Fuel (EJ yr^{-1})	361	613	171	217	248	384	177	267	142 EJ yr^{-1}[a]

[a] This is the oil consumption for the year 1998.

Table I.15. Technical potential of biomass energy for the year 2050 for four SRES scenarios, compared to present consumption.[12]

Commenting on their results, Hoogwijk *et al.* give the following caveat: "Finally, it should be noted that using the total of the potential covering three types of land-use categories is extreme and theoretical, as it would imply an area of almost 30–40% of the total land area. These values are in the same order of magnitude up to 200% of the current agricultural land area."[12]

Smeets *et al.* comprehensively reviewed bioenergy production potential using a Quickscan model.[2] This model is based on evaluation of data and studies on relevant factors such as population growth, per capita food consumption and the efficiency of food production.

"Three types of biomass energy sources are included: dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth. The bioenergy production potential in a region is limited by various factors, such as the demand for food, industrial roundwood, traditional woodfuel, and the need to maintain existing forests for the protection of biodiversity, because competition between bioenergy production and these ecosystem functions is considered unsustainable. Special attention is given to the technical potential to reduce the area of agricultural land needed for food production by increasing the efficiency of food production. The area of surplus agricultural land that is no longer required for food production is available for energy crop production. A reference scenario has been composed to analyze the demand for food. Four levels of advancement of agricultural technology in the year 2050 are assumed that vary with respect to the efficiency of food production. Results indicate that the application of very efficient agricultural systems combined with the geographic optimization of land use patterns could reduce the area of agricultural land needed to cover the global food demand in 2050 by as much as 72% of the present agricultural land."[2]

In 1998, the use of biomass for food production, materials, and bioenergy is estimated at 273 EJ/yr. Roughly 75% of this is lost during processing, harvesting, and transport.

"In terms of energy, the use of biomass for the production of food, materials and traditional bioenergy is estimated at 273 EJy-1 in 1998, equal to 12% of the total NPP *[...]*. The production of food involved an annual turnover of biomass equivalent to 213 EJy-1 in 1998; the use of industrial roundwood and traditional woodfuel in 1998 involved a turnover of biomass equivalent to 28 EJy-1 and 32 EJy-1, respectively. However, roughly ¾ of the biomass turnover used for the production of food, industrial roundwood and traditional woodfuel is lost during processing, harvesting and transport. Current estimates indicate that by 2050 the largest potential bioenergy sources are from energy crops grown on degraded and surplus agricultural land (0-1100 EJ/y) agricultural residues 10-32EJ/y and forest growth at 42-58 EJ/y."[2]

The Quickscan study includes sugar cane, wheat, maize, eucalyptus, willow, poplar, and grasses as energy crops. It also seeks to maximize production and food-crop efficiency so that surplus agricultural land can be used for energy-crop production. It also considers increasing the intensity of meat production using more industrialized systems.

Tables I.16 to I.19 show the key variables, the estimated production of systems 1–4, and the production systems descriptions.

Parameter	1998	2050	unit	Remark	Source
Population	5.9	8.8	billion	Medium growth scenario.	[26]
Per capita consumption	2739	3302	kcal cap^{-1} day^{-1}	Figures for 2050 are based on trend extrapolations from 2030.	[16]
Economic growth	2.6		% y^{-1}	World Bank economic projections are used as exogenous assumptions in the FAO projections on food consumption, which are used in the Quickscan model. The figure of 2.6 % y^{-1} is the average GDP growth in the period 1998-2030.	[16]
Climate change	Excluded		-	The impact of climate change on expected crop yields is limited compared to increase in yields that is technically attainable and is thus excluded.	-
Feed conversion efficiency	0.02-0.28	0.07-0.32	kg product kg dm feed^{-1}	Data are based on a high level of advancement of agricultural technology. The first figure is for bovine meat and the second for poultry meat	[3]
Woody bioenergy crop yields	8.4	18	t dm ha^{-1} y^{-1}	Global average yield level based on the suitability of the total area land on earth for bioenergy crop production.	[3]
Plantations for industrial roundwood and woodfuel	123	124-284	Mha	Low and high plantation establishment scenario.	[50]
Forest growth	3.4		m^3 ha^{-1}	Average for all forest areas.	[43]
Industrial roundwood demand	1.5	1.9-3.1	Gm^3	Low and high projection in the year 2050.	Various, e.g. [72-74, 50]
Woodfuel demand	1.8	1.7-2.6	Gm^3	Low and high projection in the year 2050.	Various, e.g. [72, 3, 73]
Deforestation	0	0	% y^{-1}	In our analysis deforestation is assumed to be negligible, as it endangers biodiversity, also it can be avoided.	-
Global primary energy demand	418	601-1041	EJ y^{-1}	The 418 EJ y^{-1} refers to 2001. Low and high scenario.	[57, 1]

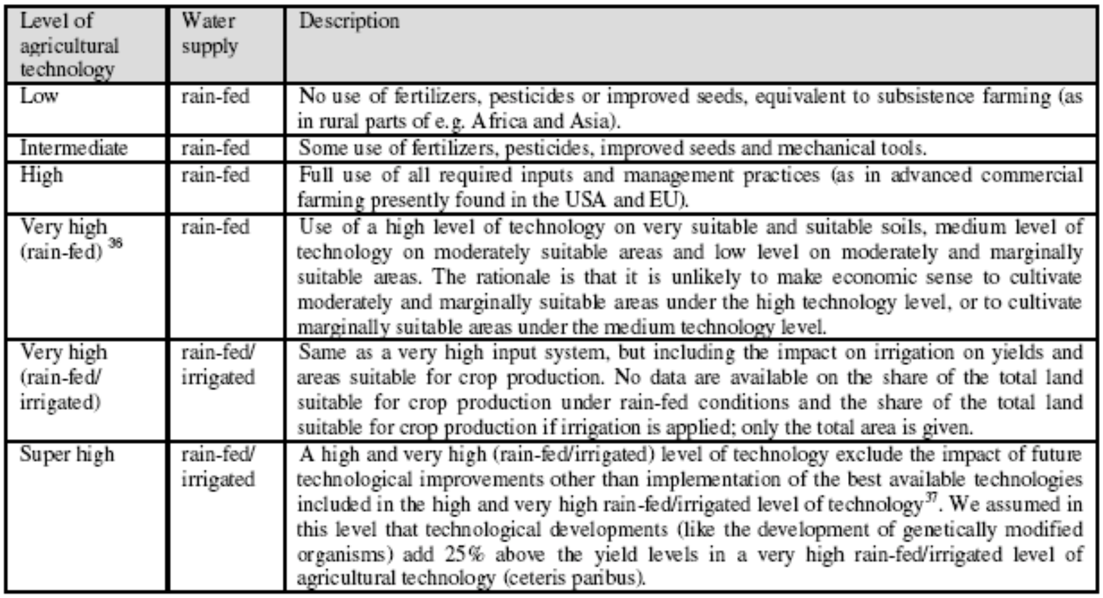
Table I.16. Quickscan model key parameters.[2]

Factor	System 1	System 2	System 3	System 4
Animal production system used (pastoral, mixed, landless)	mixed	mixed	landless	landless
Feed conversion efficiency	high	high	high	high
Level of technology for crop production	very high	very high	very high	super high
Water supply for agriculture (rain-fed = r.f., irrigated = irri)	r.f.	r.f./irri.	r.f./irri.	r.f./irri.

Table I.17. Overview of the four systems studied.[2]

Level of agricultural technology	Description
Low	No or limited use of animal breeding, no disease prevention and treatment, equivalent to subsistence farming (as in rural parts of e.g. Africa and Asia).
Intermediate	Some use of animal breeding, some use of feed supplements (e.g. minerals, enzymes, bacterial inoculates) and some use of dedicated animal housing.
High	Full use of all required inputs and management practices (as in advanced commercial farming presently found in the USA and EU), such as animal breeding, animal disease prevention, diagnosis and treatment, the use of feed supplements (e.g. minerals, enzymes, bacterial inoculates), the use of dedicated animal housing.

Table I.18. Level of advancement of animal production systems.[2]



Level of agricultural technology	Water supply	Description
Low	rain-fed	No use of fertilizers, pesticides or improved seeds, equivalent to subsistence farming (as in rural parts of e.g. Africa and Asia).
Intermediate	rain-fed	Some use of fertilizers, pesticides, improved seeds and mechanical tools.
High	rain-fed	Full use of all required inputs and management practices (as in advanced commercial farming presently found in the USA and EU).
Very high (rain-fed) [36]	rain-fed	Use of a high level of technology on very suitable and suitable soils, medium level of technology on moderately suitable areas and low level on moderately and marginally suitable areas. The rationale is that it is unlikely to make economic sense to cultivate moderately and marginally suitable areas under the high technology level, or to cultivate marginally suitable areas under the medium technology level.
Very high (rain-fed/ irrigated)	rain-fed/ irrigated	Same as a very high input system, but including the impact on irrigation on yields and areas suitable for crop production. No data are available on the share of the total land suitable for crop production under rain-fed conditions and the share of the total land suitable for crop production if irrigation is applied; only the total area is given.
Super high	rain-fed/ irrigated	A high and very high (rain-fed/irrigated) level of technology exclude the impact of future technological improvements other than implementation of the best available technologies included in the high and very high rain-fed/irrigated level of technology[37]. We assumed in this level that technological developments (like the development of genetically modified organisms) add 25% above the yield levels in a very high rain-fed/irrigated level of agricultural technology (ceteris paribus).

Table I.19. Level of advancement of agricultural technology.[2]

Today, 70% of global agricultural land use is devoted to the production of animal products. As a result, the efficiency of meat production significantly affects the amount of land needed to feed the global population. Meat production efficiency ranges from 3 kg of biomass/kg of poultry meat in an efficient production system to over 100 kg of biomass/kg of bovine meat in a pastoral system with low levels of technology. By converting production to more efficient systems globally, this study is able to dedicate considerable land for bioenergy crop production while still feeding the growing populations.

Table I.20 “shows that in 2050, compared to 1998, the area of land required for food production could be decreased by 14%, 22%, 64% and 70% in system 1 to 4, respectively. The total area of surplus agricultural land ranges between 0.7 Gha in system 1 to 3.6 Gha in system 4. These results are broadly in line with data found in other studies. E.g. Wolf *et al.* … calculated the area of land available for bioenergy production in 2050 as a function of the demand for food and the level of external inputs in agriculture, such as mechanized operations and the use of fertilizers and agricultural chemicals.”[2]

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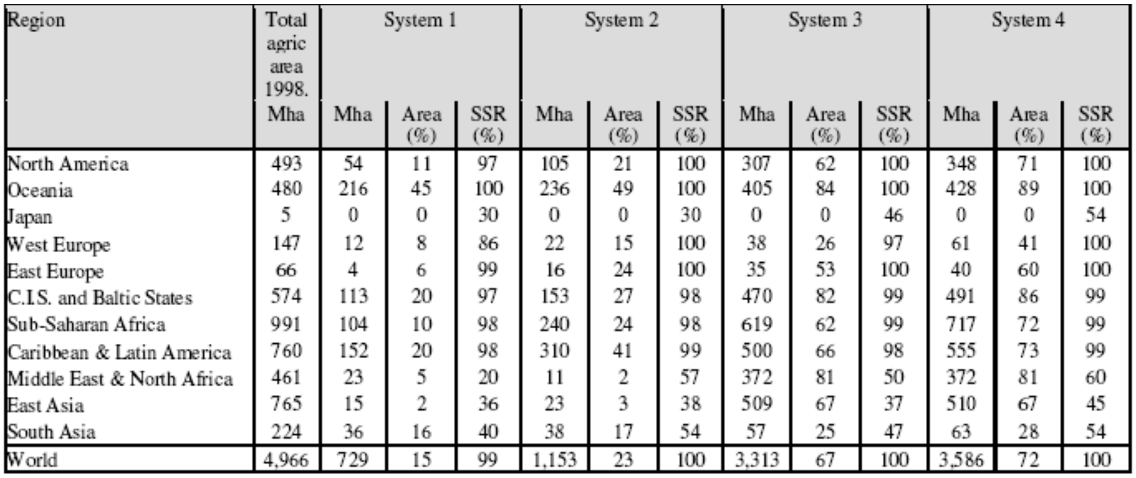


Region	Total agric area 1998. Mha	System 1 Mha	System 1 Area (%)	System 1 SSR (%)	System 2 Mha	System 2 Area (%)	System 2 SSR (%)	System 3 Mha	System 3 Area (%)	System 3 SSR (%)	System 4 Mha	System 4 Area (%)	System 4 SSR (%)
North America	493	54	11	97	105	21	100	307	62	100	348	71	100
Oceania	480	216	45	100	236	49	100	405	84	100	428	89	100
Japan	5	0	0	30	0	0	30	0	0	46	0	0	54
West Europe	147	12	8	86	22	15	100	38	26	97	61	41	100
East Europe	66	4	6	99	16	24	100	35	53	100	40	60	100
C.I.S. and Baltic States	574	113	20	97	153	27	98	470	82	99	491	86	99
Sub-Saharan Africa	991	104	10	98	240	24	98	619	62	99	717	72	99
Caribbean & Latin America	760	152	20	98	310	41	99	500	66	98	555	73	99
Middle East & North Africa	461	23	5	20	11	2	57	372	81	50	372	81	60
East Asia	765	15	2	36	23	3	38	509	67	37	510	67	45
South Asia	224	36	16	40	38	17	54	57	25	47	63	28	54
World	4,966	729	15	99	1,153	23	100	3,313	67	100	3,586	72	100

Table I.20. Total agricultural land in 1998 and the potential surplus by 2050 under various systems, as well as the self-sufficiency ratio in percent.[2]

As seen in table I.20, the Quickscan model indicates surplus agricultural land of 0.7, 1.2, 3.3, and 3.6 Gha for systems 1–4. Figure I.17 indicates the bulk of this surplus land is not suitable for conventional crop production, but this does not preclude it from bioenergy crop production.

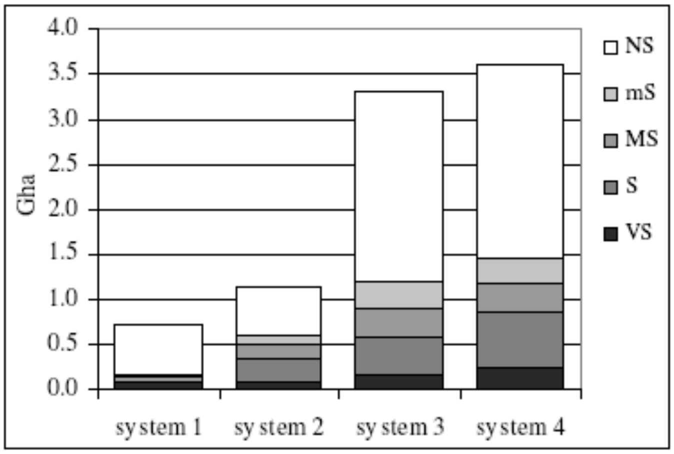


Figure 5. Suitability of the global surplus agricultural land in 2050 (in Gha). VS = very suitable for crop production, S = suitable, MS = moderately suitable, mS = marginally suitable, NS = not suitable.

Figure I.17. Suitability of the global surplus agricultural land in 2050.[2]

Table I.21 indicates the yield level projected on this land in the various agricultural systems by 2050 using an IMAGE modeled yield of 12 oven-dry-ton/ha (odt/ha) annually.

Region	System 1 [t dw ha^{-1}]	System 2 [t dw ha^{-1}]	System 3 [t dw ha^{-1}]	System 4 [t dw ha^{-1}]
North America	19	27	25	27
Oceania	9	11	11	13
Japan	-	-	-	-
West Europe	20	26	23	18
East Europe	35	35	33	36
C.I.S. and Baltic States	21	25	21	25
Sub-Saharan Africa	16	22	22	24
Caribbean & Latin America	16	20	20	23
Middle East & North Africa	5	5	4	5
East Asia	38	39	15	19
South Asia	22	24	20	22
World	16	21	17	20

Table I.21. Woody bioenergy crop yields in various regions by 2050 on surplus agricultural land.[18]

Table I.22 summarizes the total estimated energy from energy corps grown on the surplus agricultural land under the four systems.

Region	System 1 [EJy^{-1}]	System 2 [EJy^{-1}]	System 3 [EJy^{-1}]	System 4 [EJy^{-1}]
North America	20	53	144	174
Oceania	38	51	87	102
Japan	0	0	0	0
West Europe	5	11	16	30
East Europe	3	11	22	26
C.I.S. and Baltic States	45	73	184	199
Sub-Saharan Africa	31	102	260	317
Caribbean & Latin America	47	120	190	221
Middle East & North Africa	2	1	30	31
East Asia	11	17	146	147
South Asia	15	17	21	25
World	215	455	1,101	1,272

Table I.22. Bioenergy crop-production potential in 2050 based on woody crops on surplus agricultural land. [2]

Table I.23 displays the energy available from crop residues by 2050.

Region	Crop harvest residues			Crop process residues	Wood harvest residues, medium demand and plantation scenario	Wood process residues, medium demand and plantation scenario	Wood wastes, medium demand and plantation scenario	Sum of all residues and wastes, excl. demand for feed from residues			Use of residues for feed	Sum of all residues and wastes, incl. demand for feed from residues		
system	1	2	3, 4	1, 2, 3, 4	-	-	-	1	2	3, 4	1, 2, 3, 4	1	2	3, 4
North America	5	8	10	1	2	4	4	16	19	21	2	14	17	19
Oceania	2	4	5	0	0	0	0	2	4	5	0	2	4	5
Japan	0	0	0	0	0	1	1	2	2	2	0	2	2	2
West Europe	2	2	3	1	1	2	2	8	8	9	2	6	6	7
East Europe	1	1	1	0	0	0	0	1	1	1	0	1	1	1
C.I.S. and Baltic States	3	3	4	0	1	1	1	6	6	7	1	5	5	6
Sub-Saharan Africa	15	12	20	2	0	0	0	17	14	22	2	15	12	20
Caribbean & Latin America	11	10	12	2	1	1	1	16	15	17	3	13	12	14
Middle East & North Africa	1	2	2	1	0	0	0	2	3	3	2	0	1	1
East Asia	4	4	5	5	2	2	2	15	15	16	5	10	10	11
South Asia	5	6	7	4	1	0	0	10	11	12	2	8	9	10
World	49	52	69	16	8	11	11	95	98	115	19	76	79	96

Table I.23. Potential supply of agricultural residues and waste in 2050 (units of EJ/yr).[2]

"The results clearly show that in 2050 the technical potential to increase the efficiency of food production is sufficiently large to compensate for the increasing food consumption in principle. The total global bioenergy production potential in 2050 is 364 EJy-1, 607 EJy-1, 1270 EJy-1 and 1545 EJy-1 for system 1, 2, 3 and 4, respectively. The bulk of this potential comes from specialized bioenergy crops grown on surplus agricultural land not required for food production. The variation between the various systems is mainly dependent on the efficiency with which animal products are produced. Residues and wastes account for 76 EJy-1 to 96 EJy-1 of the technical potentials, although the use of residues and wastes as traditional fuel, animal bedding, for soil improvement or as a source of fibre for the paper industry will reduce these figures. The difference in the potential of residues and wastes between various production systems is the result of differences in the demand for feed crops. The surplus (technical) bioenergy production potential from wood obtained from natural forests is estimated at 82 EJy-1, based on a medium demand for wood scenario and high plantation establishment scenario. The potential of surplus forest growth and woody residues and wastes is further analysed in a separate article."[2]

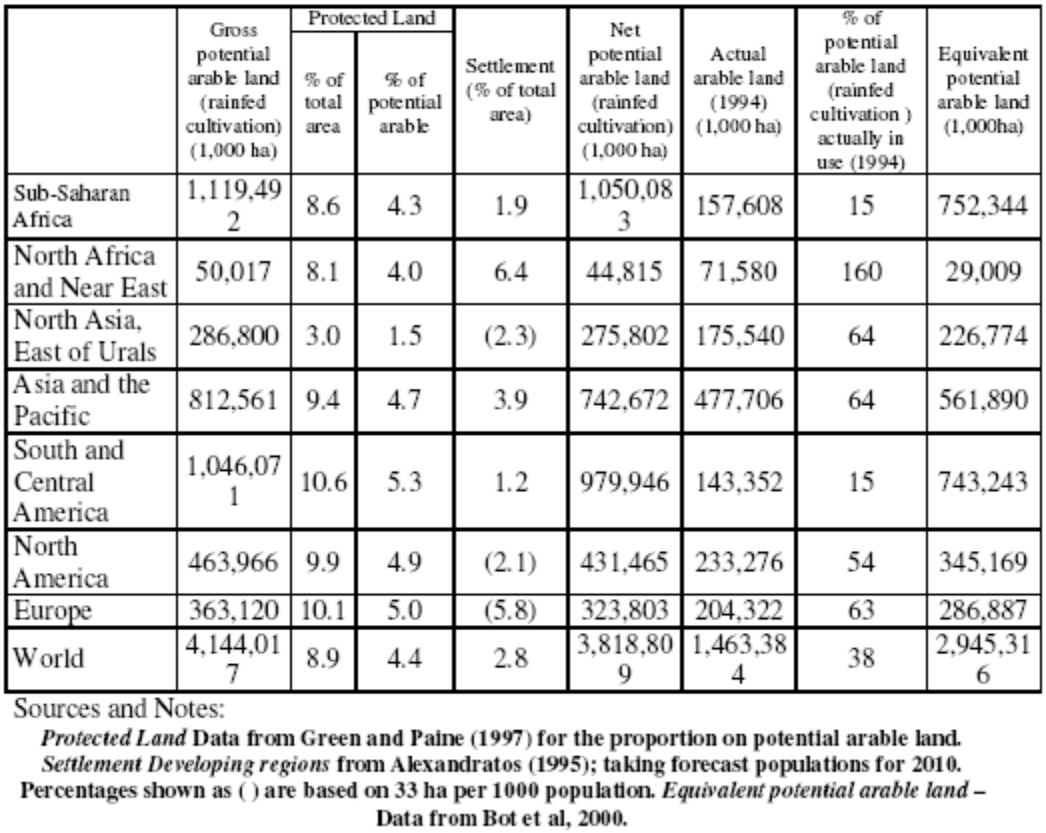
Although, the Quickscan study arrived at a similar land surplus for energy crop production as several prior studies (Wolf and Hoogwijk),[5,10] it calculated bioenergy potentials 60 to 40% higher, mainly by projecting a much higher 2050 yield per acre. This higher yield is justified by future yield improvements and more advanced management practices.

There is considerable room to achieve these higher yields for both energy and conventional crops. The current average photosynthetic efficiency for the global production of biomass is 0.3%. Maximum efficiency for C-3 plants is 3.3% and for C-4 plants is 6.7%. (C-3 and C-4 plants use different metabolic pathways for fixing carbon dioxide: C-4 plants can achieve higher efficiencies.) While achieving maximal levels is unlikely, yields of 2% may be attainable.

These studies have shown considerable theoretical potential bioenergy if the world develops a strategic plan to embrace renewable energy that would drive investment in agricultural production of both food and fuel. Table I.8 probably best summarizes the global potential for bioenergy, with mid-range projections of 250–500 EJ/yr most likely. The higher projections would require a transformation in agricultural production around the world. In contrast, 150 EJ/yr could probably be extracted from crop residues, forest residues, and dung without new agricultural practices but would require infrastructure to collect, transport and convert these commodities.

X. Selected Energy Crop Possibilities

Several studies have investigated the promise of individual crops for bioenergy in the future. Their results help determine the potential for energy crops to make significant contributions with the appropriate drivers in place. Table X.1 details the estimated available land for expanding energy crop production in various regions.[15]



	Gross potential arable land (rainfed cultivation) (1,000 ha)	Protected Land		Settlement (% of total area)	Net potential arable land (rainfed cultivation) (1,000 ha)	Actual arable land (1994) (1,000 ha)	% of potential arable land (rainfed cultivation) actually in use (1994)	Equivalent potential arable land (1,000ha)
		% of total area	% of potential arable					
Sub-Saharan Africa	1,119,492	8.6	4.3	1.9	1,050,083	157,608	15	752,344
North Africa and Near East	50,017	8.1	4.0	6.4	44,815	71,580	160	29,009
North Asia, East of Urals	286,800	3.0	1.5	(2.3)	275,802	175,540	64	226,774
Asia and the Pacific	812,561	9.4	4.7	3.9	742,672	477,706	64	561,890
South and Central America	1,046,071	10.6	5.3	1.2	979,946	143,352	15	743,243
North America	463,966	9.9	4.9	(2.1)	431,465	233,276	54	345,169
Europe	363,120	10.1	5.0	(5.8)	323,803	204,322	63	286,887
World	4,144,017	8.9	4.4	2.8	3,818,809	1,463,384	38	2,945,316

Sources and Notes:

***Protected Land* Data from Green and Paine (1997) for the proportion on potential arable land.**
***Settlement Developing regions* from Alexandratos (1995); taking forecast populations for 2010.**
Percentages shown as ( ) are based on 33 ha per 1000 population. *Equivalent potential arable land* – Data from Bot et al, 2000.

Table X.1. Comparison of actual and potential available land for rain-fed agriculture.[15]

As a perennial and highly productive source of easily fermentable sugars, sugar cane is often promoted as a potential energy crop. For example, just 21 Mha of sugar cane worldwide produce 1,750 Mt/yr of biomass, compared to 2,400 Mt/yr produced by all cereal crops covering more than 700 Mha. In addition, sugarcane bagasse (pulp) is readily available to run ethanol plants or produce electricity.

"Sugarcane can yield in the near term 260 GJ/ha·yr, while the most efficient tropical forests may yield around 135 GJ/ha·yr, when starting from 450 GJ/ha·yr of primary energy. In the long term sugarcane can provide up to 400 GJ/ha·yr, while tropical forests may reach 300 GJ/ha·yr. The major drivers for long-term yields from sugarcane are the use of all above ground biomass (bagasse, juice and barbojo) that can be sustainably harvested, as well as species improvement and dissemination of the best varieties and practices to all plantation sites. For forests (including tropical) genetic improvement, better fertilization and even irrigation (which may not be sustainable due to global water limitations) are considered. In order to obtain 390 GJ/ha·yr of final energy from 860 GJ/ha·yr of primary energy (all above ground biomass average yield by 2020–30) the following assumptions are made:

1) 40% of the barbojo is left on the ground to protect the soil
2) all remaining solid biomass primary energy will be converted to final energy through cogeneration plants.

This last assumption is quite feasible since today most sugar mills produce their entire steam requirement, as well as their electricity needs through the use of cogeneration facilities. It is quite important to observe that the overall conversion efficiency for ethanol and electricity production may approach 55%, which is a high value."[15]

Based on this yield of sugar cane, if a regional program went into effect to further develop sugarcane plantations for energy production in appropriate areas so that a total area of 143 Mha was in production by 2030 yielding 140 tons/ha/yr (wet), the total energy production was calculated. This calculation was also based on assuming that breeding would allow an increase of the sugar content of the cane harvested by 26%. With this in place, the plantations would produce 163.9 EJ/yr of primary energy. This would be done on 4,000 plantations each able to process 25,000 t/day. Table X.2 summarizes these figures.[15]

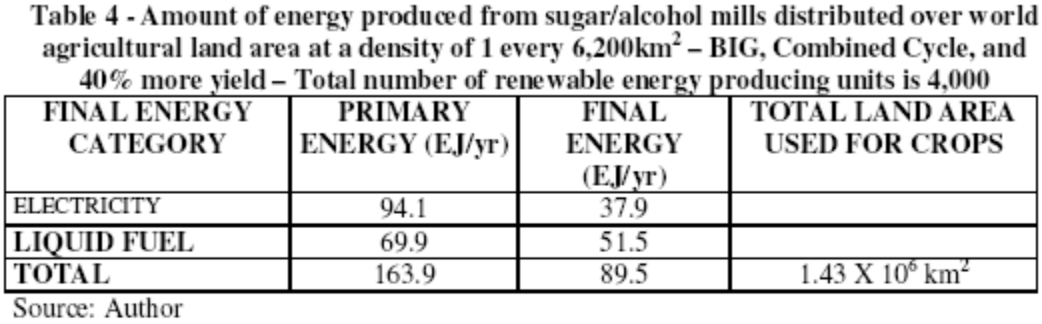


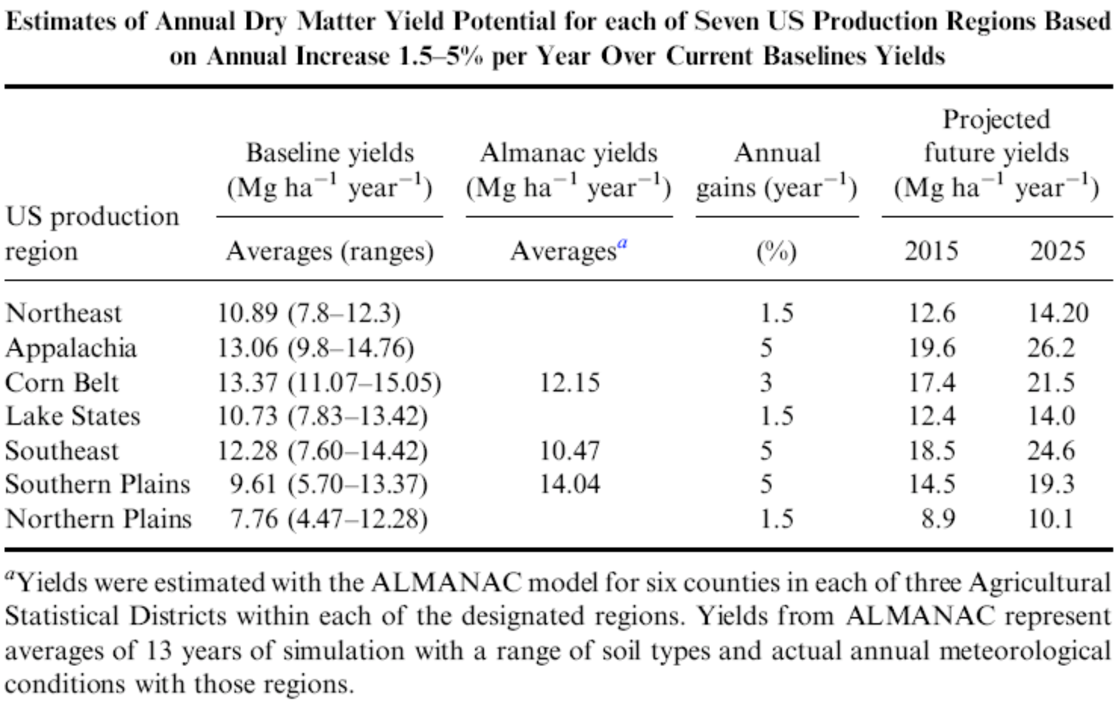
Table 4 - Amount of energy produced from sugar/alcohol mills distributed over world agricultural land area at a density of 1 every 6,200km^2 – BIG, Combined Cycle, and 40% more yield – Total number of renewable energy producing units is 4,000

FINAL ENERGY CATEGORY	PRIMARY ENERGY (EJ/yr)	FINAL ENERGY (EJ/yr)	TOTAL LAND AREA USED FOR CROPS
ELECTRICITY	94.1	37.9	
LIQUID FUEL	69.9	51.5	
TOTAL	163.9	89.5	1.43 X 10^6 km^2

Source: Author

Table X.2. Energy produced from sugar-alcohol mills distributed over world agricultural land area at a density of 1 per 6,200 km^2.[15]

A second energy crop often discussed is switchgrass. This temperate crop is also a perennial and has potential for growth on more sensitive arable land. It has not undergone a long history of breeding and as such may permit significant increases in productivity. Table X.3 shows projections for switchgrass improvement over the next 20 years, with maximal yields in the range of 20–25 Mg/Ha/yr in selected regions.[18] Because switchgrass has an energy content of 17.4 million BTU/Mg (Table X.4), this equates to ~400 GJ/ha. While this projected yield approaches that of sugar cane, as cellulosic biomass, switchgrass would be more difficult to convert to ethanol.



Estimates of Annual Dry Matter Yield Potential for each of Seven US Production Regions Based on Annual Increase 1.5–5% per Year Over Current Baselines Yields

US production region	Baseline yields (Mg ha^{-1} year^{-1})	Almanac yields (Mg ha^{-1} year^{-1})	Annual gains (year^{-1})	Projected future yields (Mg ha^{-1} year^{-1})	
	Averages (ranges)	Averages[a]	(%)	2015	2025
Northeast	10.89 (7.8–12.3)		1.5	12.6	14.20
Appalachia	13.06 (9.8–14.76)		5	19.6	26.2
Corn Belt	13.37 (11.07–15.05)	12.15	3	17.4	21.5
Lake States	10.73 (7.83–13.42)		1.5	12.4	14.0
Southeast	12.28 (7.60–14.42)	10.47	5	18.5	24.6
Southern Plains	9.61 (5.70–13.37)	14.04	5	14.5	19.3
Northern Plains	7.76 (4.47–12.28)		1.5	8.9	10.1

[a] Yields were estimated with the ALMANAC model for six counties in each of three Agricultural Statistical Districts within each of the designated regions. Yields from ALMANAC represent averages of 13 years of simulation with a range of soil types and actual annual meteorological conditions with those regions.

Table X.3. Estimates of annual dry-matter switchgrass yield potential for each of seven U.S. production regions.[18]

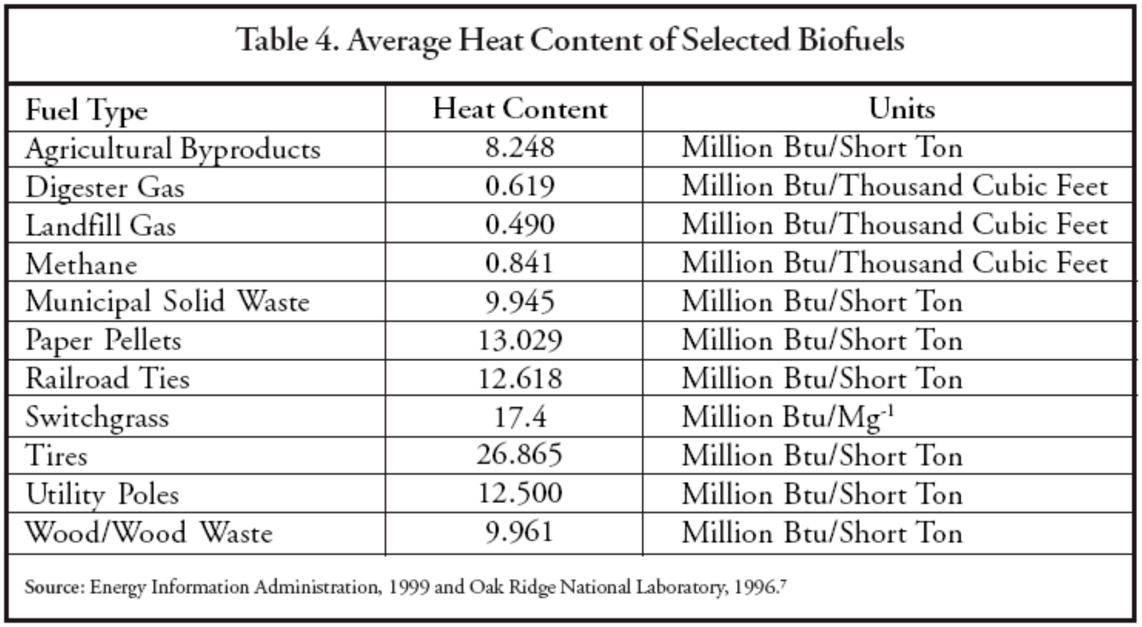


Table 4. Average Heat Content of Selected Biofuels

Fuel Type	Heat Content	Units
Agricultural Byproducts	8.248	Million Btu/Short Ton
Digester Gas	0.619	Million Btu/Thousand Cubic Feet
Landfill Gas	0.490	Million Btu/Thousand Cubic Feet
Methane	0.841	Million Btu/Thousand Cubic Feet
Municipal Solid Waste	9.945	Million Btu/Short Ton
Paper Pellets	13.029	Million Btu/Short Ton
Railroad Ties	12.618	Million Btu/Short Ton
Switchgrass	17.4	Million Btu/Mg^{-1}
Tires	26.865	Million Btu/Short Ton
Utility Poles	12.500	Million Btu/Short Ton
Wood/Wood Waste	9.961	Million Btu/Short Ton

Source: Energy Information Administration, 1999 and Oak Ridge National Laboratory, 1996.[7]

Table X.4. Average heat content of selected biofuels (English units).[19]

Corn is also an energy crop, albeit an annual that also produces a high-protein component. If both the stover and the grain were harvested, its potential yield of biomass would be similar to that of switchgrass or sugar cane. Because corn is an annual crop, some of the stover must be retained to maintain productivity, and, unlike switchgrass, corn cannot be grown on a sensitive landscape. From a pure energy perspective, corn also suffers from the fact that it produces high-protein grain which requires nitrogen fertilizers to maintain productivity. As long as meat production requires the high-protein component, this allows the economical use of the corn carbohydrate fractions for energy production. Recent Monsanto projections for the potential corn improvements via biotechnology indicate the corn yields in the United States could increase from 153 bu/acre today to an average of 300 bu/acre in <what year?>.[20] With moderate acreage increases through drought tolerance traits, this could lead to a national production level of 25 billion bushels, with 20 billion bushels available for ethanol production. Using existing dry-mill technology, this crop would produce about 54 billion gallons of ethanol, 154 million metric tons of distillers dried grain (DDG) and, if the oil were extracted and converted to biodiesel, 6 billion gallons of B100 (100% biodiesel). Because corn-stover yields have historically remained constant at a 1:1 stover:grain mass ratio, 509 million metric tons of stover would also be available at a 15% moisture basis. If 60% were collected and converted to ethanol at a rate of 70 gallons per MT of stover, an extra 18 billion gallons of ethanol would be available from stover for at total biofuel production of 72 billion gallons of ethanol and 6 billion gallons of biodiesel for a total of 6.6 EJ.

A second study on corn production in the United States estimated the effect $60/bbl oil and $4/bu corn prices will have on corn production both in the USA and globally. The study predicted that at $4.05/bu corn and $60/bbl crude oil, corn-based ethanol production would reach 31.5 billion gallons per year in 2015.

Supporting this level of production would require 95.6 million acres of corn to be planted. This increase in acreage would occur because of economic drivers over other crops. Also the corn export market would be lost because non-domestic corn production would also increase to fill those markets.

Total corn production in the USA would be approximately 15.6 billion bushels, compared to 11.0 billion bushels today.[21]

Thus far, the potential of agriculture to produce biomass for energy production has been reviewed. The track record of agricultural improvements, combined with projected declining population growth, indicates that food needs will not limit biomass production. As detailed above, food production has increased since the 1960s even with a decline in real value for commodity crops. This decline has been caused by demand growth, which has not grown at the rate that the supply could have grown.[16] In addition, per acre yields of a variety of commodity crops vary widely, globally depending on not only environmental conditions but also government policies encouraging production. In areas of the world that lack farm support, there has been no impetus to breed better-yielding varieties or to use more-productive farming practices. As suggested by studies projecting biomass production on surplus land, the new demands of bioenergy may shift agricultural economics so that demand actually outstrips supply. This should drive investment in more-efficient farming practices and improved crops for growing regions around the world. As a result, under the correct policies, agriculture in the bioenergy era may potentially provide not only food and fuel but also livelihood for portions of the world now in abject poverty.

A wide variety of studies has projected bioenergy production levels under optimal policies with wide variations in results. Based on a survey of the results, the mid-range of 300–400 EJ from biomass seems feasible by 2050, if not sooner. Most of these studies have avoided examining the competition between food and fuel production, but it seems likely that there would need to be competing demands to drive agricultural investment and therefore production.

Several specific crops have been investigated for bioenergy potential. Increasing sugarcane cultivation from 21 Mha today to 143 Mha, along with projected yield improvements, would produce total primary energy of 169 EJ, which could be converted to 37.9 EJ of electricity and 51.5 EJ of ethanol fuel.[15] Because palm-oil yields per hectare are also relatively high,[17] it is equally promising as a tropical energy crop, if similar acreage growth could occur.

Switchgrass dry-basis yields were estimated to approach 20 to 25 Mg/ha in selected areas of the USA by 2025.[18] This level of production would give energy yields per hectare similar to sugar cane, but as a cellulosic source it would require different technology for conversion to transportation fuel.

Corn is also expected to increase in yield over the coming decades. Future yield gains appear to be increasing rapidly, and a 25 billion bushel U.S. corn crop through moderate expansion in acreage is proposed in 2030, up from approximately 11 billion bushels today.[20] This scale of production could potentially supply 54 billion gallons of ethanol and 6 billion gallons of biodiesel, with enough corn stover to either supply energy for the ethanol plants or produce another 21 billion gallons of ethanol.

The corn, palm, and sugarcane scenarios require crop enhancements and moderate-to-large increases in cultivated acreage. While switchgrass has tremendous potential for bioenergy production in temperate climates on marginal land, it also requires technology to convert biomass to fuel on smaller scale with more distributed production systems.

XI. United States Production Potential

As one of the largest users of energy, the United States is in a position of needing to diversify its sources of energy for economic and strategic reasons. The USA is endowed with large oil, coal, and biomass production potential. This study is focused on the bioenergy potential by 2025. What could the USA produce in the form of bioenergy? In one scenario described above, corn potentially could be producing 6 EJ of ethanol. This is about the equivalent of 33% of our current gasoline usage. Is the potential larger? In 2005, Oak Ridge National Laboratory published “the Billion Ton Study,”[22] that explores the potential supply of biomass for energy production within the USA. Several key assumptions underlie the report’s conclusions. For agricultural production, yields of grain were projected to increase by 50% by 2030. Soybeans were assumed to be selected for varieties that increase the residue-to-oilseed ratio to 2:1. Future harvest equipment was envisioned to recover 75% of the residue, with all cropland converted to no-till methods to allow this recovery level without topsoil destruction. In addition, all manure and other residues in excess of that applied to land was assumed to be converted to biofuels. Through the increased crop yields per acre, 55 million acres could be converted to energy crop production from food production.

For forestry production only forest lands with current road accessibility were included, environmentally sensitive areas were omitted, equipment recovery limitations were considered, and production was split into usage categories of conventional forest products, energy and biomaterials. Results are shown in the following tables and figures.

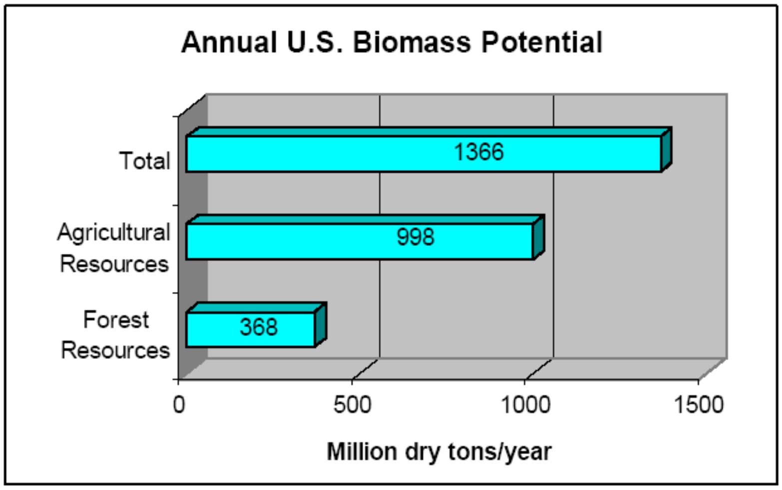
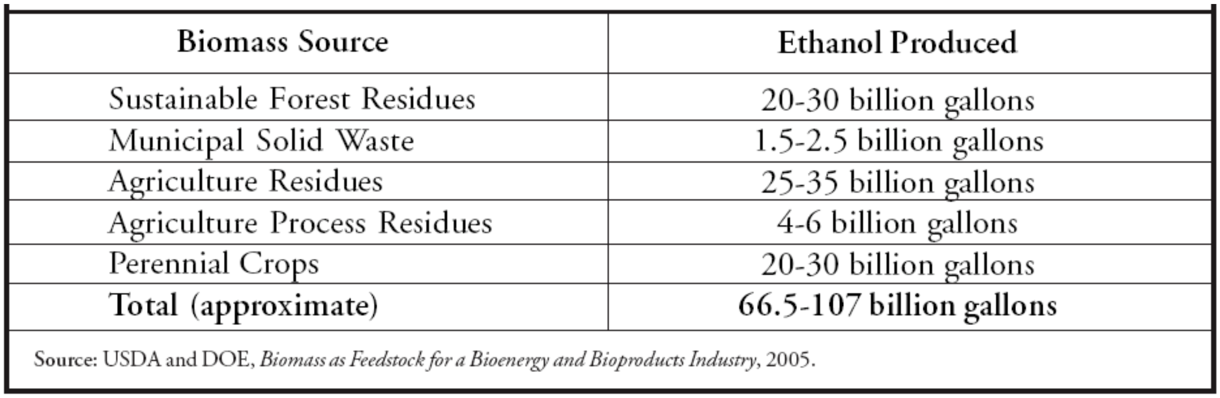


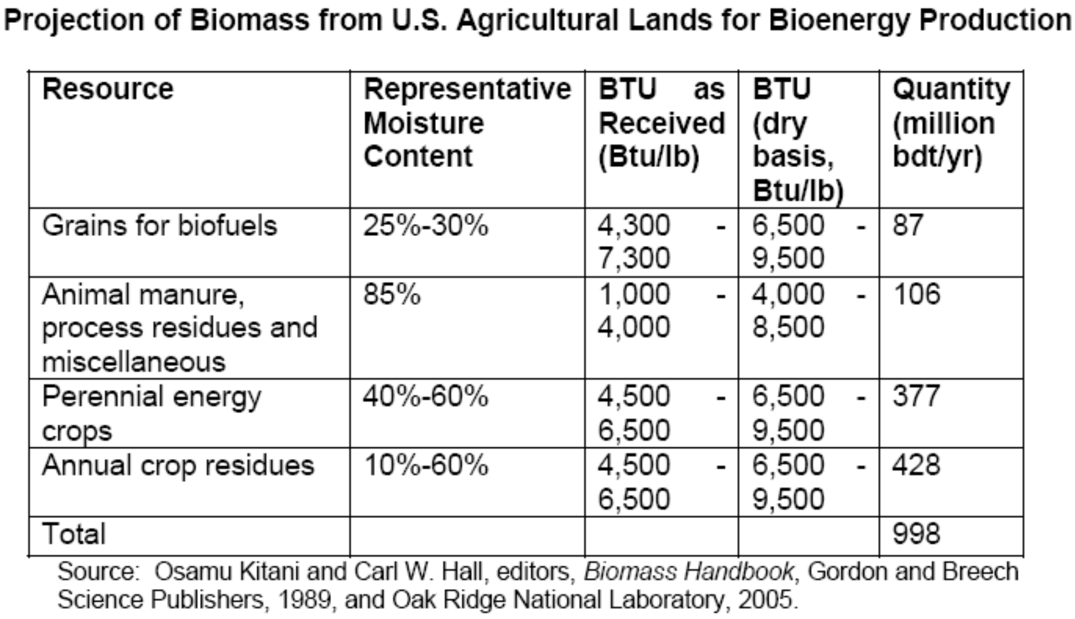
Table XI.1. Annual U.S. biomass potential.[22]



Biomass Source	Ethanol Produced
Sustainable Forest Residues	20-30 billion gallons
Municipal Solid Waste	1.5-2.5 billion gallons
Agriculture Residues	25-35 billion gallons
Agriculture Process Residues	4-6 billion gallons
Perennial Crops	20-30 billion gallons
Total (approximate)	**66.5-107 billion gallons**

Source: USDA and DOE, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry*, 2005.

Table XI.2. Ethanol potential from cellulosic feedstock assuming a 70 gallon/ton yield.[19]

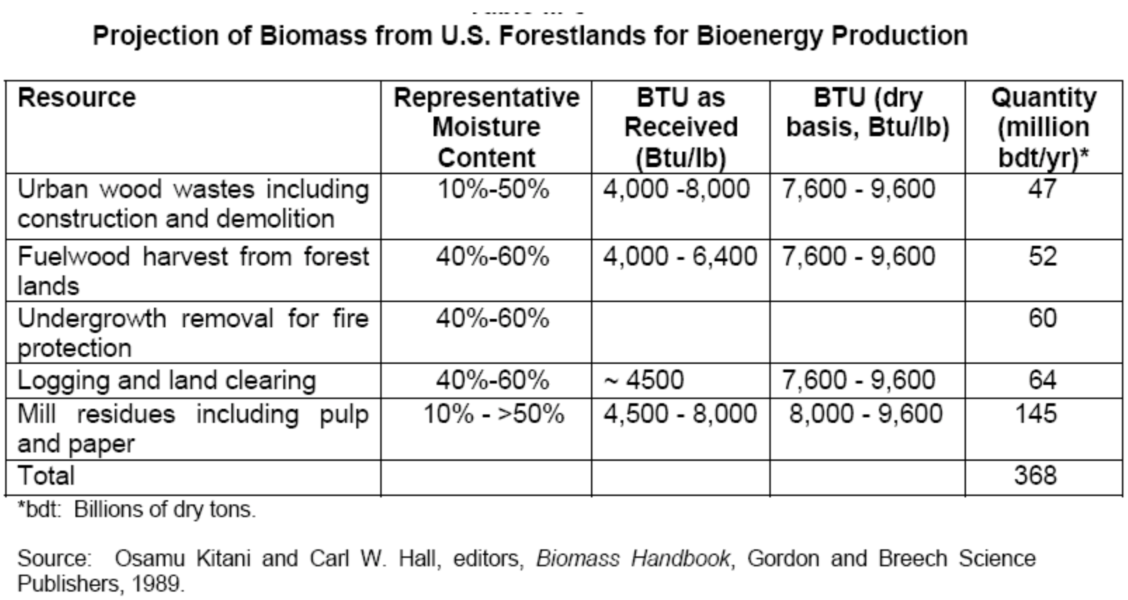


Projection of Biomass from U.S. Agricultural Lands for Bioenergy Production

Resource	Representative Moisture Content	BTU as Received (Btu/lb)	BTU (dry basis, Btu/lb)	Quantity (million bdt/yr)
Grains for biofuels	25%-30%	4,300 - 7,300	6,500 - 9,500	87
Animal manure, process residues and miscellaneous	85%	1,000 - 4,000	4,000 - 8,500	106
Perennial energy crops	40%-60%	4,500 - 6,500	6,500 - 9,500	377
Annual crop residues	10%-60%	4,500 - 6,500	6,500 - 9,500	428
Total				998

Source: Osamu Kitani and Carl W. Hall, editors, *Biomass Handbook*, Gordon and Breech Science Publishers, 1989, and Oak Ridge National Laboratory, 2005.

Table XI.3. Projection of biomass from U.S. agricultural lands for bioenergy production.[23]



Projection of Biomass from U.S. Forestlands for Bioenergy Production

Resource	Representative Moisture Content	BTU as Received (Btu/lb)	BTU (dry basis, Btu/lb)	Quantity (million bdt/yr)*
Urban wood wastes including construction and demolition	10%-50%	4,000 -8,000	7,600 - 9,600	47
Fuelwood harvest from forest lands	40%-60%	4,000 - 6,400	7,600 - 9,600	52
Undergrowth removal for fire protection	40%-60%			60
Logging and land clearing	40%-60%	~ 4500	7,600 - 9,600	64
Mill residues including pulp and paper	10% - >50%	4,500 - 8,000	8,000 - 9,600	145
Total				368

*bdt: Billions of dry tons.

Source: Osamu Kitani and Carl W. Hall, editors, *Biomass Handbook*, Gordon and Breech Science Publishers, 1989.

Table XI.4. Projection of biomass from U.S. forest lands for bioenergy production.[23]

The billion-ton study indicates that with changes in agricultural and forestry practices to maximize biofuel production, the USA could produce up to 1.3 billion tons of biomass for energy production. Assuming a yield of 70 gallons of ethanol per dry ton, this crop could produce 91 billion gallons of ethanol.

	Land required within a given radius to feed plant of given size,[1] %				
Feedstock collection radius, miles	**Plant size at 90% capacity, tons/day**				
	500	**1000**	**5000**	**10000**	**20000**
10	6.5	13.1	65.5	-	-
20	1.6	3.3	16.4	32.7	65
30	0.7	1.5	7.3	14.6	29
40	0.4	0.8	4.1	8.2	16.4
50	0.3	0.5	2.6	5.2	10.5
60	0.2	0.4	1.8	3.6	7.3
70	0.1	0.3	1.3	2.7	5.3
Ethanol production,[2] million gal/yr	12	24	122	244	488

[1] 12.5 tons/acre of switchgrass
[2] 70 gallons of ethanol/ton

Table XI.5. Percent of land required within a given radius to feed several plant sizes.[24]

As the preceding studies suggest, the development of significant supplies of biomass for energy in the near future is feasible. Actual conversion of this source into usable fuels will depend on the technical competence to convert it into useful, transportable fuels. Biomass is, in general, broadly distributed, whether from forestry wastes, agricultural wastes, or dedicated energy crops. Table XI.5 indicates the availability of feedstock under current tillage practices and the potential if no-till is developed fully within a 50-mile radius in the agricultural producing region of the USA. Large plants processing 1000 bone dry ton (bdt)/day are possible in areas with highly concentrated biomass sources such as sugarcane plantations, but in order to fully utilize biomass potential efficient plants that utilize on the order of 500 bdt/day will be needed. The table below indicates the collection area requirements for plants of various scales using a dedicated energy crop that produces on average 12.5 tons per acre of dry biomass, such as switch grass. Highly promising crop residues sources such as corn stover yield only approximately 3 tons per acre of harvestable biomass, placing a further limitation on plant size. Smaller plants capable of using multiple feedstocks would be less vulnerable to changes in local production than large ones dedicated to single crops. Developing technologies, which can efficiently operate at small scales, will be crucial to bioenergy success.

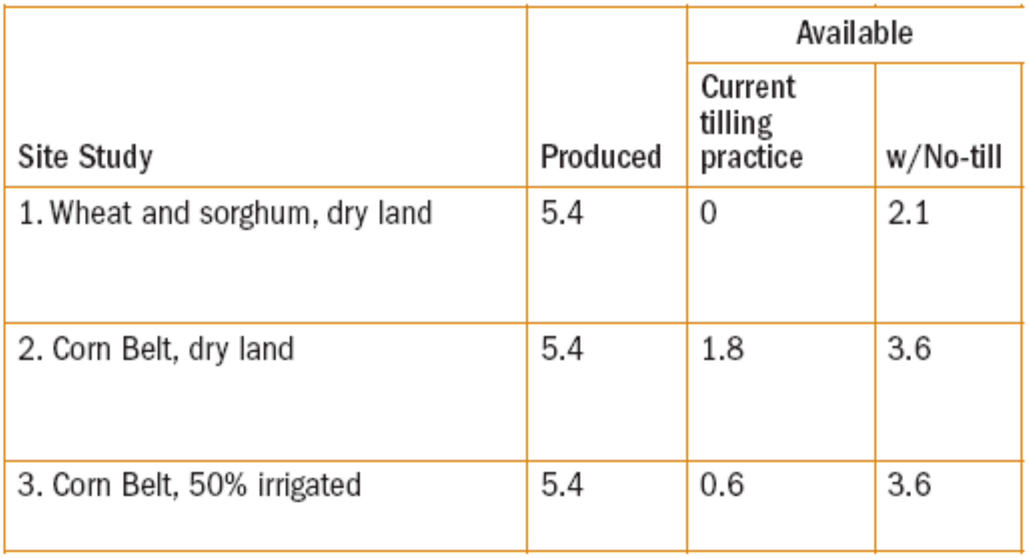
Because biomass in general has a low density and comes from disperse sources, bioenergy faces unique logistical challenges. The energy and economic expense of biomass transportation and storage necessitate local conversion technologies. Successful biorefineries will require large, reliable feedstock sources. Using current ethanol technologies, the yield of ethanol per dry ton of feedstock is about 65 gallons per ton, while future technologies may afford up to 100 gallons per ton. At 65 gallons per ton, a mid-size ethanol plant (65 million gallon per year) would require 1 million dry tons or about 3,000 tons per day. Using crop residues, such a plant would require 500,000 acres or more of land or most of the residue from land within a 15-mile supply radius (see Figure XI.6). Therefore, small biorefineries based on crop residues would require the following practices to be developed:[25]

1) Large Area: Minimum of 500,000 acres of available cropland
2) Sustainable: Cropping practice to maintain or enhance long-term health of the soil
3) Reliable: Consistent crop supply history with dry harvest weather
4) Economic: High-yielding cropland.

Larger facilities could be developed if rail transportation would be available, although the logistics of integrating truck and rail transport would add extra costs.

The cost of biomass at the refinery is one of the key variables discussed in many articles. Often, $25/ton at the refinery gate is cited as a potential price. While this may be the current case at selected locations, if a true market develops for bioenergy crops and crop residues, then new economics will probably come into play. A more likely estimate is $50 per dry ton, including the cost of collecting crop residues and a $20 margin for the farmers supplying the residue.[25]

Table XI.7 shows the economics of crop residue collection of baling versus one-pass harvesting, bulk storage, and rail transport to a processing plant with $50 delivered cost.



Site Study	Produced	Available	
		Current tilling practice	w/No-till
1. Wheat and sorghum, dry land	5.4	0	2.1
2. Corn Belt, dry land	5.4	1.8	3.6
3. Corn Belt, 50% irrigated	5.4	0.6	3.6

Table XI.6. Feedstock production and availability in a 50-mile radius (million dry tons).[25]

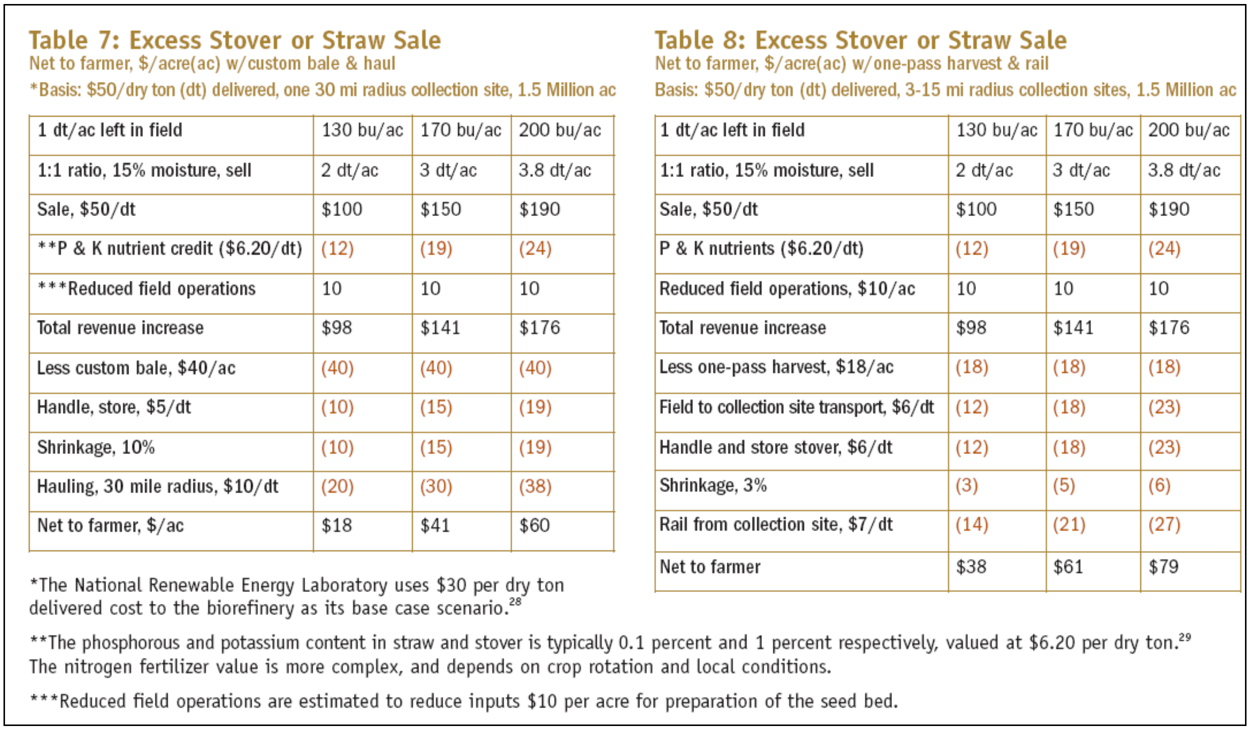


Table 7: Excess Stover or Straw Sale

Net to farmer, $/acre(ac) w/custom bale & haul

*Basis: $50/dry ton (dt) delivered, one 30 mi radius collection site, 1.5 Million ac

1 dt/ac left in field	130 bu/ac	170 bu/ac	200 bu/ac
1:1 ratio, 15% moisture, sell	2 dt/ac	3 dt/ac	3.8 dt/ac
Sale, $50/dt	$100	$150	$190
**P & K nutrient credit ($6.20/dt)	(12)	(19)	(24)
***Reduced field operations	10	10	10
Total revenue increase	$98	$141	$176
Less custom bale, $40/ac	(40)	(40)	(40)
Handle, store, $5/dt	(10)	(15)	(19)
Shrinkage, 10%	(10)	(15)	(19)
Hauling, 30 mile radius, $10/dt	(20)	(30)	(38)
Net to farmer, $/ac	$18	$41	$60

Table 8: Excess Stover or Straw Sale

Net to farmer, $/acre(ac) w/one-pass harvest & rail

Basis: $50/dry ton (dt) delivered, 3-15 mi radius collection sites, 1.5 Million ac

1 dt/ac left in field	130 bu/ac	170 bu/ac	200 bu/ac
1:1 ratio, 15% moisture, sell	2 dt/ac	3 dt/ac	3.8 dt/ac
Sale, $50/dt	$100	$150	$190
P & K nutrients ($6.20/dt)	(12)	(19)	(24)
Reduced field operations, $10/ac	10	10	10
Total revenue increase	$98	$141	$176
Less one-pass harvest, $18/ac	(18)	(18)	(18)
Field to collection site transport, $6/dt	(12)	(18)	(23)
Handle and store stover, $6/dt	(12)	(18)	(23)
Shrinkage, 3%	(3)	(5)	(6)
Rail from collection site, $7/dt	(14)	(21)	(27)
Net to farmer	$38	$61	$79

*The National Renewable Energy Laboratory uses $30 per dry ton delivered cost to the biorefinery as its base case scenario.[28]

**The phosphorous and potassium content in straw and stover is typically 0.1 percent and 1 percent respectively, valued at $6.20 per dry ton.[29] The nitrogen fertilizer value is more complex, and depends on crop rotation and local conditions.

***Reduced field operations are estimated to reduce inputs $10 per acre for preparation of the seed bed.

Table XI.7. Excess stover or straw sales.[25]

In a study of the economics of corn stover harvest and transport in Minnesota for a 50 million gallon per year ethanol plant, the marginal stover cost was estimated to be between $54 and $65 a dry ton, depending on the harvesting method.[26]

Even with a mature bioenergy crop production scenario, the acreage planted will depend heavily on the price offered for the crop. Figure III.7 shows the effect of price offered for switchgrass and the acreage planted.[27]

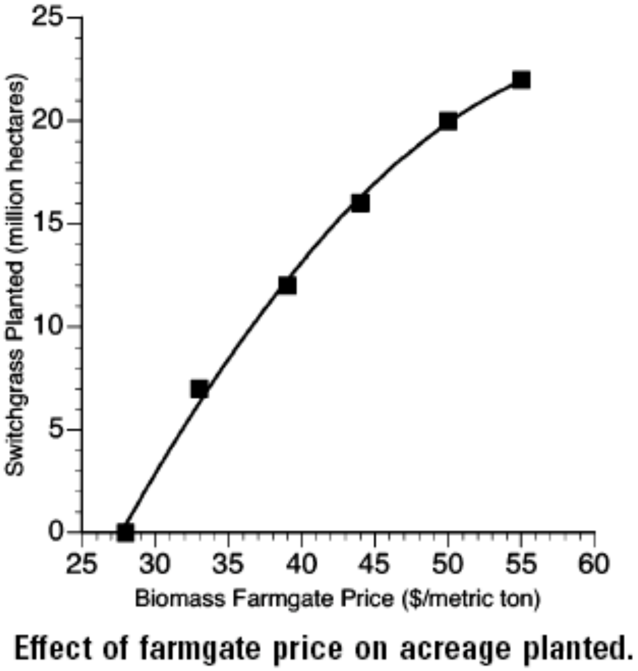


Figure III.7. Effect of farm-gate price on acreage planted.[27]

Transportation costs are a key factor in determining the size of a mature bioenergy industry, which can maximize the acreage planted in energy crops. Truck costs are estimated at $0.22 per ton-mile and rail costs at $0.07 per ton-mile. Conversion processes that can be scaled to local production and transportation systems will be needed.[27]

XII. Biomass Conversion Technologies

The definition of energy crops will change as technologies develop to convert the various types of biomass into more useful fuels in the future. Current technologies such as direct combustion and the production of ethanol or biodiesel have made wood, dung, cereals, sugar crops, and oilseeds the current leaders in bioenergy crops. The development of technologies to convert lignin and cellulose more efficiently into useful fuel may change the direction of energy crop development. Figure XII.1 diagrams some of the flow patterns of commonly used biomass fuel.[28]

The development of new bioenergy crops based on lignocellulose face several hurdles. The first issue of logistics has already been discussed. At 20 cents per mile per ton transportation cost this equates to about a $4 charge per ton for a plant drawing on biomass within a 30 mile radius. Providing a $25/ton margin for the farmer as well as paying for collection, fertilizer needs, and handling will rapidly bring the cost at the plant gate to over $50 dollars a dry ton. Using current technology with yields in the range of 70 gallons of ethanol per ton, the minimum feedstock contribution to the ethanol cost will be 70 cents per gallon. Processing costs will have to be minimized and economies of scale that fit the distributed nature of biomass feedstocks will need to be developed to make this a profitable venture.

There are a variety of technologies being looked at for biomass conversion. The first and most efficient is direct combustion for electricity and heat generation. This is a relatively mature technology and the major limitation for its growth is the economy of scale. Biomass can only play a role as a co-firing feed unless a more distributed power generation technology is developed. If so, some of the energy loss in distributing electricity would be minimized. See Table XII.2 for some current technology efficiencies.

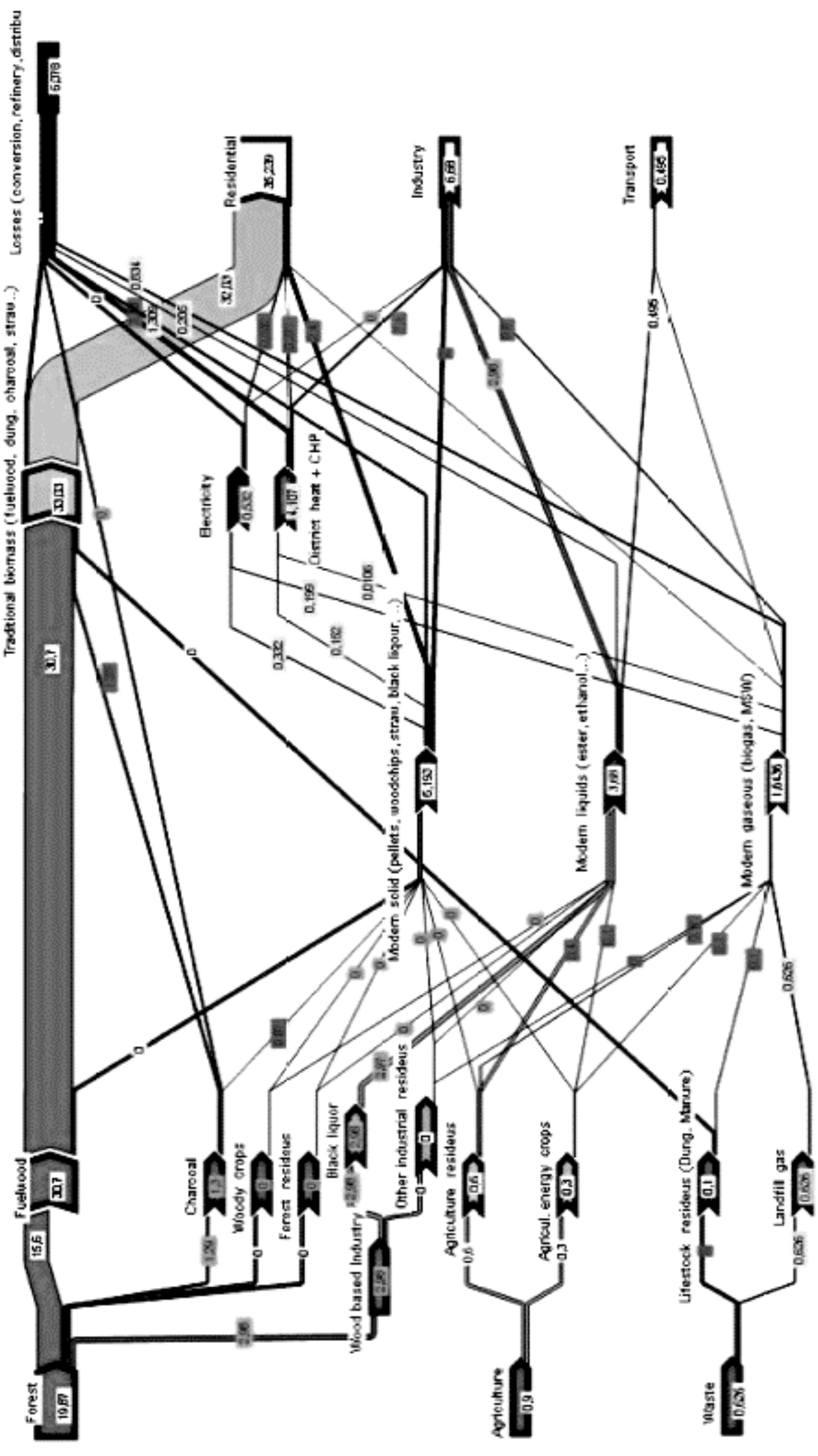


Fig. 1 Global biomass energy flows (EJ) to produce heat, power and transport fuels (the width of the line is proportional to the flow).

Figure XII.1. Flow patterns of commonly used biomass fuel.[28]

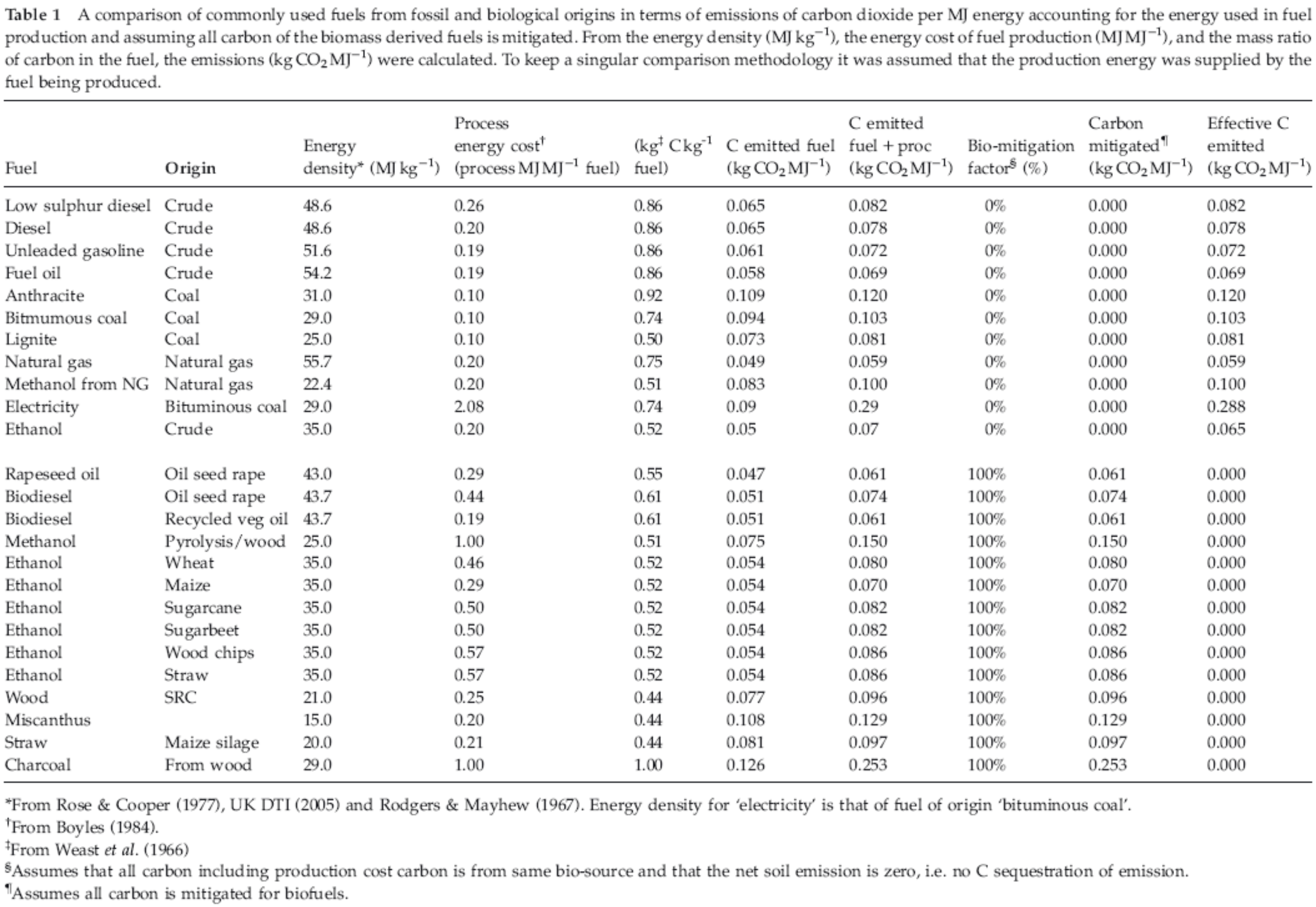


Table 1 A comparison of commonly used fuels from fossil and biological origins in terms of emissions of carbon dioxide per MJ energy accounting for the energy used in fuel production and assuming all carbon of the biomass derived fuels is mitigated. From the energy density (MJ kg^{-1}), the energy cost of fuel production (MJ MJ^{-1}), and the mass ratio of carbon in the fuel, the emissions (kg CO_2 MJ^{-1}) were calculated. To keep a singular comparison methodology it was assumed that the production energy was supplied by the fuel being produced.

Fuel	**Origin**	Energy density* (MJ kg^{-1})	Process energy cost† (process MJ MJ^{-1} fuel)	(kg‡ C kg^{-1} fuel)	C emitted fuel (kg CO_2 MJ^{-1})	C emitted fuel + proc (kg CO_2 MJ^{-1})	Bio-mitigation factor§ (%)	Carbon mitigated¶ (kg CO_2 MJ^{-1})	Effective C emitted (kg CO_2 MJ^{-1})
Low sulphur diesel	Crude	48.6	0.26	0.86	0.065	0.082	0%	0.000	0.082
Diesel	Crude	48.6	0.20	0.86	0.065	0.078	0%	0.000	0.078
Unleaded gasoline	Crude	51.6	0.19	0.86	0.061	0.072	0%	0.000	0.072
Fuel oil	Crude	54.2	0.19	0.86	0.058	0.069	0%	0.000	0.069
Anthracite	Coal	31.0	0.10	0.92	0.109	0.120	0%	0.000	0.120
Bitmumous coal	Coal	29.0	0.10	0.74	0.094	0.103	0%	0.000	0.103
Lignite	Coal	25.0	0.10	0.50	0.073	0.081	0%	0.000	0.081
Natural gas	Natural gas	55.7	0.20	0.75	0.049	0.059	0%	0.000	0.059
Methanol from NG	Natural gas	22.4	0.20	0.51	0.083	0.100	0%	0.000	0.100
Electricity	Bituminous coal	29.0	2.08	0.74	0.09	0.29	0%	0.000	0.288
Ethanol	Crude	35.0	0.20	0.52	0.05	0.07	0%	0.000	0.065
Rapeseed oil	Oil seed rape	43.0	0.29	0.55	0.047	0.061	100%	0.061	0.000
Biodiesel	Oil seed rape	43.7	0.44	0.61	0.051	0.074	100%	0.074	0.000
Biodiesel	Recycled veg oil	43.7	0.19	0.61	0.051	0.061	100%	0.061	0.000
Methanol	Pyrolysis/wood	25.0	1.00	0.51	0.075	0.150	100%	0.150	0.000
Ethanol	Wheat	35.0	0.46	0.52	0.054	0.080	100%	0.080	0.000
Ethanol	Maize	35.0	0.29	0.52	0.054	0.070	100%	0.070	0.000
Ethanol	Sugarcane	35.0	0.50	0.52	0.054	0.082	100%	0.082	0.000
Ethanol	Sugarbeet	35.0	0.50	0.52	0.054	0.082	100%	0.082	0.000
Ethanol	Wood chips	35.0	0.57	0.52	0.054	0.086	100%	0.086	0.000
Ethanol	Straw	35.0	0.57	0.52	0.054	0.086	100%	0.086	0.000
Wood	SRC	21.0	0.25	0.44	0.077	0.096	100%	0.096	0.000
Miscanthus		15.0	0.20	0.44	0.108	0.129	100%	0.129	0.000
Straw	Maize silage	20.0	0.21	0.44	0.081	0.097	100%	0.097	0.000
Charcoal	From wood	29.0	1.00	1.00	0.126	0.253	100%	0.253	0.000

*From Rose & Cooper (1977), UK DTI (2005) and Rodgers & Mayhew (1967). Energy density for 'electricity' is that of fuel of origin 'bituminous coal'.

†From Boyles (1984).

‡From Weast *et al*. (1966)

§Assumes that all carbon including production cost carbon is from same bio-source and that the net soil emission is zero, i.e. no C sequestration of emission.

¶Assumes all carbon is mitigated for biofuels.

Table XII.1. Comparison of commonly used fuel properties.[28]

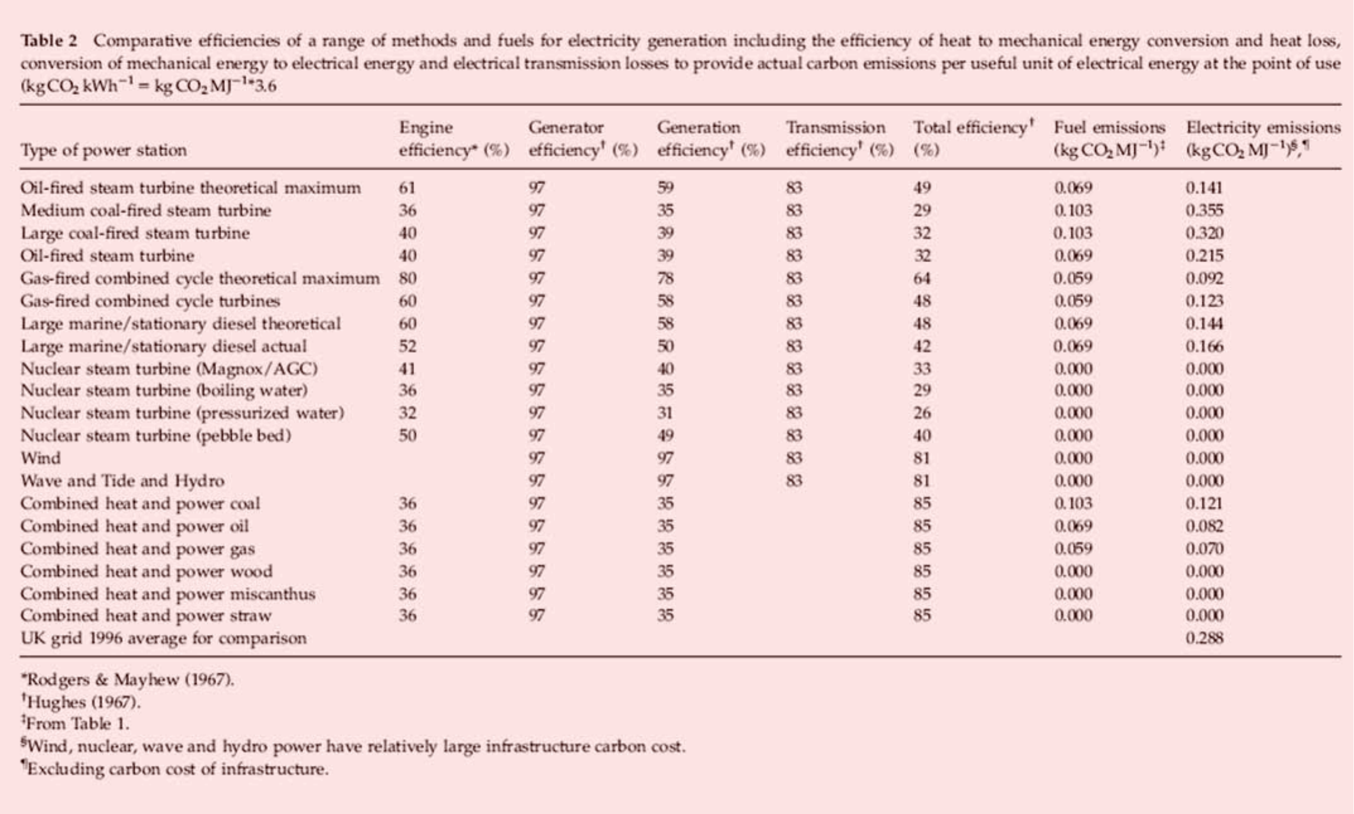


Table 2 Comparative efficiencies of a range of methods and fuels for electricity generation including the efficiency of heat to mechanical energy conversion and heat loss, conversion of mechanical energy to electrical energy and electrical transmission losses to provide actual carbon emissions per useful unit of electrical energy at the point of use ($kg CO_2 kWh^{-1} = kg CO_2 MJ^{-1}*3.6$

Type of power station	Engine efficiency* (%)	Generator efficiency† (%)	Generation efficiency† (%)	Transmission efficiency† (%)	Total efficiency† (%)	Fuel emissions ($kg CO_2 MJ^{-1}$)‡	Electricity emissions ($kg CO_2 MJ^{-1}$)§,¶
Oil-fired steam turbine theoretical maximum	61	97	59	83	49	0.069	0.141
Medium coal-fired steam turbine	36	97	35	83	29	0.103	0.355
Large coal-fired steam turbine	40	97	39	83	32	0.103	0.320
Oil-fired steam turbine	40	97	39	83	32	0.069	0.215
Gas-fired combined cycle theoretical maximum	80	97	78	83	64	0.059	0.092
Gas-fired combined cycle turbines	60	97	58	83	48	0.059	0.123
Large marine/stationary diesel theoretical	60	97	58	83	48	0.069	0.144
Large marine/stationary diesel actual	52	97	50	83	42	0.069	0.166
Nuclear steam turbine (Magnox/AGC)	41	97	40	83	33	0.000	0.000
Nuclear steam turbine (boiling water)	36	97	35	83	29	0.000	0.000
Nuclear steam turbine (pressurized water)	32	97	31	83	26	0.000	0.000
Nuclear steam turbine (pebble bed)	50	97	49	83	40	0.000	0.000
Wind		97	97	83	81	0.000	0.000
Wave and Tide and Hydro		97	97	83	81	0.000	0.000
Combined heat and power coal	36	97	35		85	0.103	0.121
Combined heat and power oil	36	97	35		85	0.069	0.082
Combined heat and power gas	36	97	35		85	0.059	0.070
Combined heat and power wood	36	97	35		85	0.000	0.000
Combined heat and power miscanthus	36	97	35		85	0.000	0.000
Combined heat and power straw	36	97	35		85	0.000	0.000
UK grid 1996 average for comparison							0.288

*Rodgers & Mayhew (1967).
†Hughes (1967).
‡From Table 1.
§Wind, nuclear, wave and hydro power have relatively large infrastructure carbon cost.
¶Excluding carbon cost of infrastructure.

Table XII.2. Comparative efficiencies of a range of methods and fuels for electricity generation.[28]

A second technology for the conversion of biomass that is being looked at seriously is the production of ethanol by fermentation. This technology has several deficiencies in its current state. Lignocellulose is not of a set composition so that the technology for converting wheat straw may not be the same as that needed for corn stover or woody biomass. This severely limits a production plant often to a single feedstock, which could have serious consequences if local conditions for that feedstock's production changes.

A second issue with biomass is its recalcitrance to conversion to free sugars for fermentation. Lignocellulose was developed by nature to be a structural material. As such it is not readily digested or hydrated. It has a relatively crystalline nature. Pretreatment technologies are being developed to overcome these limitations. They are strong acid, weak acid, enzymatic treatments, mixtures of these methods, steam explosion with and without acid, and alkaline treatment such as ammonia. Strong acid technology is relatively straightforward and is run at low temperatures. Its major limitation is that it requires efficient recovery of the acid. Weak acid recovers both pentose and glucose streams, requires two steps, one for the recovery of the pentose and one for the glucose. While this produces less inhibitors, it may still require cleanup prior to fermentation. Steam explosion and alkaline treatment open up the cellulose to provide more surface area for enzymatic attack. The final process is enzymatic. This has lately seen the most research. In this process, some pretreatment is carried out to break up the lignin-cellulose interactions and open up the hemicellulose and cellulose to enzymatic attack. This technology has issues with enzyme costs, length of time needed for depolymerization of the cellulose, dilute nature of the process because of the water-holding capacity of the cellulose, the specificity of the enzymes for individual feedstocks, and feedback inhibition of the enzymes by glucose. With the other processes it also has issues with the development of fermentation inhibitors in the pretreatment stage.

The development of fermentation technology to deal with the products from biomass conversion is also problematic. The dilute-acid and enzymatic processes produce dilute sugar streams. Because both the pentoses and hexoses are available for fermentation, the development of micro-organisms to ferment both sugars simultaneously is a goal of fermentation-culture development. With the enzymatic processes, simultaneous saccharification and fermentation processes are being developed to overcome the glucose inhibition of the enzymes. While overcoming the inhibition, the enzymatic process must be run at the temperature optimum of the fermentation culture rather than the enzyme system. Long fermentation times required to match the enzyme activity for the fermentation can lead to sluggish microbial systems and open the process up to contamination from other micro-organisms, lowering the yield of ethanol. With all of these processes, unlike cereal crops or sugar cane, there are no other nutrients for culture growth in the hydrolysates that necessitate the addition of nutrients to the media for successful fermentations.

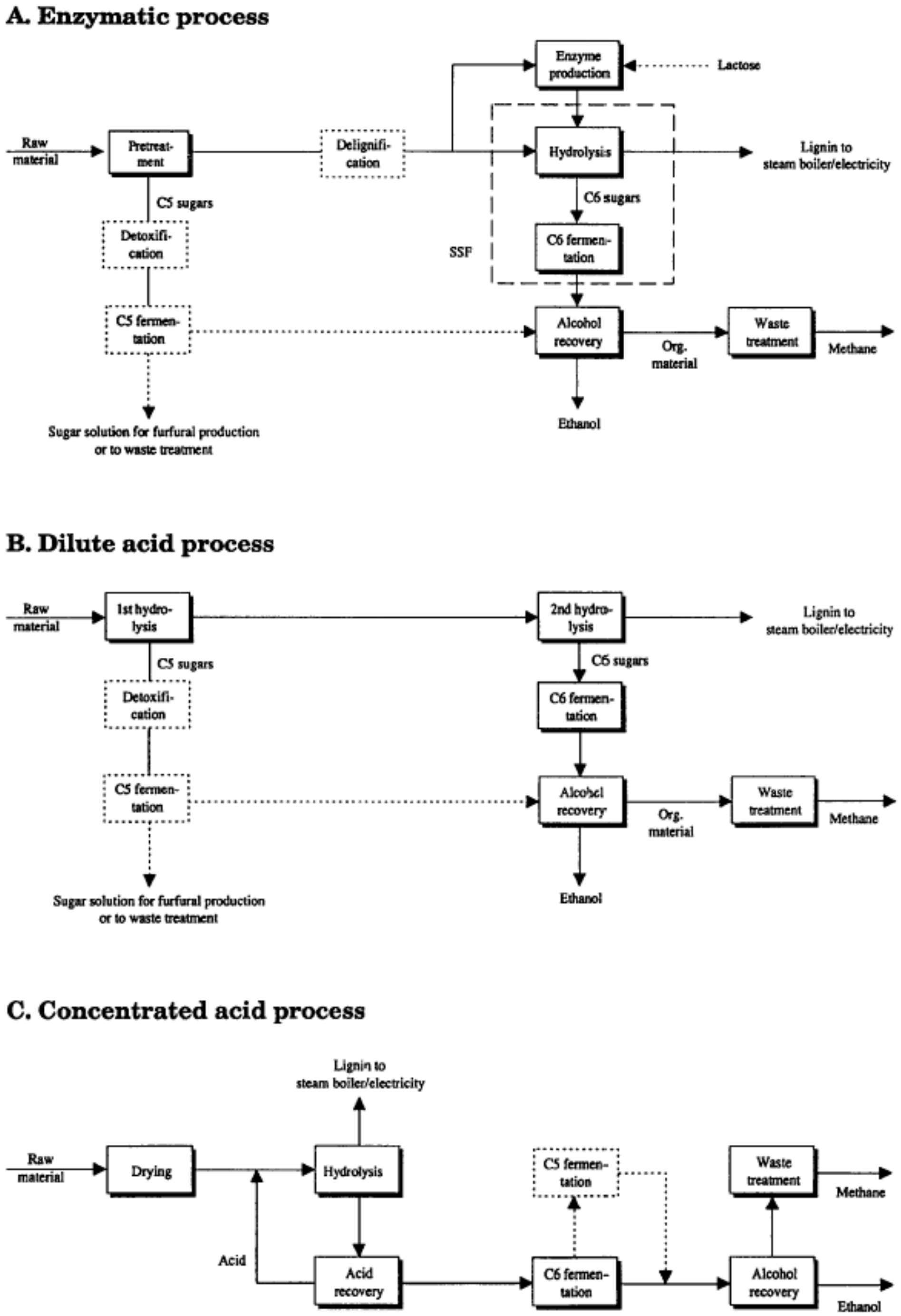


Fig. 1. Block diagrams of the different process configurations.

Figure XII.2 Proposed configurations for the use of waste products from the lignocellulosic conversion process to be used as energy source for running the production of ethanol.[29]

Energy requirements for cellulosic fermentations are somewhat higher than for conventional ethanol fermentation because of the more dilute nature of the processes. The waste products of the lignocellulosic conversion process are proposed to be used as energy source for running the production of ethanol, which leads to the higher fossil energy efficiencies proposed for these processes. Figure XII.2 diagrams proposed configurations for these processes.[29]

Table XII.3 shows some of the economics assumed in a variety of studies in the literature.[29] Ethanol yield is only calculated on the actual yield over the theoretical yield from the hexoses present in the feedstock, not the pentoses.

In the GREET model developed at ORNL, the future energy efficiency of cellulosic ethanol production by fermentation was projected.[30] At cellulosic ethanol plants, the unfermentable biomass components, primarily lignin, can be used to generate steam (needed in ethanol plants) and electricity in cogeneration systems. Recent simulations of cellulosic ethanol production by NREL indicated an ethanol yield of 76 gal per dry ton of hardwood biomass for ethanol plants that will be in operation around the year 2005. Such ethanol plants consume 2,719 Btu of diesel fuel and generate 1.73 kWh of electricity per gallon of ethanol produced.

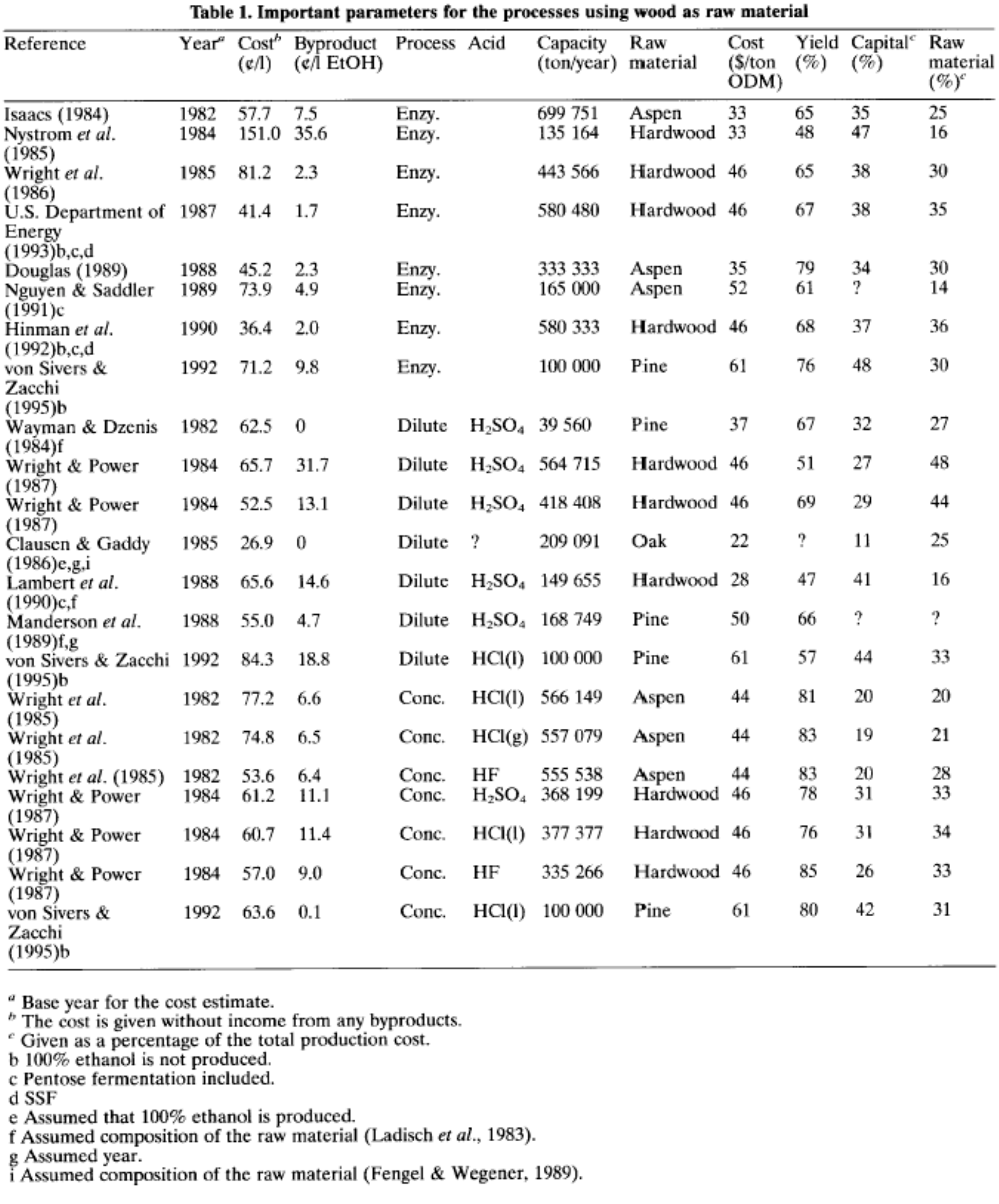


Table 1. Important parameters for the processes using wood as raw material

Reference	Year[a]	Cost[b] (¢/l)	Byproduct (¢/l EtOH)	Process	Acid	Capacity (ton/year)	Raw material	Cost ($/ton ODM)	Yield (%)	Capital[c] (%)	Raw material (%)[c]
Isaacs (1984)	1982	57.7	7.5	Enzy.		699 751	Aspen	33	65	35	25
Nystrom *et al.* (1985)	1984	151.0	35.6	Enzy.		135 164	Hardwood	33	48	47	16
Wright *et al.* (1986)	1985	81.2	2.3	Enzy.		443 566	Hardwood	46	65	38	30
U.S. Department of Energy (1993)b,c,d	1987	41.4	1.7	Enzy.		580 480	Hardwood	46	67	38	35
Douglas (1989)	1988	45.2	2.3	Enzy.		333 333	Aspen	35	79	34	30
Nguyen & Saddler (1991)c	1989	73.9	4.9	Enzy.		165 000	Aspen	52	61	?	14
Hinman *et al.* (1992)b,c,d	1990	36.4	2.0	Enzy.		580 333	Hardwood	46	68	37	36
von Sivers & Zacchi (1995)b	1992	71.2	9.8	Enzy.		100 000	Pine	61	76	48	30
Wayman & Dzenis (1984)f	1982	62.5	0	Dilute	H_2SO_4	39 560	Pine	37	67	32	27
Wright & Power (1987)	1984	65.7	31.7	Dilute	H_2SO_4	564 715	Hardwood	46	51	27	48
Wright & Power (1987)	1984	52.5	13.1	Dilute	H_2SO_4	418 408	Hardwood	46	69	29	44
Clausen & Gaddy (1986)e,g,i	1985	26.9	0	Dilute	?	209 091	Oak	22	?	11	25
Lambert *et al.* (1990)c,f	1988	65.6	14.6	Dilute	H_2SO_4	149 655	Hardwood	28	47	41	16
Manderson *et al.* (1989)f,g	1988	55.0	4.7	Dilute	H_2SO_4	168 749	Pine	50	66	?	?
von Sivers & Zacchi (1995)b	1992	84.3	18.8	Dilute	HCl(l)	100 000	Pine	61	57	44	33
Wright *et al.* (1985)	1982	77.2	6.6	Conc.	HCl(l)	566 149	Aspen	44	81	20	20
Wright *et al.* (1985)	1982	74.8	6.5	Conc.	HCl(g)	557 079	Aspen	44	83	19	21
Wright *et al.* (1985)	1982	53.6	6.4	Conc.	HF	555 538	Aspen	44	83	20	28
Wright & Power (1987)	1984	61.2	11.1	Conc.	H_2SO_4	368 199	Hardwood	46	78	31	33
Wright & Power (1987)	1984	60.7	11.4	Conc.	HCl(l)	377 377	Hardwood	46	76	31	34
Wright & Power (1987)	1984	57.0	9.0	Conc.	HF	335 266	Hardwood	46	85	26	33
von Sivers & Zacchi (1995)b	1992	63.6	0.1	Conc.	HCl(l)	100 000	Pine	61	80	42	31

[a] Base year for the cost estimate.
[b] The cost is given without income from any byproducts.
[c] Given as a percentage of the total production cost.
b 100% ethanol is not produced.
c Pentose fermentation included.
d SSF
e Assumed that 100% ethanol is produced.
f Assumed composition of the raw material (Ladisch *et al.*, 1983).
g Assumed year.
i Assumed composition of the raw material (Fengel & Wegener, 1989).

Table XII.3. Economics of ethanol yield.[29]

For cellulosic ethanol plants operating in 2010, the simulations indicated an ethanol yield of 98 gal per dry ton of hardwood biomass. The plants will consume

2,719 Btu of diesel fuel and generate 0.56 kWh of electricity per gallon of ethanol produced. Table XII.4 presents the assumptions used in our analysis."[30]

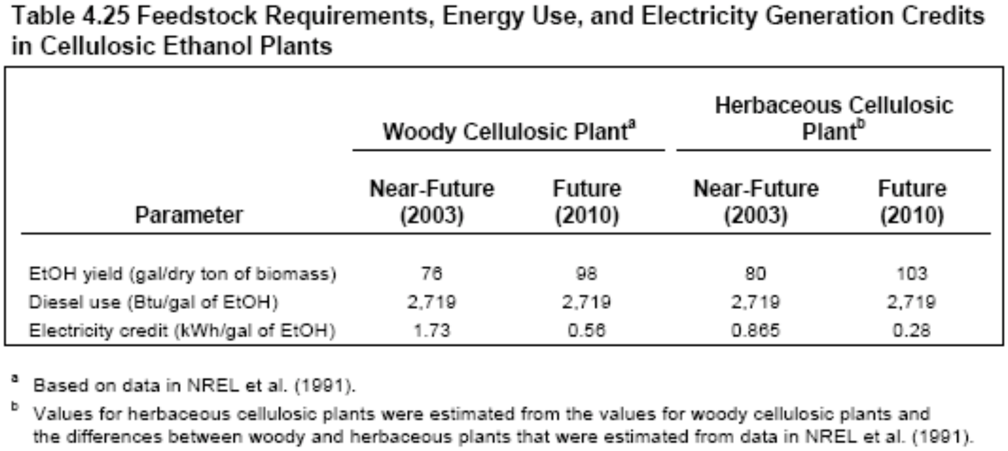


Table 4.25 Feedstock Requirements, Energy Use, and Electricity Generation Credits in Cellulosic Ethanol Plants

	Woody Cellulosic Plant[a]		Herbaceous Cellulosic Plant[b]	
Parameter	Near-Future (2003)	Future (2010)	Near-Future (2003)	Future (2010)
EtOH yield (gal/dry ton of biomass)	76	98	80	103
Diesel use (Btu/gal of EtOH)	2,719	2,719	2,719	2,719
Electricity credit (kWh/gal of EtOH)	1.73	0.56	0.865	0.28

[a] Based on data in NREL et al. (1991).

[b] Values for herbaceous cellulosic plants were estimated from the values for woody cellulosic plants and the differences between woody and herbaceous plants that were estimated from data in NREL et al. (1991).

Table XII.4. Assumption in the GREET analysis.[30]

Other technologies for converting biomass to fuels are gasification, pyrolysis, and anaerobic digestion. These are shown along with current technologies in Figure XII.3.[31]

Gasification is a proven technology practiced on coal and biomass to produce syngas that can be utilized for a variety of applications. Key technological barriers for the production of synthetic fuels from biomass are gas cleanup and the economies of scale for such operations. Production of a syngas suitable for upgrading to biofuels by alcohol synthesis or Fischer-Topsch (F-T) diesel production requires either direct gasification with oxygen or indirect steam gasification. While biomass gasification can be run at a lower temperatures than coal, putting a complete process together with enough biomass feedstock to justify building an oxygen plant, or a catalytic upgrading plant to make alcohol or F-T diesel is problematic. Either building a plant that uses both coal and biomass or a change in the economy of scale needs to occur. Fermentations of syngas to fuels are also in development.[32]

Pyrolysis and hydrothermal liquefaction have some potential to be practiced locally to produce a liquid fuel that could be used as fuel oil and upgraded at centralized sites into motor fuels. There are several different types of pyrolysis reactions that can be carried out yielding different products. Slow pyrolysis at a temperature of 220°C to 280°C is called torrefaction. Under these conditions the hemicellulose and lignin fractions are modified, conferring hydrophobic properties on the biomass and making it more friable. Treatment at higher temperatures, 500°C leads to the production of charcoal. Traditional methods only retain 55% to 65% of the energy in the feedstock. New technology has yields over 70%. This might be an option for generation of an easily transported intermediate for further conversion.[33]

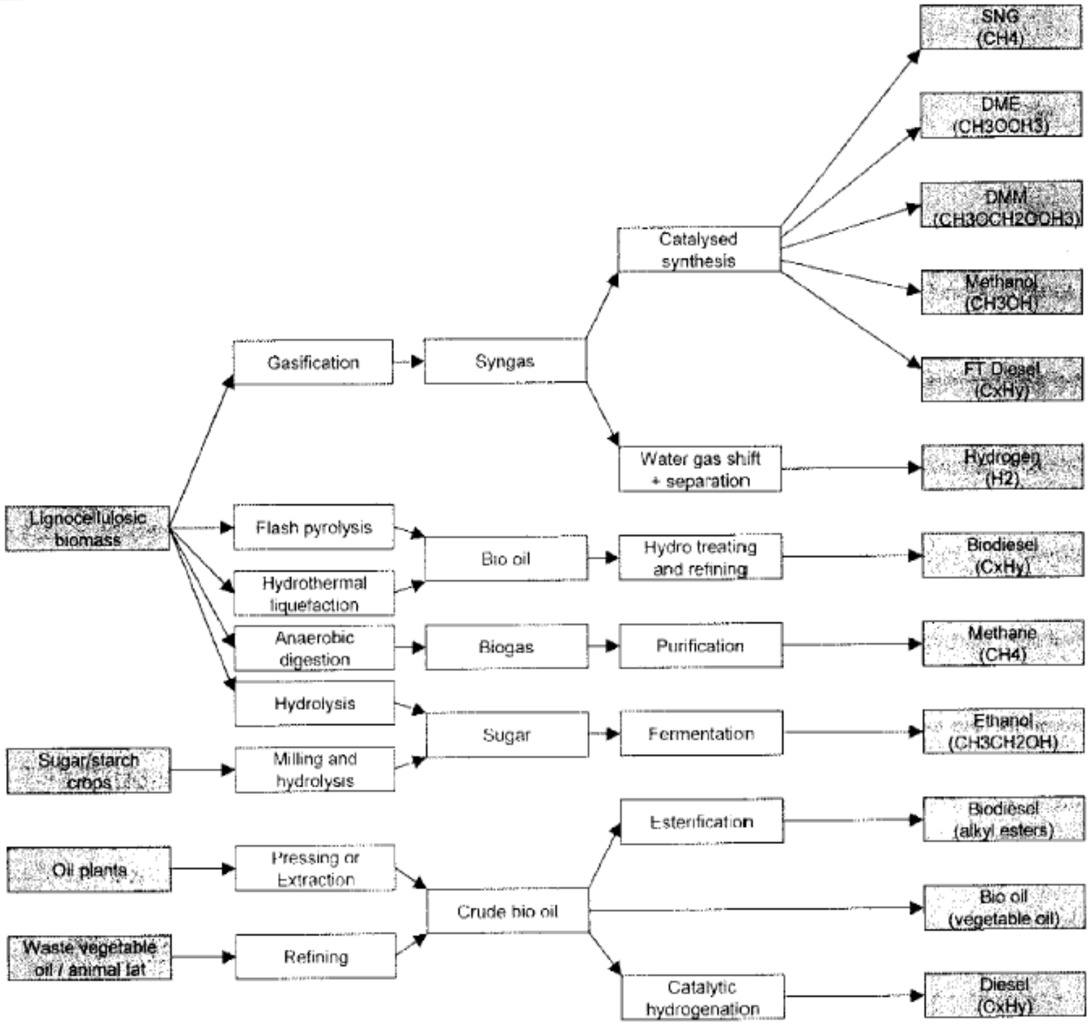
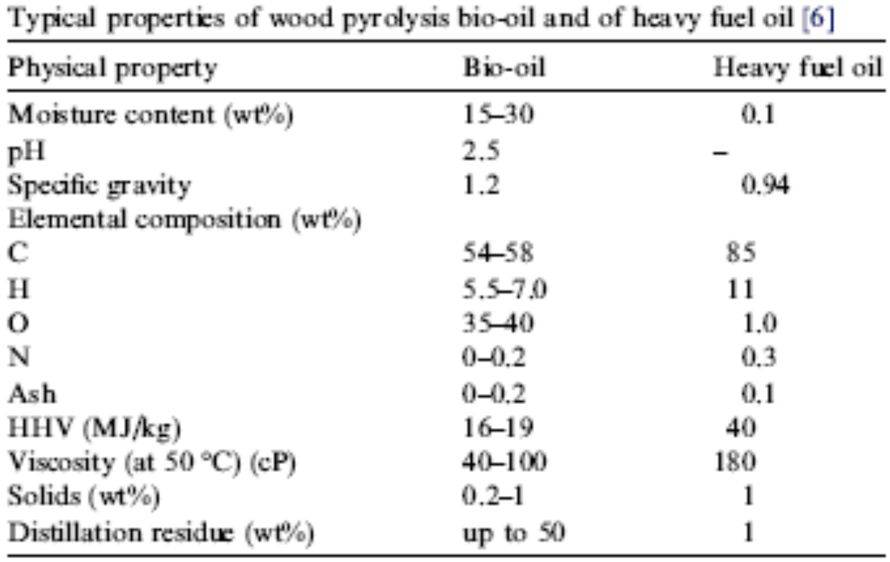


Figure XII.3. Technologies for converting biomass to fuels.[31]

Flash pyrolysis results in a liquid stream that has an elemental composition similar to the feedstock but generates a bio-oil that is easily transported for other processing. This process also generates a gaseous and char stream that are burned to provide the energy for the pyrolysis process. In this process, low-moisture biomass particles are rapidly heated to 450°C to 500°C, volatilizing the biomass to produce the bio-oil. Residence time is under one second and can yield up to 70% of the original feedstock in the bio-oil. The following tables show some typical properties of bio-oil produced by flash pyrolysis.[34]



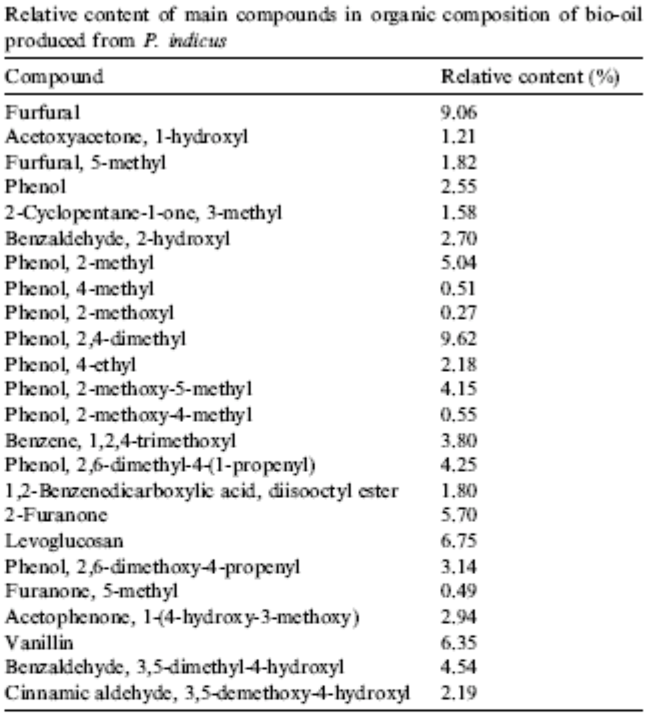
Typical properties of wood pyrolysis bio-oil and of heavy fuel oil [6]

Physical property	Bio-oil	Heavy fuel oil
Moisture content (wt%)	15–30	0.1
pH	2.5	–
Specific gravity	1.2	0.94
Elemental composition (wt%)		
C	54–58	85
H	5.5–7.0	11
O	35–40	1.0
N	0–0.2	0.3
Ash	0–0.2	0.1
HHV (MJ/kg)	16–19	40
Viscosity (at 50 °C) (cP)	40–100	180
Solids (wt%)	0.2–1	1
Distillation residue (wt%)	up to 50	1

Table XII.5. Typical properties of bio-oil produced by flash pyrolysis.[34]

This bio-oil can be used as heating oil and in industrial applications. Upgrading through catalytic processes may yield suitable transportation fuels. Because it is a liquid product with a reasonable energy density, transportation to a large processing facility is also possible. Utilizing all the energy stored in the bio-oil will be a key factor in the economics of a centralized conversion facility.

A final thermal-conversion process that has been worked on is hydrothermal treatment (HTU). This process involves heating wet biomass at approximately 30% solids to 300°C at over 100 bars pressure. The biomass is converted to an oil, tar, and gas phase. A simplified process diagram and typical process yields are shown below (see Figure XII.4 and Table XII.7).[35]



Relative content of main compounds in organic composition of bio-oil produced from *P. indicus*

Compound	Relative content (%)
Furfural	9.06
Acetoxyacetone, 1-hydroxyl	1.21
Furfural, 5-methyl	1.82
Phenol	2.55
2-Cyclopentane-1-one, 3-methyl	1.58
Benzaldehyde, 2-hydroxyl	2.70
Phenol, 2-methyl	5.04
Phenol, 4-methyl	0.51
Phenol, 2-methoxyl	0.27
Phenol, 2,4-dimethyl	9.62
Phenol, 4-ethyl	2.18
Phenol, 2-methoxy-5-methyl	4.15
Phenol, 2-methoxy-4-methyl	0.55
Benzene, 1,2,4-trimethoxyl	3.80
Phenol, 2,6-dimethyl-4-(1-propenyl)	4.25
1,2-Benzenedicarboxylic acid, diisooctyl ester	1.80
2-Furanone	5.70
Levoglucosan	6.75
Phenol, 2,6-dimethoxy-4-propenyl	3.14
Furanone, 5-methyl	0.49
Acetophenone, 1-(4-hydroxy-3-methoxy)	2.94
Vanillin	6.35
Benzaldehyde, 3,5-dimethyl-4-hydroxyl	4.54
Cinnamic aldehyde, 3,5-demethoxy-4-hydroxyl	2.19

Table XII.6. Typical properties of bio-oil produced by flash pyrolysis.[34]

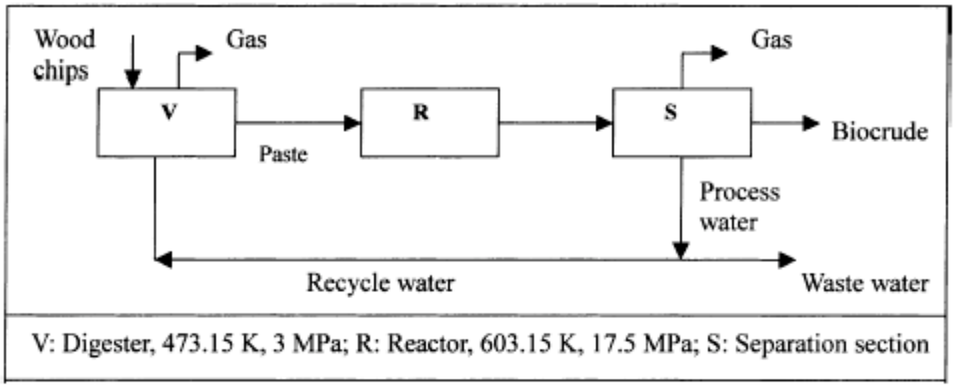
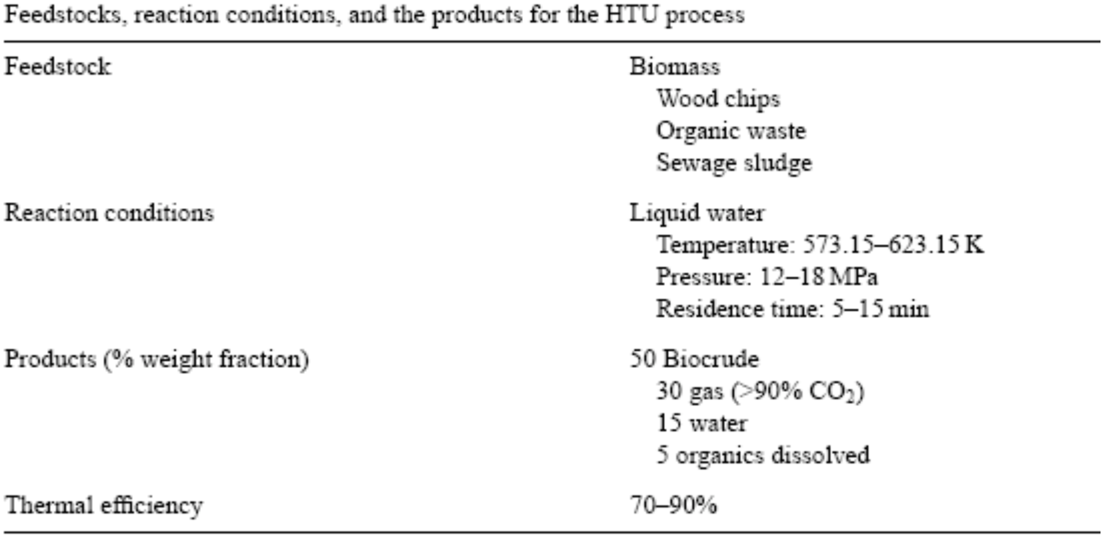


Figure XII.4. Simplified HTU process for converting biomass to an oil, tar, and gas.[35]


Feedstocks, reaction conditions, and the products for the HTU process

Feedstock	Biomass Wood chips Organic waste Sewage sludge
Reaction conditions	Liquid water Temperature: 573.15–623.15 K Pressure: 12–18 MPa Residence time: 5–15 min
Products (% weight fraction)	50 Biocrude 30 gas (>90% CO_2) 15 water 5 organics dissolved
Thermal efficiency	70–90%

Table XII.7. Typical yields from HTU biomass conversion.[35]

The boiling range of the oil product is: naphta 10%, kerosene 20%, gas oil 25%, and 370°C+ fraction 35%. The product also is deoxygenated to about 10% oxygen content.[36]

A final technology is anaerobic digestion. Anaerobic digestion occurs in the absence of oxygen with wet biomass. A mixture of organisms digests the biomass to produce carbon dioxide and methane. This process has been used for waste-water, sewage, and animal waste treatment, and in landfills. New applications are being developed as incentives make the process profitable. It is a slow process, depending on the recalcitrance of the feedstock, but uses simple technology. Anaerobic processes can occur naturally or in very controlled systems. Depending on the feedstock and the process, the biogas can be between 55% and 75% methane. State-of-the-art systems report producing more than 95% methane (note this probably requires gas cleanup to achieve this purity).[37] Digesters around the world range from 1 cubic meter to units as large as 2,000 cubic meters. As natural gas prices rise, more industrial systems are being put in place. Figure XII.5 below show deployment rate of digesters.[37]

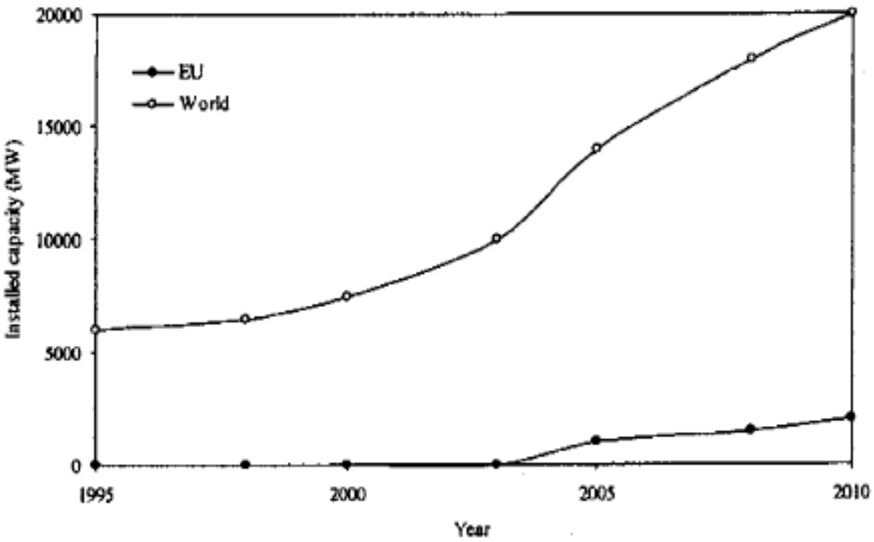


Figure XII.5. Deployment of anaerobic digesters globally and in Europe.[37]

A. Energy Yields

Various processes are being used or have been proposed for converting biomass to useful fuels. These processes include fermentation, gasification, pyrolysis, and anaerobic digestion. All begin with biomass streams. Current technology in the United States for liquid-fuel production utilizes corn to a large extent. Future technologies are looking at utilizing lignocellulosic feedstreams such as energy crops. There has been considerable debate over the energy balance of current ethanol-production processes. Most recent studies show a positive energy balance. Figure XIIA.1 below summarizes the net Btu per gallon of corn ethanol above the energy inputs.[38]

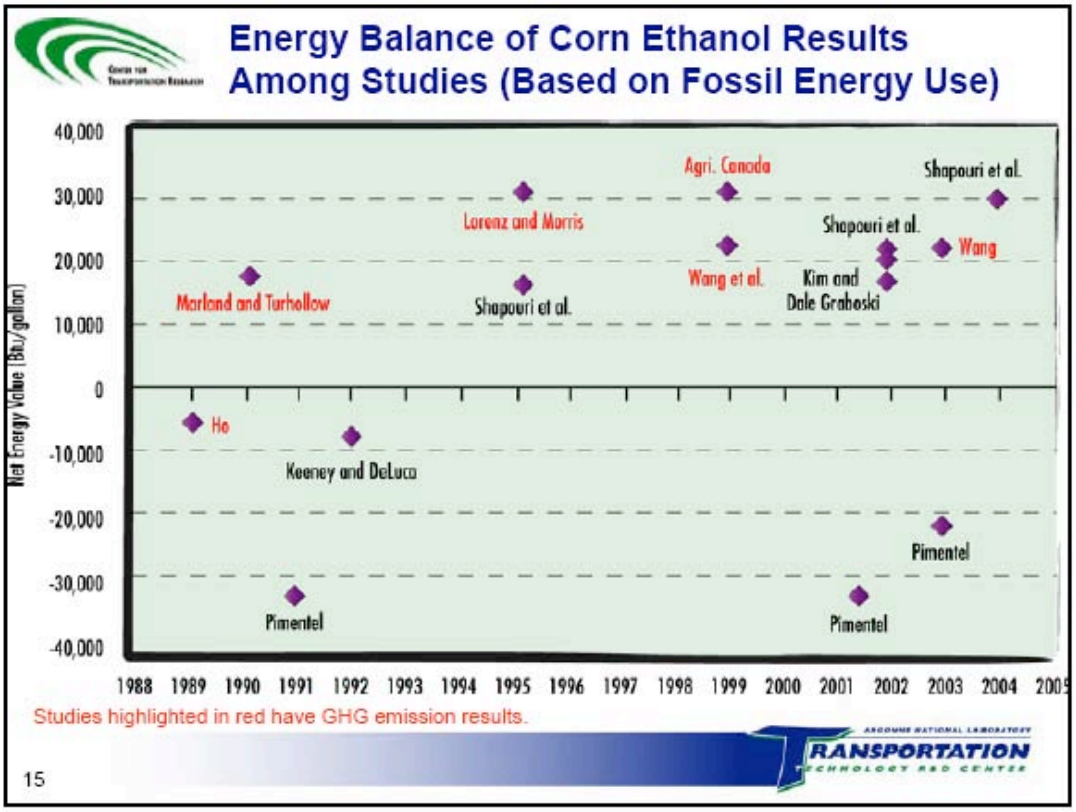


Figure XIIA.1 Btu per gallon of corn ethanol above the energy inputs.[38]

A detailed diagram of these inputs and outputs is in Figure XIIA.2 for both biodiesel production and ethanol.[39]

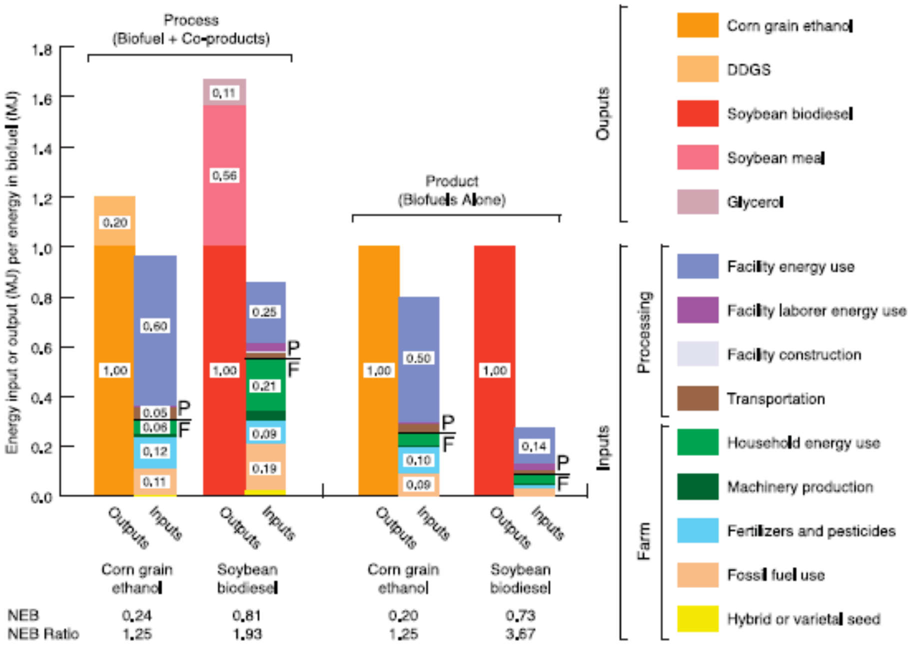


Fig. 1. NEB of corn grain ethanol and soybean biodiesel production. Energy inputs and outputs are expressed per unit energy of the biofuel. All nine input categories are consistently ordered in each set of inputs, as in the legend, but some are so small as to be nearly imperceptible. Individual inputs and outputs of ≥0.05 are labeled; values <0.05 can be found in Tables 7 and 8. The NEB (energy output − energy input) and NEB ratio (energy output/energy input) of each biofuel are presented both for the entire production process (*Left*) and for the biofuel only (i.e., after excluding coproduct energy credits and energy allocated to coproduct production) (*Right*).

Figure XIIA.2. Biodiesel and ethanol production.[39]

Tables XIIA.1 and XIIA.2 summarize the energy inputs for corn production and for bioenergy crops.[40] Note that one bushel of corn represents ~390,000 Btu and switchgrass has about 17 million Btu/ton.[19] Woody biomass would be in the same range as switchgrass, depending on the lignin content. Also note the natural gas usage as well as the nitrogen usage for producing a bushel of corn. The need for increased usage of natural gas and nitrogen as corn acreage expands should be considered (2,866 Btu/ bushel).

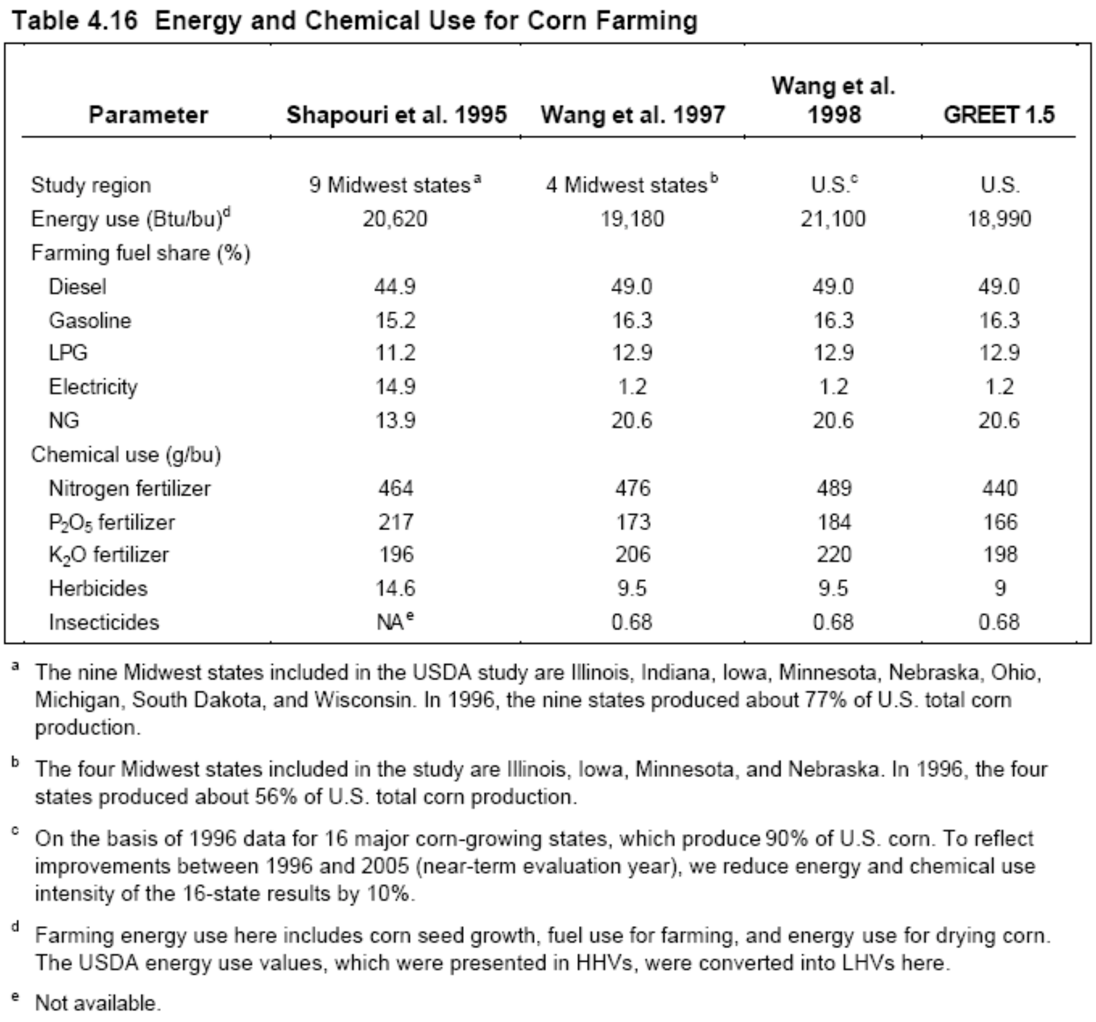


Table 4.16 Energy and Chemical Use for Corn Farming

Parameter	Shapouri et al. 1995	Wang et al. 1997	Wang et al. 1998	GREET 1.5
Study region	9 Midwest states[a]	4 Midwest states[b]	U.S.[c]	U.S.
Energy use (Btu/bu)[d]	20,620	19,180	21,100	18,990
Farming fuel share (%)				
Diesel	44.9	49.0	49.0	49.0
Gasoline	15.2	16.3	16.3	16.3
LPG	11.2	12.9	12.9	12.9
Electricity	14.9	1.2	1.2	1.2
NG	13.9	20.6	20.6	20.6
Chemical use (g/bu)				
Nitrogen fertilizer	464	476	489	440
P_2O_5 fertilizer	217	173	184	166
K_2O fertilizer	196	206	220	198
Herbicides	14.6	9.5	9.5	9
Insecticides	NA[e]	0.68	0.68	0.68

[a] The nine Midwest states included in the USDA study are Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin. In 1996, the nine states produced about 77% of U.S. total corn production.

[b] The four Midwest states included in the study are Illinois, Iowa, Minnesota, and Nebraska. In 1996, the four states produced about 56% of U.S. total corn production.

[c] On the basis of 1996 data for 16 major corn-growing states, which produce 90% of U.S. corn. To reflect improvements between 1996 and 2005 (near-term evaluation year), we reduce energy and chemical use intensity of the 16-state results by 10%.

[d] Farming energy use here includes corn seed growth, fuel use for farming, and energy use for drying corn. The USDA energy use values, which were presented in HHVs, were converted into LHVs here.

[e] Not available.

Table XIIA.1. Energy inputs for corn production[40]

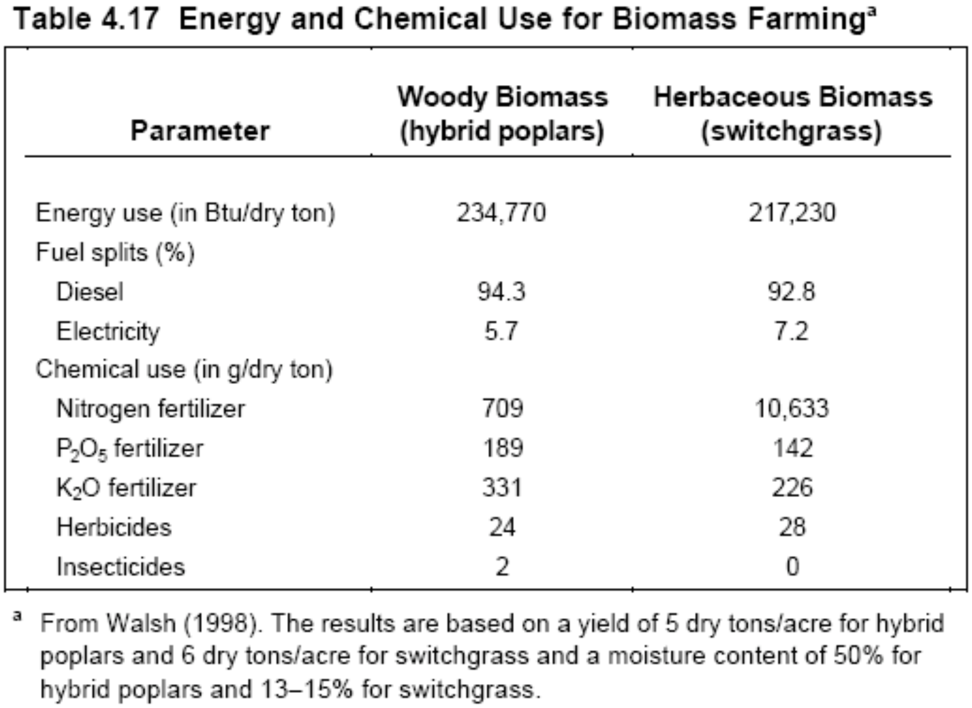


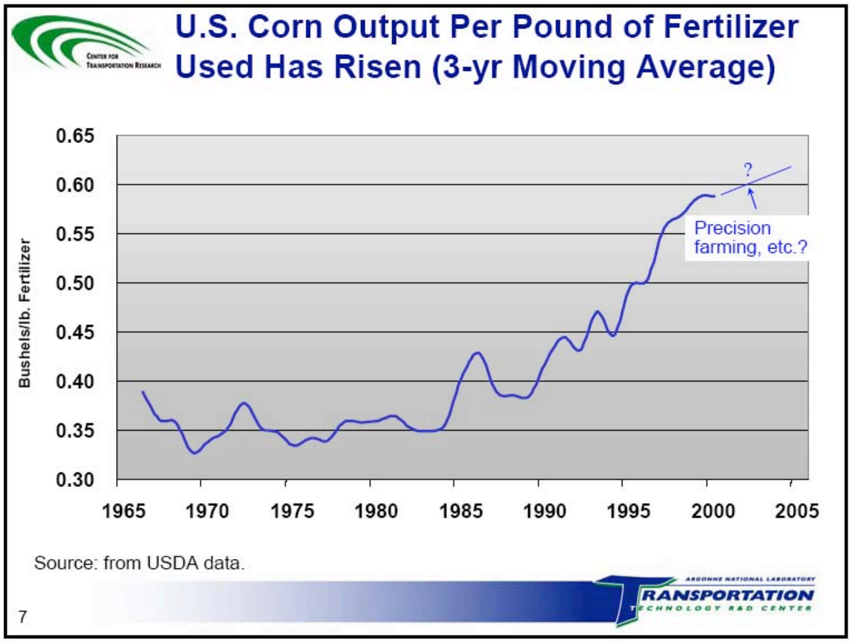
Table 4.17 Energy and Chemical Use for Biomass Farming[a]

Parameter	Woody Biomass (hybrid poplars)	Herbaceous Biomass (switchgrass)
Energy use (in Btu/dry ton)	234,770	217,230
Fuel splits (%)		
Diesel	94.3	92.8
Electricity	5.7	7.2
Chemical use (in g/dry ton)		
Nitrogen fertilizer	709	10,633
P_2O_5 fertilizer	189	142
K_2O fertilizer	331	226
Herbicides	24	28
Insecticides	2	0

[a] From Walsh (1998). The results are based on a yield of 5 dry tons/acre for hybrid poplars and 6 dry tons/acre for switchgrass and a moisture content of 50% for hybrid poplars and 13–15% for switchgrass.

Table XIIA.2. Energy inputs for bioenergy crops.[40]

Corn production has also become more energy efficient over the past three decades due to several factors. Ammonia production is more energy efficient, no-till and minimum tillage practices have minimized energy use for cultivation, and biotechnology has increased yield over inputs. Figure XIIA.3 shows the effects on ammonia usage as an example.[38]



Source: from USDA data.

Figure XIIA.3. Effects on ammonia usage.[38]

Table XIIA.3 compares several other crops and woody biomass fermentation energy in to energy out.[41] A description also follows of the information provided in the table. Note that sugar cane has a very high efficiency due to the fact that energy inputs for growing cane is closer to that in the tables above for energy crops and the bagasse residue is burned to provide energy for the fermentation process. Further details follow.

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

Table 6: Ethanol production efficiency (adapted from [5])

Table XIIA.3. Comparison of woody-biomass fermentation energy to other crops.[41]

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

For the production of 1 ton of FT diesel about 8.5 tons of wood are necessary, representing a yield of about 150 litres of FT diesel by ton of wood. Increasing efficiency is expected and 200 l/t should be reached through advanced gasification technology presenting a more appropriate H_2/CO ratio. With such performance, fast growing plantation under the tropical climate conditions of various developing countries would considerably reduce FT diesel production cost."[41]

The next five tables (XIIA.4, XIIA.5, XIIA.6, XIIA.7, XIIA.8) provide information on yields and costs of various technologies for fuel production from biomass.[42, 32, 43]

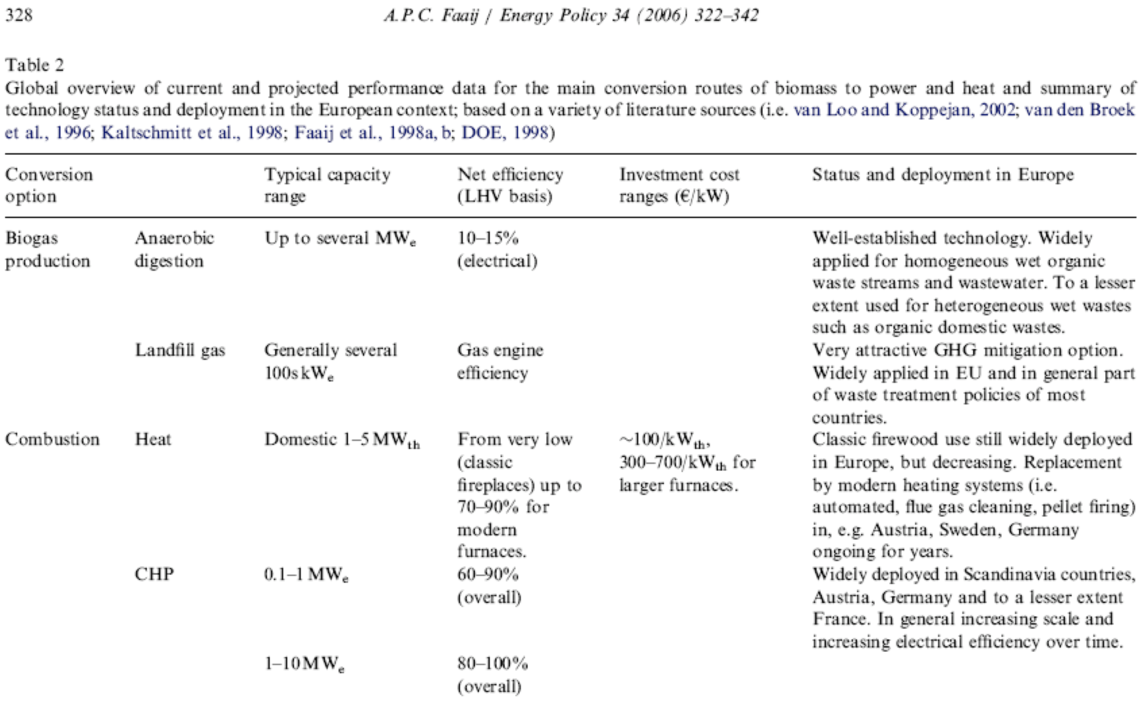


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Table 2

Global overview of current and projected performance data for the main conversion routes of biomass to power and heat and summary of technology status and deployment in the European context; based on a variety of literature sources (i.e. van Loo and Koppejan, 2002; van den Broek et al., 1996; Kaltschmitt et al., 1998; Faaij et al., 1998a, b; DOE, 1998)

Conversion option		Typical capacity range	Net efficiency (LHV basis)	Investment cost ranges (€/kW)	Status and deployment in Europe
Biogas production	Anaerobic digestion	Up to several MW_e	10–15% (electrical)		Well-established technology. Widely applied for homogeneous wet organic waste streams and wastewater. To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.
	Landfill gas	Generally several 100s kW_e	Gas engine efficiency		Very attractive GHG mitigation option. Widely applied in EU and in general part of waste treatment policies of most countries.
Combustion	Heat	Domestic 1–5 MW_{th}	From very low (classic fireplaces) up to 70–90% for modern furnaces.	~100/kW_{th}, 300–700/kW_{th} for larger furnaces.	Classic firewood use still widely deployed in Europe, but decreasing. Replacement by modern heating systems (i.e. automated, flue gas cleaning, pellet firing) in, e.g. Austria, Sweden, Germany ongoing for years.
	CHP	0.1–1 MW_e	60–90% (overall)		Widely deployed in Scandinavia countries, Austria, Germany and to a lesser extent France. In general increasing scale and increasing electrical efficiency over time.
		1–10 MW_e	80–100% (overall)		

			(overall)		
	Stand alone	20–100s MW_e	20–40% (electrical)	2.500–1600	Well-established technology, especially deployed in Scandinavia; various advanced concepts using Fluid Bed technology giving high efficiency, low costs and high flexibility commercially deployed. Mass burning or waste incineration goes with much higher capital costs and lower efficiency, widely applied in countries like the Netherlands, Germany a.o.
	Co-combustion	Typically 5–20 MW_e at existing coal-fired stations. Higher for new multi-fuel power plants.	30–40% (electrical)	~250 + costs of existing power station.	Widely deployed in many EU countries. Interest for larger biomass co-firing shares and utilization of more advanced options (e.g. by feeding fuel gas from gasifiers) is growing in more recent years.
Gasification	Heat	Usually smaller capacity range around 100s kW_{th}.	80–90% (overall)	Several 100s/kW_{th}, depending on capacity.	Commercially available and deployed; but total contribution to energy production in the EU is very limited.
	CHP gas engine	0.1–1 MW_e	15–30%	3.000–1.000 (depends on configuration)	Various systems on the market. Deployment limited due to relatively high costs, critical operational demands and fuel quality.
	BIG/CC	30–100 MW_e	40–50% (or higher; electrical efficiency)	5.000–3.500 (demos), 2.000–1.000 (longer term, larger scale)	Demonstration phase at 5–10 MW_e range obtained. Rapid development in the nineties has stalled in recent years. First generation concepts prove capital intensive.
Pyrolysis	Bio-oil	Generally smaller capacities are proposed of several 100s kW_{th}.	60–70% heat content of bio-oil/feedstock.		Not commercially available; mostly considered a pre-treatment option for longer distance transport.

Note: Due to the variability of data in the various references and conditions assumed, all cost figures should be considered as indicative. Some key assumptions for the estimated production cost ranges are given in footnotes; generally they reflect European conditions.

Table XIIA.4. Biomass conversion routes.[42]

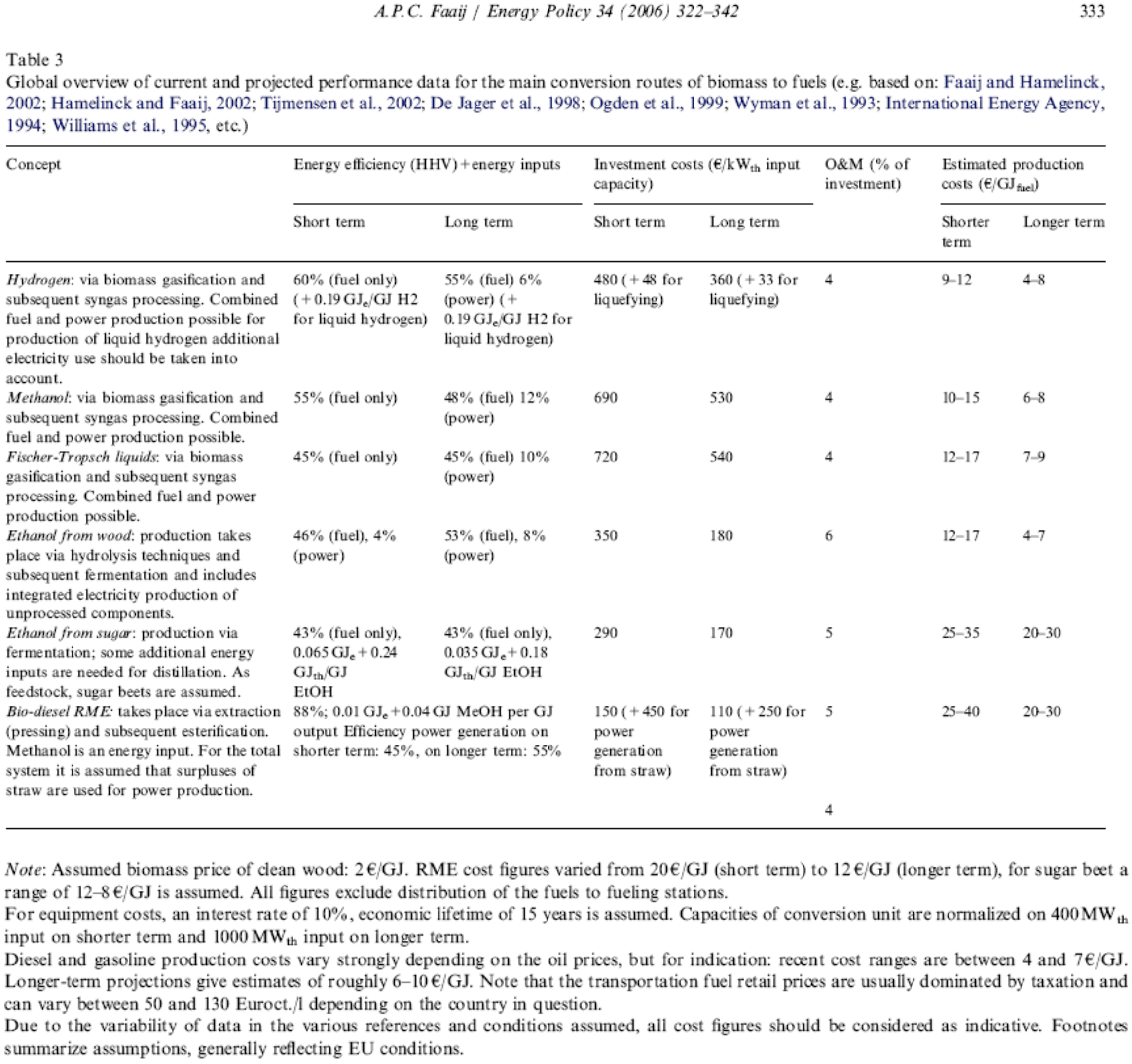


Table 3

Global overview of current and projected performance data for the main conversion routes of biomass to fuels (e.g. based on: Faaij and Hamelinck, 2002; Hamelinck and Faaij, 2002; Tijmensen et al., 2002; De Jager et al., 1998; Ogden et al., 1999; Wyman et al., 1993; International Energy Agency, 1994; Williams et al., 1995, etc.)

Concept	Energy efficiency (HHV) + energy inputs		Investment costs (€/kW$_{th}$ input capacity)		O&M (% of investment)	Estimated production costs (€/GJ$_{fuel}$)	
	Short term	Long term	Short term	Long term		Shorter term	Longer term
Hydrogen: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible for production of liquid hydrogen additional electricity use should be taken into account.	60% (fuel only) (+0.19 GJ$_e$/GJ H2 for liquid hydrogen)	55% (fuel) 6% (power) (+ 0.19 GJ$_e$/GJ H2 for liquid hydrogen)	480 (+48 for liquefying)	360 (+33 for liquefying)	4	9–12	4–8
Methanol: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible.	55% (fuel only)	48% (fuel) 12% (power)	690	530	4	10–15	6–8
Fischer-Tropsch liquids: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible.	45% (fuel only)	45% (fuel) 10% (power)	720	540	4	12–17	7–9
Ethanol from wood: production takes place via hydrolysis techniques and subsequent fermentation and includes integrated electricity production of unprocessed components.	46% (fuel), 4% (power)	53% (fuel), 8% (power)	350	180	6	12–17	4–7
Ethanol from sugar: production via fermentation; some additional energy inputs are needed for distillation. As feedstock, sugar beets are assumed.	43% (fuel only), 0.065 GJ$_e$ + 0.24 GJ$_{th}$/GJ EtOH	43% (fuel only), 0.035 GJ$_e$ + 0.18 GJ$_{th}$/GJ EtOH	290	170	5	25–35	20–30
Bio-diesel RME: takes place via extraction (pressing) and subsequent esterification. Methanol is an energy input. For the total system it is assumed that surpluses of straw are used for power production.	88%; 0.01 GJ$_e$ + 0.04 GJ MeOH per GJ output Efficiency power generation on shorter term: 45%, on longer term: 55%		150 (+450 for power generation from straw)	110 (+250 for power generation from straw)	5	25–40	20–30
					4		

Note: Assumed biomass price of clean wood: 2 €/GJ. RME cost figures varied from 20 €/GJ (short term) to 12 €/GJ (longer term), for sugar beet a range of 12–8 €/GJ is assumed. All figures exclude distribution of the fuels to fueling stations.

For equipment costs, an interest rate of 10%, economic lifetime of 15 years is assumed. Capacities of conversion unit are normalized on 400 MW$_{th}$ input on shorter term and 1000 MW$_{th}$ input on longer term.

Diesel and gasoline production costs vary strongly depending on the oil prices, but for indication: recent cost ranges are between 4 and 7 €/GJ. Longer-term projections give estimates of roughly 6–10 €/GJ. Note that the transportation fuel retail prices are usually dominated by taxation and can vary between 50 and 130 Euroct./l depending on the country in question.

Due to the variability of data in the various references and conditions assumed, all cost figures should be considered as indicative. Footnotes summarize assumptions, generally reflecting EU conditions.

Table XIIA.5. Performance data on conversion routes.[42]

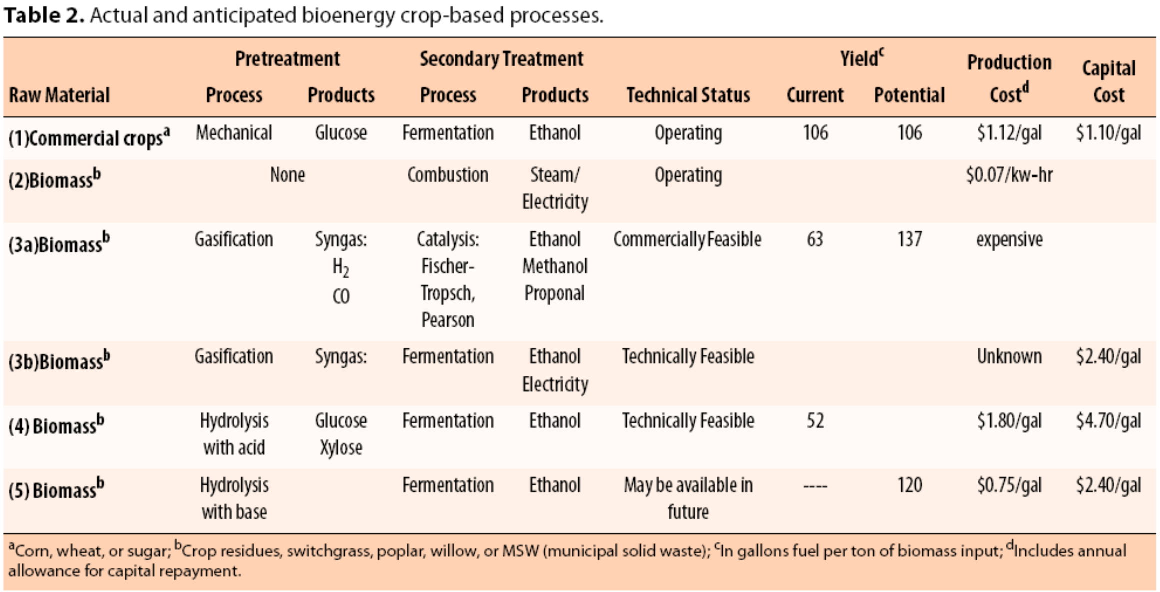


Table 2. Actual and anticipated bioenergy crop-based processes.

	Pretreatment		Secondary Treatment			Yield[c]			
Raw Material	**Process**	**Products**	**Process**	**Products**	**Technical Status**	**Current**	**Potential**	**Production Cost[d]**	**Capital Cost**
(1)Commercial crops[a]	Mechanical	Glucose	Fermentation	Ethanol	Operating	106	106	$1.12/gal	$1.10/gal
(2)Biomass[b]	None		Combustion	Steam/ Electricity	Operating			$0.07/kw-hr	
(3a)Biomass[b]	Gasification	Syngas: H_2 CO	Catalysis: Fischer-Tropsch, Pearson	Ethanol Methanol Proponal	Commercially Feasible	63	137	expensive	
(3b)Biomass[b]	Gasification	Syngas:	Fermentation	Ethanol Electricity	Technically Feasible			Unknown	$2.40/gal
(4) Biomass[b]	Hydrolysis with acid	Glucose Xylose	Fermentation	Ethanol	Technically Feasible	52		$1.80/gal	$4.70/gal
(5) Biomass[b]	Hydrolysis with base		Fermentation	Ethanol	May be available in future	----	120	$0.75/gal	$2.40/gal

[a]Corn, wheat, or sugar; [b]Crop residues, switchgrass, poplar, willow, or MSW (municipal solid waste); [c]In gallons fuel per ton of biomass input; [d]Includes annual allowance for capital repayment.

Table XIIA.6. Actual and anticipated bioenergy crop-based processes.[32]

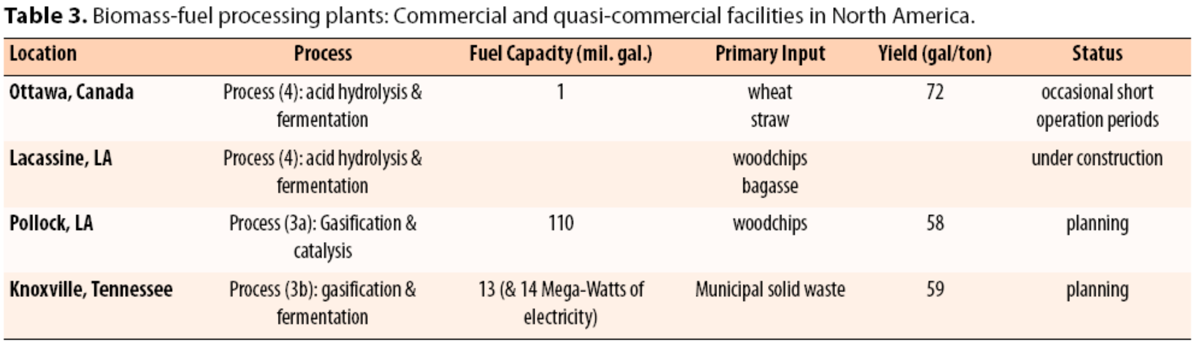


Table 3. Biomass-fuel processing plants: Commercial and quasi-commercial facilities in North America.

Location	Process	Fuel Capacity (mil. gal.)	Primary Input	Yield (gal/ton)	Status
Ottawa, Canada	Process (4): acid hydrolysis & fermentation	1	wheat straw	72	occasional short operation periods
Lacassine, LA	Process (4): acid hydrolysis & fermentation		woodchips bagasse		under construction
Pollock, LA	Process (3a): Gasification & catalysis	110	woodchips	58	planning
Knoxville, Tennessee	Process (3b): gasification & fermentation	13 (& 14 Mega-Watts of electricity)	Municipal solid waste	59	planning

Table XIIA.7. Biomass-fuel processing plants: commercial and quasi-commercial facilities in North America.[32]

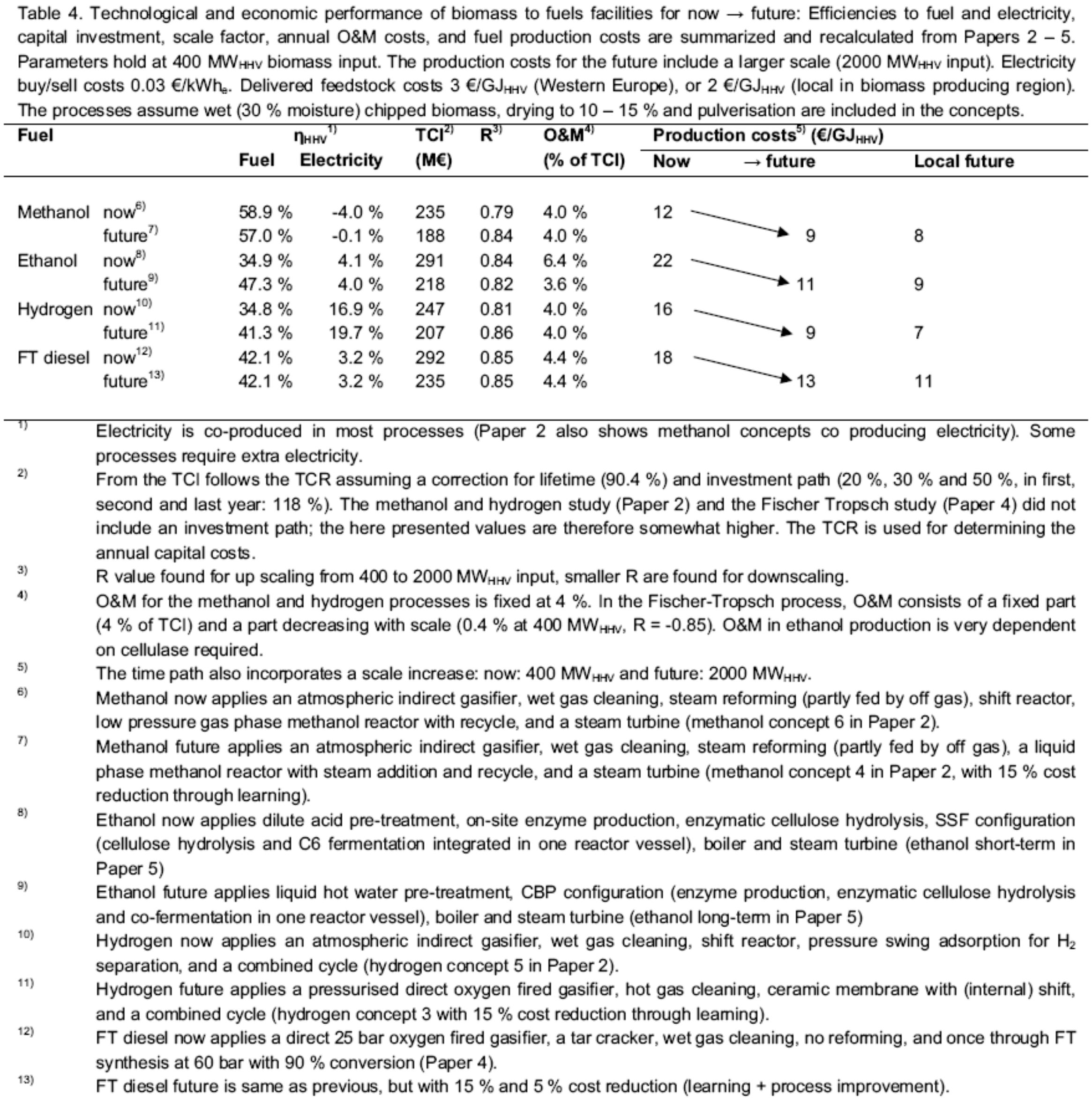


Table 4. Technological and economic performance of biomass to fuels facilities for now → future: Efficiencies to fuel and electricity, capital investment, scale factor, annual O&M costs, and fuel production costs are summarized and recalculated from Papers 2 – 5. Parameters hold at 400 $\mathrm{MW_{HHV}}$ biomass input. The production costs for the future include a larger scale (2000 $\mathrm{MW_{HHV}}$ input). Electricity buy/sell costs 0.03 €/$\mathrm{kWh_e}$. Delivered feedstock costs 3 €/$\mathrm{GJ_{HHV}}$ (Western Europe), or 2 €/$\mathrm{GJ_{HHV}}$ (local in biomass producing region). The processes assume wet (30 % moisture) chipped biomass, drying to 10 – 15 % and pulverisation are included in the concepts.

Fuel		η_{HHV} 1)		TCI 2)	R 3)	O&M 4)	Production costs 5) (€/$\mathrm{GJ_{HHV}}$)		
		Fuel	Electricity	(M€)		(% of TCI)	Now	→ future	Local future
Methanol	now 6)	58.9 %	-4.0 %	235	0.79	4.0 %	12		
	future 7)	57.0 %	-0.1 %	188	0.84	4.0 %		9	8
Ethanol	now 8)	34.9 %	4.1 %	291	0.84	6.4 %	22		
	future 9)	47.3 %	4.0 %	218	0.82	3.6 %		11	9
Hydrogen	now 10)	34.8 %	16.9 %	247	0.81	4.0 %	16		
	future 11)	41.3 %	19.7 %	207	0.86	4.0 %		9	7
FT diesel	now 12)	42.1 %	3.2 %	292	0.85	4.4 %	18		
	future 13)	42.1 %	3.2 %	235	0.85	4.4 %		13	11

1) Electricity is co-produced in most processes (Paper 2 also shows methanol concepts co producing electricity). Some processes require extra electricity.

2) From the TCI follows the TCR assuming a correction for lifetime (90.4 %) and investment path (20 %, 30 % and 50 %, in first, second and last year: 118 %). The methanol and hydrogen study (Paper 2) and the Fischer Tropsch study (Paper 4) did not include an investment path; the here presented values are therefore somewhat higher. The TCR is used for determining the annual capital costs.

3) R value found for up scaling from 400 to 2000 $\mathrm{MW_{HHV}}$ input, smaller R are found for downscaling.

4) O&M for the methanol and hydrogen processes is fixed at 4 %. In the Fischer-Tropsch process, O&M consists of a fixed part (4 % of TCI) and a part decreasing with scale (0.4 % at 400 $\mathrm{MW_{HHV}}$, R = -0.85). O&M in ethanol production is very dependent on cellulase required.

5) The time path also incorporates a scale increase: now: 400 $\mathrm{MW_{HHV}}$ and future: 2000 $\mathrm{MW_{HHV}}$.

6) Methanol now applies an atmospheric indirect gasifier, wet gas cleaning, steam reforming (partly fed by off gas), shift reactor, low pressure gas phase methanol reactor with recycle, and a steam turbine (methanol concept 6 in Paper 2).

7) Methanol future applies an atmospheric indirect gasifier, wet gas cleaning, steam reforming (partly fed by off gas), a liquid phase methanol reactor with steam addition and recycle, and a steam turbine (methanol concept 4 in Paper 2, with 15 % cost reduction through learning).

8) Ethanol now applies dilute acid pre-treatment, on-site enzyme production, enzymatic cellulose hydrolysis, SSF configuration (cellulose hydrolysis and C6 fermentation integrated in one reactor vessel), boiler and steam turbine (ethanol short-term in Paper 5)

9) Ethanol future applies liquid hot water pre-treatment, CBP configuration (enzyme production, enzymatic cellulose hydrolysis and co-fermentation in one reactor vessel), boiler and steam turbine (ethanol long-term in Paper 5)

10) Hydrogen now applies an atmospheric indirect gasifier, wet gas cleaning, shift reactor, pressure swing adsorption for H_2 separation, and a combined cycle (hydrogen concept 5 in Paper 2).

11) Hydrogen future applies a pressurised direct oxygen fired gasifier, hot gas cleaning, ceramic membrane with (internal) shift, and a combined cycle (hydrogen concept 3 with 15 % cost reduction through learning).

12) FT diesel now applies a direct 25 bar oxygen fired gasifier, a tar cracker, wet gas cleaning, no reforming, and once through FT synthesis at 60 bar with 90 % conversion (Paper 4).

13) FT diesel future is same as previous, but with 15 % and 5 % cost reduction (learning + process improvement).

Table XIIA.8. Projected performance of selected biomass conversion routes.[43]

Hydrothermal upgrading also provides a bio-oil that can be upgraded to transportation fuel. In one study on upgrading sugar beet pulp, the process had a thermal efficiency of 75%. It did require an input of process heat equivalent to 2% of the incoming feed, though.[44] Figure XIIA.4 shows the energy flow in pyrolysis reactions.[45]

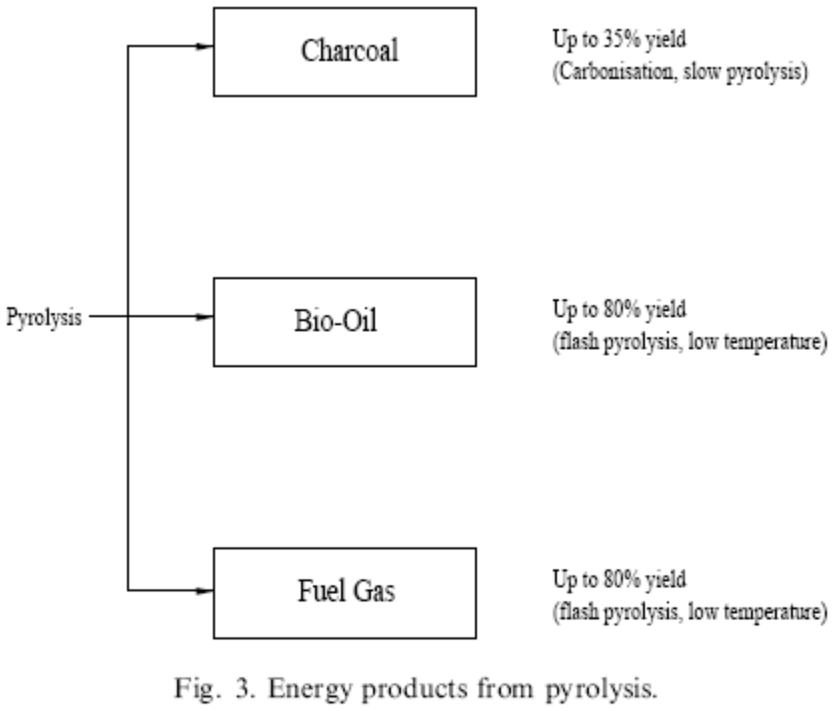


Figure XIIA.4 Energy flow in pyrolysis reactions.[45]

Anaerobic digestion produces and biogas that has an energy content of about 20–40% of the lower heating value of the feedstock. It consists mainly of methane and carbon dioxide.[45]

In summary, there are a wide variety of technologies available for converting biomass to energy. They have different requirements for capital, scale, and feedstock. They also vary in the energy yield in the liquid fuel produced, as well as compatibility with our current transportation infrastructure. The continued development of these technologies will see there deployment where each fits the local environment best.

XIII. Proposed Recommendations

The primary driver to ensure that both food and fuel production needs are met is to develop a robust food and energy market based on current food crops that are suitable for such production. This will bring the value of these crops up to a point where there is incentive to use best practices in crop production, storage, and transportation of these products. This should make more land and crop volumes available for energy production. This will not happen overnight, but definitely could be developed over the next 10 years.

The secomd step is to continue to develop high yielding crops, both for food and energy. The non-food energy crops should be perennial crops developed for either very high oil yield or lignocellulose yield with minimal protein components. Such crops would require lower amounts of fertilizer and be suitable for more marginal arable lands.

The third need is to develop efficient use of agricultural production waste such as straw, stover, dung, and woody residues from forestry. While these sources are not as large as the potential for bioenergy crops, they still globally account for over 100 EJ in energy, more than the current use of transportation fuel. These must be gathered in a sustainable fashion, and agricultural practices may have to be developed in order to do this.

The fourth step is to develop suitable harvesting, storage, and transportation systems for energy crops to conversion sites. Since most crops are of low density and produced over large areas, efficient transportation systems are a requirement. This would indicate that there should be some focus on rail and water transportation systems.

A fifth need is to develop suitable high-yielding conversion systems for turning the primary energy of the crops into suitable secondary-energy fuel sources. Several technologies can be developed; these are fermentation, gasification, and pyrolysis. All three have positive characteristics and may be suitable with different crops and the logistics required.

A final step would be to develop technologies to efficiently use biomass fuels in various systems including co-firing and internal combustion systems.

XIV. Issues Overview

While agricultural and forestry production look like environmentally sound future energy sources, this will only be true if done sustainably. This will require a systems approach that will ensure that the natural resources at our disposal are not depleted. Closed-loop systems with energy production linked to meat production from the process wastes and methane production from the animal wastes generated are attempts at such systems. Much must be done to truly understand what the consequences will be of these different options.

Policies must be put into place that will encourage sustainable agricultural production globally. Food production should be encouraged locally to ensure that food is available where needed and excess arable land can be used either for export food or fuel production. This will ensure the most energy-efficient use of agriculture. Education and demonstration projects for sustainable high-yielding crop production must be developed around the world, and crop development for these varying environments must be carried out.

Good economic modeling should be done on the effect of bioenergy production. This would establish what the price for commodity crops will need to be to drive investment in modern agricultural production practices globally. It would also give a good assessment of the logistical issues around various crop production and conversion technologies as well as those involved in getting the final fuel to the consumer. This would narrow the research priorities and ensure that there are no major surprises in following a bioenergy policy.

Energy crop development for production on marginal and surplus agricultural land should be carried out. Most current crops were developed for food and feed use or for fiber production. Crops specifically for energy production will have different characteristics and will need to be developed for a wide variety of environments.

Preferably they would have low water and external nutrient requirements. For both food and fuel, developing higher photosynthetic efficiencies will have major benefits.

Local conversion technologies need to be developed to manage the low density of biomass and its disperse nature of production. Compaction, torrefaction, or conversion to a bio-oil all are technologies to be explored.

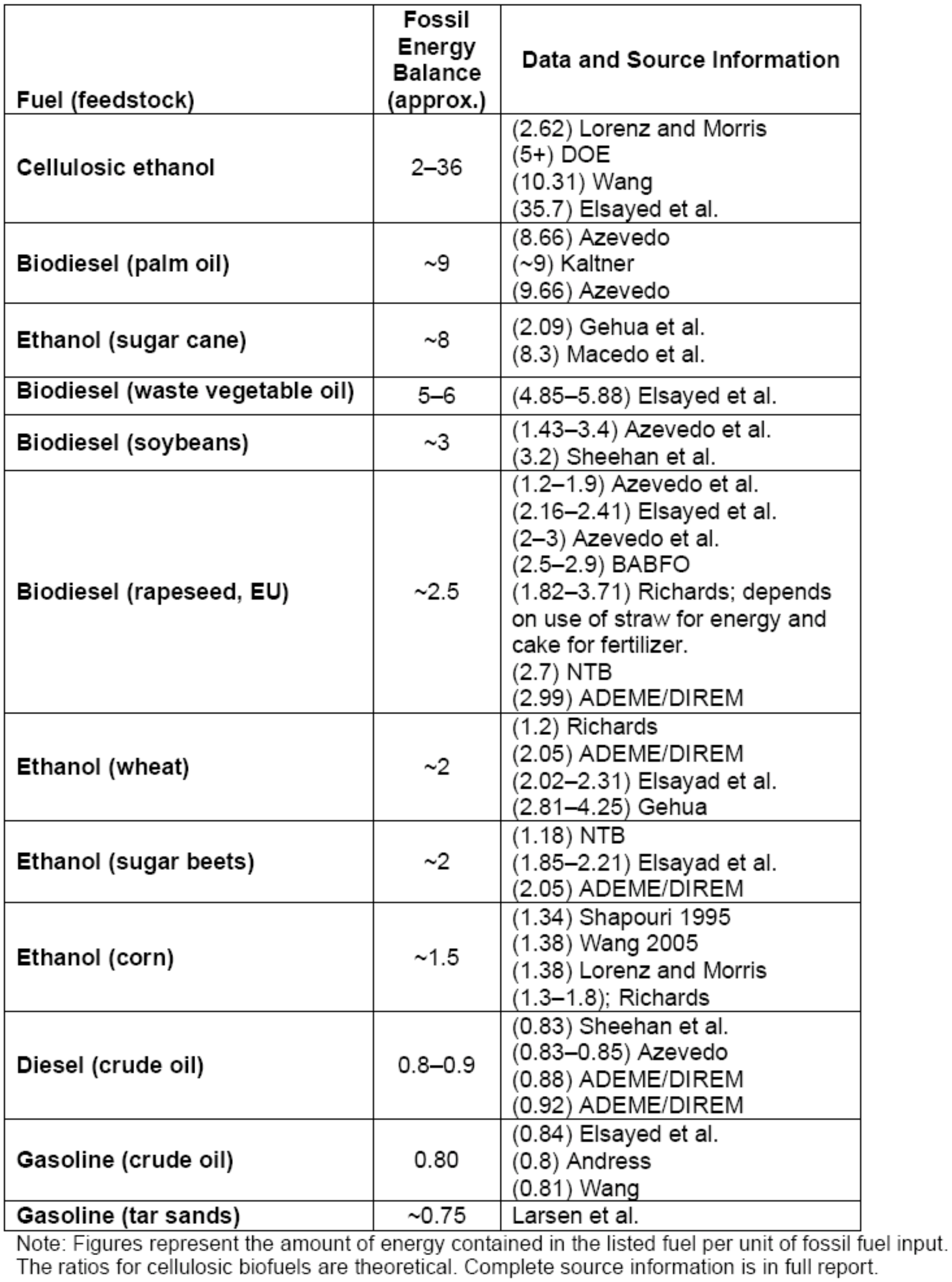
Logistics of biofuel transportation is a key hurdle. Investment in rail, waterway, and pipeline transportation will be needed to get the fuel from the producing regions to the consuming regions.

Most biomass conversion technologies also have the potential to produce electricity. Developing technologies and means to capture this potential will be important.

Many current bioenergy feedstocks have just as much or more potential in consumer products displacing non-renewable feedstocks. Developing these markets where they have positive energy balances should be supported.

If there is to be a policy on carbon dioxide emissions, doing this sooner rather than later will have positive impacts on deployments of technologies, whether they be coal based or biobased.

Development of clean biomass conversion and energy utilization is necessary for co-firing and transportation fuels. See Table XIV.1 for energy balance for various current biofuels:[17]



Fuel (feedstock)	Fossil Energy Balance (approx.)	Data and Source Information
Cellulosic ethanol	2–36	(2.62) Lorenz and Morris (5+) DOE (10.31) Wang (35.7) Elsayed et al.
Biodiesel (palm oil)	~9	(8.66) Azevedo (~9) Kaltner (9.66) Azevedo
Ethanol (sugar cane)	~8	(2.09) Gehua et al. (8.3) Macedo et al.
Biodiesel (waste vegetable oil)	5–6	(4.85–5.88) Elsayed et al.
Biodiesel (soybeans)	~3	(1.43–3.4) Azevedo et al. (3.2) Sheehan et al.
Biodiesel (rapeseed, EU)	~2.5	(1.2–1.9) Azevedo et al. (2.16–2.41) Elsayed et al. (2–3) Azevedo et al. (2.5–2.9) BABFO (1.82–3.71) Richards; depends on use of straw for energy and cake for fertilizer. (2.7) NTB (2.99) ADEME/DIREM
Ethanol (wheat)	~2	(1.2) Richards (2.05) ADEME/DIREM (2.02–2.31) Elsayad et al. (2.81–4.25) Gehua
Ethanol (sugar beets)	~2	(1.18) NTB (1.85–2.21) Elsayad et al. (2.05) ADEME/DIREM
Ethanol (corn)	~1.5	(1.34) Shapouri 1995 (1.38) Wang 2005 (1.38) Lorenz and Morris (1.3–1.8); Richards
Diesel (crude oil)	0.8–0.9	(0.83) Sheehan et al. (0.83–0.85) Azevedo (0.88) ADEME/DIREM (0.92) ADEME/DIREM
Gasoline (crude oil)	0.80	(0.84) Elsayed et al. (0.8) Andress (0.81) Wang
Gasoline (tar sands)	~0.75	Larsen et al.

Note: Figures represent the amount of energy contained in the listed fuel per unit of fossil fuel input. The ratios for cellulosic biofuels are theoretical. Complete source information is in full report.

Table XIV.1. Fossil Energy Balance of Current BioFuels.[17]

XV. Appendices

Table XV.1. Energy conversion factors.[46]

This is a quick-reference list of conversion factors used by the Bioenergy Feedstock Development Programs at ORNL. It was compiled from a wide range of sources, and is designed to be concise and convenient rather than all-inclusive. Most conversion factors and data are given to only 3 significant figures. Users are encouraged to consult other original sources for independent verification of these numbers. The following are links to Web sites we have found useful (many universities worldwide maintain good guides and conversion calculator pages):

- U.S. National Institute of Standards and Technology (NIST)
- Centre for Innovation in Mathematics Teaching, University of Exeter, U.K.
- Department of Geological Sciences, University of Michigan
- Convertit.com Measurement Converter

Energy contents are expressed here as lower heating value (LHV) unless otherwise stated (this is closest to the actual energy yield in most cases). Higher heating value (HHV, including condensation of combustion products) is greater by between 5% (in the case of coal) and 10% (for natural gas), depending mainly on the hydrogen content of the fuel. For most biomass feedstocks this difference appears to be 6–7%. The appropriateness of using LHV or HHV when comparing fuels, calculating thermal efficiencies, etc. really depends upon the application. For stationary combustion where exhaust gases are cooled before discharging (e.g. power stations), HHV is more appropriate. Where no attempt is made to extract useful work from hot exhaust gases (e.g. motor vehicles), the LHV is more suitable. In practice, many European publications report LHV, whereas North American publications use HHV.

Energy units

Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2).
- 1.0 joule = 0.239 calories (cal)
- 1.0 calorie = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 joules = 0.948 million Btu = 239 million calories = 278 kWh
- 1.0 British thermal unit (Btu) = 1,055 joules (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (BOE)
- 1,000 Btu/lb = 2.33 gigajoules per tonne (GJ/t)
- 1,000 Btu/U.S. gallon = 0.279 megajoules per liter (MJ/l)

Power

- 1.0 watt = 1.0 joule/second = 3.413 Btu/hr
- 1.0 kilowatt (kW) = 3,413 Btu/hr = 1.341 horsepower
- 1.0 kilowatt-hour (kWh) = 3.6 MJ = 3,413 Btu
- 1.0 horsepower (hp) = 550 foot-pounds per second = 2,545 Btu per hour = 745.7 watts = 0.746 kW

Energy Costs

- $1.00 per million Btu = $0.948/GJ
- $1.00/GJ = $1.055 per million Btu

Some common units of measure

- 1.0 U.S. ton (short ton) = 2,000 pounds
- 1.0 imperial ton (long ton or shipping ton) = 2,240 pounds
- 1.0 metric tonne (tonne) = 1,000 kilograms = 2,205 pounds
- 1.0 U.S. gallon = 3.79 liter = 0.833 Imperial gallon
- 1.0 imperial gallon = 4.55 liter = 1.20 U.S. gallon

- 1.0 liter = 0.264 U.S. gallon = 0.220 imperial gallon
- 1.0 U.S. bushel = 0.0352 m^3 = 0.97 UK bushel = 56 lb, 25 kg (corn or sorghum) = 60 lb, 27 kg (wheat or soybeans) = 40 lb, 18 kg (barley)

Areas and crop yields

- 1.0 hectare = 10,000 m^2 (an area 100 m x 100 m, or 328 x 328 ft) = 2.47 acres
- 1.0 km^2 = 100 hectares = 247 acres
- 1.0 acre = 0.405 hectares
- 1.0 U.S. ton/acre = 2.24 t/ha
- 1 metric tonne/hectare = 0.446 ton/acre
- 100 g/m^2 = 1.0 tonne/hectare = 892 lb/acre
  - for example, a “target” bioenergy crop yield might be: 5.0 U.S. tons/acre (10,000 lb/acre) = 11.2 tonnes/hectare (1120 g/m^2)

Biomass energy

- Cord: a stack of wood comprising 128 cubic feet (3.62 m^3); standard dimensions are 4 x 4 x 8 feet, including air space and bark. One cord contains approx. 1.2 U.S. tons (oven-dry) = 2,400 pounds = 1,089 kg
  - 1.0 metric tonne wood = 1.4 cubic meters (solid wood, not stacked)
  - Energy content of wood fuel (HHV, bone dry) = 18–22 GJ/t (7,600–9,600 Btu/lb)
  - Energy content of wood fuel (air dry, 20% moisture) = about 15 GJ/t (6,400 Btu/lb)
- Energy content of agricultural residues (range due to moisture content) = 10–17 GJ/t (4,300–7,300 Btu/lb)
- Metric tonne charcoal = 30 GJ (= 12,800 Btu/lb) (but usually derived from 6–12 t air-dry wood, i.e. 90–180 GJ original energy content)
- Metric tonne ethanol = 7.94 petroleum barrels = 1,262 liters
  - ethanol energy content (LHV) = 11,500 Btu/lb = 75,700 Btu/gallon = 26.7 GJ/t =

21.1 MJ/liter. HHV for ethanol = 84,000 Btu/gallon = 89 MJ/gallon = 23.4 MJ/liter
  - ethanol density (average) = 0.79 g/ml (= metric tonnes/m^3)
- Metric tonne biodiesel = 37.8 GJ (33.3 - 35.7 MJ/liter)
  - biodiesel density (average) = 0.88 g/ml (= metric tonnes/m^3)

Fossil fuels

- Barrel of oil equivalent (BOE) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh. “Petroleum barrel” is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 liters); about 7.2 barrels oil are equivalent to one tonne of oil (metric) = 42–45 GJ.
- Gasoline: U.S. gallon = 115,000 Btu = 121 MJ = 32 MJ/liter (LHV). HHV = 125,000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
  - Metric tonne gasoline = 8.53 barrels = 1356 liter = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
  - gasoline density (average) = 0.73 g/ml (= metric tonnes/m^3)
- Petro-diesel = 130,500 Btu/gallon (36.4 MJ/liter or 42.8 GJ/t)
  - petro-diesel density (average) = 0.84 g/ml (= metric tonnes/m^3)
- Note that the energy content (heating value) of petroleum products per unit mass is fairly constant, but their density differs significantly—hence the energy content of a liter, gallon, etc. varies between gasoline, diesel, kerosene.
- Metric tonne coal = 27–30 GJ (bituminous/anthracite); 15–19 GJ (lignite/sub-bituminous) (the above ranges are equivalent to 11,500–13,000 Btu/lb and 6,500–8,200 Btu/lb).
  - Note that the energy content (heating value) per unit mass varies greatly between different “ranks” of coal. “Typical” coal (rank not specified) usually means bituminous coal, the most common fuel for power plants (27 GJ/t).
- Natural gas: HHV = 1,027 Btu/ft3 = 38.3 MJ/m^3; LHV = 930 Btu/ft3 = 34.6 MJ/m^3
  - Therm (used for natural gas, methane) = 100,000 Btu (= 105.5 MJ)

Carbon content of fossil fuels and bioenergy feedstocks

- coal (average) = 25.4 metric tonnes carbon per terajoule (TJ)
  - 1.0 metric tonne coal = 746 kg carbon
- oil (average) = 19.9 metric tonnes carbon/TJ
- 1.0 U.S. gallon gasoline (0.833 Imperial gallon, 3.79 liter) = 2.42 kg carbon
- 1.0 U.S. gallon diesel/fuel oil (0.833 Imperial gallon, 3.79 liter) = 2.77 kg carbon
- natural gas (methane) = 14.4 metric tonnes carbon / TJ
- 1.0 cubic meter natural gas (methane) = 0.49 kg carbon
- carbon content of bioenergy feedstocks: approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues

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XVI. References

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