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Foundations and Trends® in Microeconomics

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
USA
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is D. Rajagopal and D. Zilberman, Environmental, Economic and Policy Aspects of Biofuels, Foundations and Trends® in Microeconomics, vol 4, no 5, pp 353–468, 2008

ISBN: 978-1-60198-174-5

Full text available at: http://dx.doi.org/10.1561/0700000029

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Foundations and Trends® in Microeconomics, 2008, Volume 4, 8 issues. ISSN paper version 1547-9846. ISSN online version 1547-9854. Also available as a combined paper and online subscription.

Foundations and Trends® in
Microeconomics
Vol. 4, No. 5 (2008) 353–468

DOI: 10.1561/0700000029

Environmental, Economic and Policy Aspects of Biofuels

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Abstract

This review provides a timely summary of the current understanding of the various impacts and contributes positively to the policy debate. We have several key conclusions: (1) Biofuels are diverse and evolving; (2) Greenhouse gas (GHG) benefits vary significantly across various types of biofuels and are dependent on market conditions and policy situation; (3) Increase in income in the developing world would increase the demand for both food and fuel; (4) A diverse set of policies, which has been introduced or proposed, impacts biofuels directly; and (5) Much of the impact assessments of biofuels thus far are *ex-ante* estimates based on either optimization or equilibrium models. The short-term economic impacts of biofuels will depend on a variety of factors such as the harvest in any given year, the oil price, economic growth, strength of the dollar, and level of inventory. The long-term impacts will depend on factors such as investment in technological change, population and economic growth, climate change, and long-term policies toward energy, agriculture, and the environment. The biofuel policy debate is likely to be an ongoing one in the near future.

Summary

Seldom does a technology or a product, which accounts for just over 1% of the global supply, create as much hope and consternation as have biofuels in recent times. With the world witnessing phenomenal growth in demand for cheap and clean alternatives to oil, biofuel supply does have a positive impact on oil consumers; however, its impact on food consumers and on the environment continues to be controversial. Thus, experts today are in disagreement about biofuel policies. We hope that this review provides a timely summary of the current understanding of the various impacts and contributes positively to the policy debate. We have several key conclusions:

(1) Biofuels are diverse and evolving. The current generation of biofuels includes some that are intensive in land, water, energy, and chemical inputs and significantly affect food markets and the environment. The next generation based on cellulosic biomass and better biofuels has the potential to provide improved net benefits but requires significant technological breakthroughs.

(2) Greenhouse gas (GHG) benefits vary significantly across various types of biofuels and are dependent on market conditions and policy situation. Current application of life cycle analysis (LCA) has significant limitations for policy analysis. Life cycle indicators need to be represented as functions of prices and policies rather than as scalar numbers. The environmental evaluation of biofuel should also consider alternatives that may be adopted to meet growing demand, for example, gasoline production from tar sands, coal and gas liquefaction, hybrid electric vehicles, energy efficiency and mass transit.
(3) Increase in income in the developing world would increase the demand for both food and fuel. Surge in fuel prices increases the demand for biofuel, which reduces the supply of food and food inventories. These combined with depreciation of the US dollar, contributed to the recent spike in the price of food. While biofuel improves the welfare of gasoline consumers and food producers, it has a significant negative affect on food consumers, especially the poor. The food security threat may lead to restriction on the expansion of biofuel, and it may require enacting safety net policies. The situation in both food and fuel markets can be improved through policies that expand supply, for example, enhanced agricultural research and less restrictive regulation of agricultural biotechnology. High prices due to biofuels may provide incentives for innovation in and adoption of productivity-enhancing technologies both in agriculture and energy sectors. Policies can affect the speed, timing, and nature of these technological changes.
(4) A diverse set of policies, which has been introduced or proposed, impacts biofuels directly. These include subsidies, mandates, and regulation of carbon content of fuels. However, current policies do not provide incentives that align private and social welfare. The environmental impact of fuels including biofuels can be controlled by a combination of carbon tax as well as payments for other environmental amenities affected by fuels. These policies can improve welfare by

lowering demand for dirty fuels and enhancing demand for green fuels. However, political economy, information gaps, and transaction costs limit the implementation of first-best policies. Economics of biofuel is also affected by a myriad other policies like agricultural, energy, and R&D; trade and environmental regulations; and various types of taxes and investment policies. Assessing the marginal impact of various government policies on biofuels and designing better policies are a major research challenge.

(5) Much of the impact assessments of biofuels thus far are *ex-ante* estimates based on either optimization or equilibrium models. There is a paucity of *ex-post* econometric analysis of the marginal impact of biofuels and biofuel policies on the economy. Furthermore, the structural relationships between agriculture, the energy sector, and the environment in the context of biofuels have hardly been studied. Other issues for further research include the dynamics of food, fuel and the environment, the industrial organization implications, and its implication for regional development.

Not all biofuels are created equal. The short-term economic impacts of biofuels will depend on a variety of factors such as the harvest in any given year, the oil price, economic growth, strength of the dollar, and level of inventory. Public acceptance of biofuels should be expected to ebb and flow depending on what it perceives as these short-term impacts. The long-term impacts will depend on factors such as investment in technological change, population and economic growth, climate change, and long-term policies toward energy, agriculture, and the environment. The biofuel policy debate is likely to be an ongoing one in the near future.

List of Acronyms

ABE — acetone butanol ethanol
BTU — British thermal unit
CIWMB — California Integrated Waste Management Board
CGE — computable general equilibrium

CGF — corn gluten feed
CGM — corn gluten meal
CRP — Conservation Reserve Program
DDG — distiller's dried grain
DDGS — distiller's dried grain with solubles
EJ — exajoule
FFV — flexible fuel vehicles
FAO — Food and Agriculture Organization of the United Nations
GHG — greenhouse gas
GTAP — Global Trade Analysis Project
HC — hydrocarbon
IFRPI — International Food Policy Research Institute
LCA — life cycle assessment or life cycle analysis
MJ — megajoules
MTOE — million tonnes of oil equivalent
MSW -municipal solid waste
NER — net energy ratio
NEV — net energy value
OECD — Organization for Economic Cooperation and Development
R&D — research and development
Twh — terawatt-hour

Contents

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Biofuels — Sources, Production, and Uses

1.1 Motivation Behind the Survey

The last few years have witnessed both a dramatic increase in the demand for cheaper alternatives to oil (EIA, 2008). Similar boom in alternative energy has occurred in the past, but it was temporary. The indication this time is that the demand for alternatives to oil will be sustained for longer periods. One reason for this is that supply of conventional oil is not expected to keep up with future demand (Campbell and Laherrere, 1998). Several large energy-consuming regions are setting ambitious long-term targets for biofuels and for reduction in carbon emission (AB32; Fulton et al., 2004; EPACT, 2005; Kojima and Johnson, 2005).

However, expansion of biofuels raises a variety of concerns, such as the increase in food prices and its impact on the poor, the expansion of agricultural land and its impact on natural habitats, and increase in use of agrichemicals. Although there is much disagreement about the role of biofuels in the recent food inflation, the crisis has thrown caution into the winds (Sexton and Zilberman, 2008). Disagreement among scientists apart, public and political opinion is also one of skepticism, but not all biofuels are created equal. The economic and the environmental impact of biofuels will be heterogeneous varying with space and time.

Given this context, the time is ripe for a survey that summarizes what is known about biofuels today and what is being predicted for the future. Since this is a review of the literature, it has not been our aim to present new analysis. There are five sections in this review. Section 1 describes the drivers for biofuels, the various types of biofuels, and some of the emerging technologies. It also provides a historical perspective on biofuels. Section 2 surveys the environmental literature on biofuels. Section 3 is a review of the studies of economic impacts of biofuels. Section 4 is a review of the various policies that are influencing the evolution of biofuels and their economic implications. Section 5 concludes by summarizing the findings and identifying areas for future work.

1.2 Drivers for Biofuels

Increasing consensus about the end of cheap oil, the risks to supply due to political instability in major oil-producing regions, and the consequences of carbon emissions from fossil fuels have caused a spurt in the search for alternative sources of oil (Hazell and Pachauri, 2006; Runge and Senauer, 2007). Nowhere is the need for alternative to oil felt more than in the transportation sector. Transportation consumes 30% of the global energy, 99% of which is supplied by petroleum (EIA, 2007). World use of liquids and other petroleum is projected to grow from 83.6 million barrels oil equivalent per day in 2005 to 95.7 million barrels per day in 2015 and 112.5 million barrels per day by the year 2030 (EIA, 2008). Transportation is expected to account for about 74% of the total projected increase in global oil use between 2005 and 2030 (EIA, 2008). Transportation also accounts for 21% of global annual greenhouse gas (GHG) emissions (Watson et al., 1996). While a range of renewable technologies like wind and solar photovoltaics (PV) and carbon-free technologies like nuclear are poised to challenge coal and natural gas in the electricity sector, there seemed no alternative existed that could compete widely with oil in terms of cost and convenience for transportation. But today, plant-based fuels like ethanol and biodiesel seem to be emerging as a serious alternative fuel ahead of technologies like fuel cell vehicles, electric/hybrid vehicles, and natural gas vehicles. There are several reasons for the excitement surrounding biofuels.

1. *Biofuels can improve energy security*: The energy security argument has several flavors. One is a purely economic view that in a globalized world anything that diversifies the physical sources of energy increases energy security. The second view is a more nationalistic one, which emphasizes domestic control over supply. A third view relates to reducing dependence on trade for energy with unstable or hostile regions. Seen from any of these angles biofuels have a role to play in improving energy security.
2. *Biofuels can reduce GHG emissions*: Some consider biofuels a major solution to reducing GHG emissions. It is true that direct (i.e., ignoring land-use change) GHG emissions from biofuels is in several cases (sugarcane, cellulose, wastes, etc.) clearly lower compared to fossil fuels. However, taken together with indirect emissions due to induced agriculture expansion (about which experts are in disagreement) the net GHG effect is uncertain (Sexton and Zilberman, 2008). There is also less clarity about non-GHG environmental impacts.
3. *Biofuels are replenishable*: Biofuels are an inexhaustible resource since the stock can be replenished through agriculture. Technologies like fuel cells and electric vehicles that depend on hydrogen and the electric grid, respectively, are due to economic considerations, ultimately dependent on natural gas and coal, respectively.
4. *Biofuels can increase farm income*: Ignoring the recent surge in prices of agricultural commodities for the moment, decline in farm income has been a problem the world over (Gardner, 2003). With biofuels, most countries will be able to grow one or more types of crops in which they possess a comparative advantage and use them to meet either domestic or foreign demand or both. This increased demand for agriculture is expected to increase farm income. In countries

with oversupply, diverting some of it to biofuels might offer a double whammy, raise income for farmers, and reduce the demand for subsidies (Hazell and Pachauri, 2006). That said, one could argue that under current circumstances higher food prices would have resulted even in the absence of biofuels due to the rapid economic growth and slow productivity growth.

5. *Biofuels can create new jobs*: Biofuels are more labor intensive than other energy technologies on a per-unit-of-energy-delivered basis (Kammen et al., 2004). The production of the feedstock and the conversion require greater quantities of labor compared to that required for extraction and processing of fossil fuels or other industrially based technologies like hydrogen and electric vehicles. A majority of these job additions is expected to take place in the rural sector which can also spur rural development (Kammen, 2006).
6. *Biofuels have physical and chemical properties similar to oil*: Liquid fuels are expected to remain both the world's dominant energy source and also the most important fuels for transportation (EIA, 2008). Given this physical similarity and also several chemical similarities, biofuels provide enormous advantages to bridge the rising gap between supply and demand for oil. As a result, adapting to biofuel-based infrastructure (at least at low levels of blending like 10% or 20%) can be achieved more cost effectively than adapting to hydrogen, battery, or natural gas-based automobiles (Fulton et al., 2004; de la Torre Ugarte, 2006).
7. *Biofuels are simple and familiar*: Finally, biofuels have an aura of being simple and familiar to consumers, producers, and policymakers alike. Ethanol has been in use as an additive or as a blend with gasoline in several countries for over two decades while its production for alcohol consumption has been known for centuries. Even 100 years ago, Henry Ford and Rudolph Diesel who are considered the grandfathers of the automobile revolution of the 20th century are said to

> have prophesized a future for transportation based on fuels derived from plant-based sources.[1]

However, if agriculture is to be relied on to fuel a growing population, one that is richer and drives more, then a serious consideration of the consequences of widespread biofuel adoption is warranted, and the technology is not without costs (Sexton and Zilberman, 2008). Biofuels may mean filling the fuel tank at the cost of emptying the stomach of the poor (Msangi et al., 2006; Runge and Senauer, 2007; Rajagopal, 2008). Such criticism seems to bear more merit given the global food inflation being experienced in the first half of 2008 (Abbott et al., 2008). Biofuels are also feared for the impact they will have on the natural environment (Giampietro et al., 1997; Fearnside, 2002; Runge and Senauer, 2007; van Damm et al., 2007). Basically, biofuel technology is land intensive. Biofuel demand will put pressure on existing use of land including food production and natural habitats. It will also increase the demand for agricultural inputs (fertilizers, pesticides, etc.), which have negative environmental externalities. By increasing energy supply, biofuels can also undermine efforts aimed at managing demand through energy efficiency and energy conservation. We defer a more detailed discussion on the environmental and economic implications on biofuels to later sections. The emphasis in this section is on the sources, technologies, and uses of bioenergy systems.

Although the term biofuels is being appropriated to refer just to liquid fuels like ethanol and biodiesel, it should ideally imply fuels from plant-based sources, which can be produced, processed, and consumed in diverse forms. A matrix of some common biofuel pathways is shown in Section 1.5. Biofuels can also be crudely divided into “traditional” and “modern.” The term traditional is used to refer to combustion of wood, animal waste, and crop residues for household cooking and heating, largely by the poor in developing countries, whereas the term modern is used to refer to biomass use for electricity and transportation using more sophisticated conversion technologies like gasification and fermentation. Traditional biomass accounts for 80% of the global

[1] http://news.bbc.co.uk/2/hi/science/nature/6294133.stm.

renewable energy use (details in Section 2), while ethanol and biodiesel comprise less than 1% of the global renewable energy use (the remaining is accounted for by wind, solar, hydro, geothermal, and tidal energy). In any case the focus of this survey is largely on liquid biofuels, the reason being that it is one of the fastest-growing sources of alternative energy today. The impacts of the huge investments taking place in developing modern biofuels are not well understood, and hence more controversial, whereas several prominent works on traditional biomass already exist (Smith, 1987; Ravindranath and Hall, 1995; Barnes and Floor, 1996; Smith and Mehta, 2003; Bailis et al., 2005).

The rest of the section is organized as follows. Sub-section 1.3 provides some basic statistics on global energy use and the share of biofuels. Sub-section 1.4 provides a historical perspective on biofuel use. Sub-section 1.5 describes the various biofuel technologies in use today. Sub-section 1.6 summarizes the findings of several studies that estimate the future potential of biofuels. Sub-section 1.7 describes cutting-edge research in biofuel technologies. Sub-section 1.8 concludes the section.

1.3 Global Energy Situation and the Share of Bioenergy

The global energy production in 2004 was about 440 quadrillion Btu[2] (11000 mtoe)[3] (EIA, 2007) (Figure 1.1). In terms of end-use consumption, transportation and electricity accounted for 21% and 30%, respectively (Watson et al., 1996). In terms of sources of energy, about 80% of the supply was comprised of crude oil, coal, and natural gas while the contribution of renewable energy sources was about 13% (Figure 1.2). In terms of the sources of renewable energy, about 80% of the supply was comprised of combustible renewables like wood, dung, charcoal, and agricultural wastes, while hydro, wind, solar, tidal, and geothermal contributed the rest (Figure 1.2). Combustible renewables and waste are consumed mainly in non-OECD (Organization for Economic and Development) countries while hydro and other modern renewables are consumed largely in OECD countries (Figure 1.3). Overall Africa, non-OECD Asia, and China combined for 67% of the global renewable

[2] Btu — British thermal unit.
[3] Mtoe — million tonnes of oil equivalent.

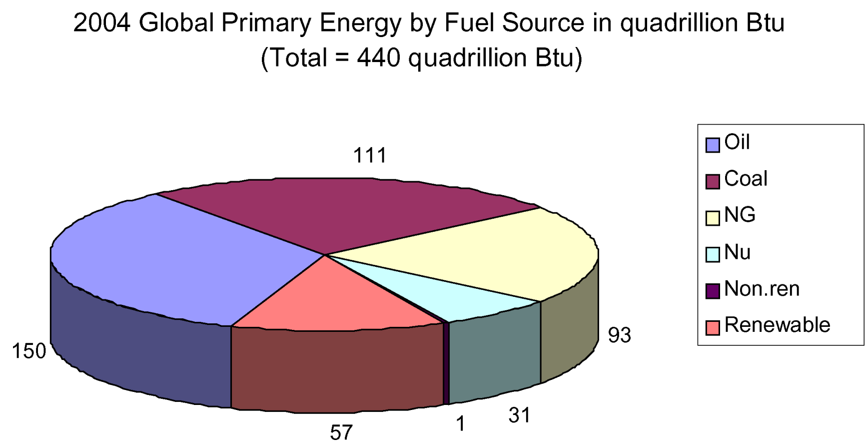

Fig. 1.1 Fuel shares in global primary energy supply (EIA, 2007).

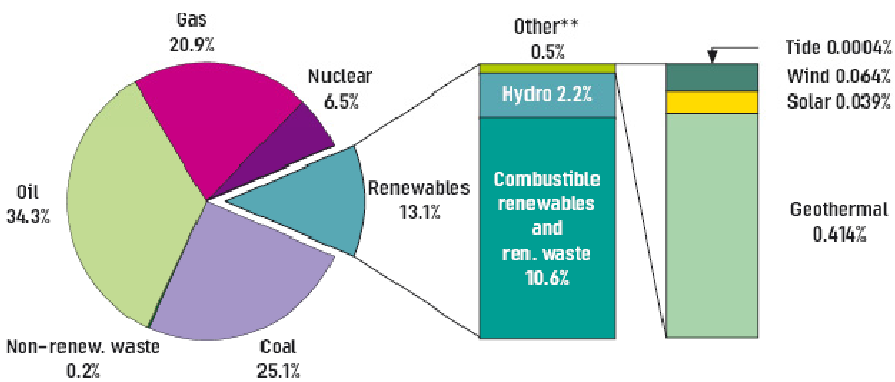

Fig. 1.2 Share of renewables in global energy supply (IEA, 2006).

energy (Figure 1.4). We can also infer that renewable energy in developing countries is comprised almost entirely of traditional biomass, where as in the developed countries it is comprised largely of modern renewables like solar, wind, and hydro (Figures 1.3 and 1.4). From an end-use energy perspective, 58% of the renewable energy is consumed by the residential, commercial, and public sector (Figure 1.5). We can also safely assume that a majority of the combustible renewables and waste is consumed for cooking and heating purposes especially in developing countries.

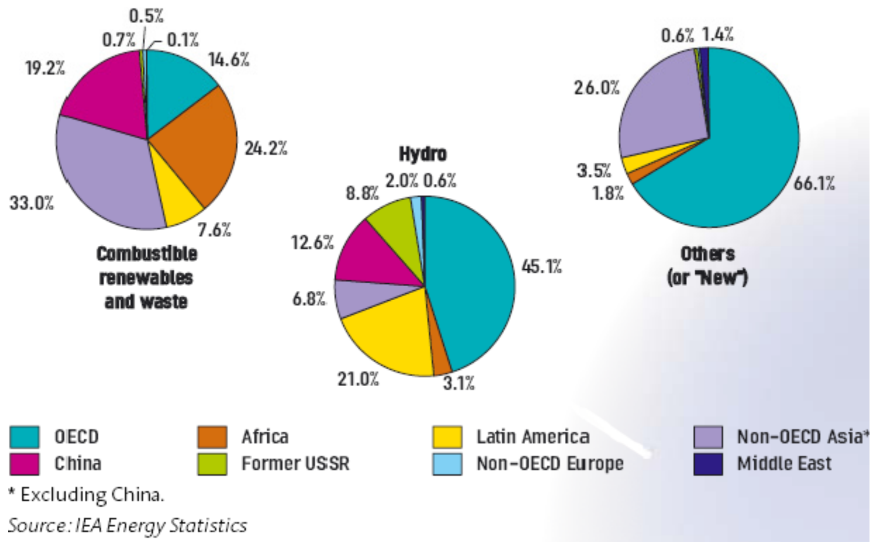

Fig. 1.3 Regional distribution for each renewable source (IEA, 2006).

	TPES*	Of which Renew-ables	Share of Renewables in TPES	Share of the main fuel categories in total renewables		
				Hydro	Geothermal, Solar, Wind, etc.	Combustible Renewables and Waste
	Mtoe	Mtoe	%	%	%	%
Africa	586	287	49.0	2.6	0.4	97.1
Latin America	486	140	28.9	36.1	1.4	62.4
Asia**	1,289	411	31.8	4.0	3.6	92.4
China***	1,627	251	15.4	12.1	0	87.9
Non-OECD Europe	104	11	10.6	43.2	2.5	54.3
Former USSR	979	30	3.0	71.4	1.2	27.3
Middle East	480	3	0.7	43.4	24.4	32.2
OECD	5,508	315	5.7	34.6	12.0	53.4
World	**11,059**	**1,404**	**13.1**	**16.7**	**4.0**	**79.4**

* Total primary energy supply calculated using the physical energy content methodology.
** Asia excludes China.
*** China includes People's Republic of China and Hong Kong, China.

Fig. 1.4 Share of various sources of renewable in each region (IEA, 2006).

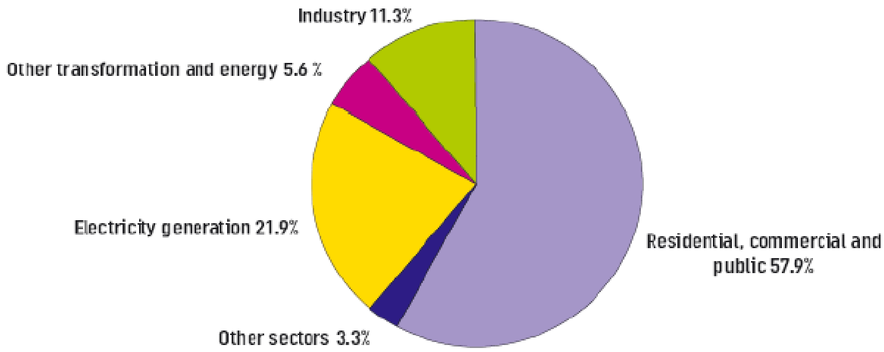

Fig. 1.5 End-use sectors that consume renewable energy (IEA, 2006).
Source: IEA Energy Statics

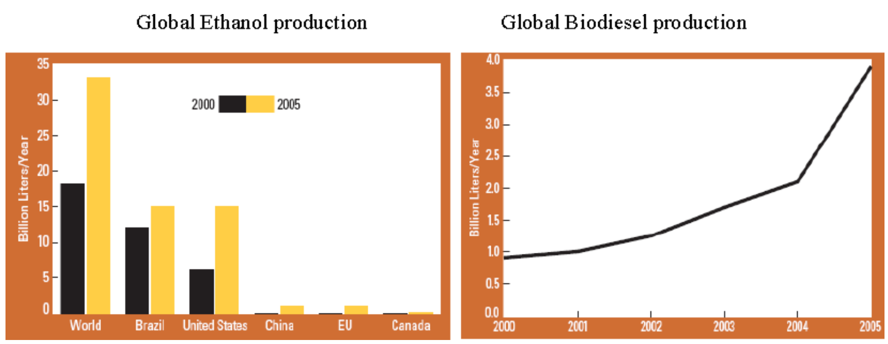

Fig. 1.6 Global production of ethanol and biodiesel (Martinot, 2005).

In the year 2006 liquid biofuels accounted for just over 1% of global renewable energy (16 mtoe out of 1430 mtoe) and just less than 1% of global crude oil supply of 4800 billion liters (IEA, 2006). That said, most of the big energy-consuming nations are considering or have already adopted policies that could result in much higher biofuels use by the next decade (Kojima and Johnson, 2005). Ethanol and biodiesel are the two main types of liquid biofuels today, and these are almost entirely used in the transportation sector. However, production of ethanol at 36 billion liters per year far exceeds the production of biodiesel, which is about 4 billion liters per year globally (Figure 1.6). Based on the origin of supply, today's biofuels can be crudely classified into three main categories, namely, Brazilian ethanol from sugarcane, American ethanol from corn, and German biodiesel from rapeseed. In 2005, Brazil and the United States combined for about 90% of ethanol production, while Germany accounted for over 50% of global biodiesel production (Figure 1.3; Martinot, 2005). In Brazil ethanol accounts for about 30% of gasoline demand, while its share is less than 2% of transport fuel in the United States (Fulton et al., 2004).

1.4 Historical Perspective on Biofuels

Prior to the industrial revolution, biomass satisfied almost all of the human energy needs across the globe. The burning of wood and charcoal supplied energy for heating and cooking in homes, while draft animals supplied the energy for tilling of land and for transport of people in horse or ox-drawn carriages. The replacement of animal power with machine power is claimed to have freed up 80 million acres of US land — land that had been used to grow grass and other feed for the millions of animals used by humans.[4] With the advent of coal and petroleum in the middle and late 19th century, respectively, the developed world rapidly transitioned away from the use of biomass for almost all end uses like household, commercial, industrial, and transportation applications. Until now, economic growth has generally resulted in a decline in the share of biomass energy and an increase in the use of modern fuels. Statistics from various countries also show that per capita income and share of modern fuels are positively correlated (Figure 1.7; Martinot, 2005). When a country's per capita income is less than $300 (in US dollars), typically 90% or more of the population uses firewood and dung for cooking (Barnes and Floor, 1996). Once incomes have exceeded $1000 per capita, most people switch to modern fuels, and substitution is nearly complete. An overview of the main forms of energy used for various end uses like cooking, lighting, running appliances, and sometimes space heating in rural areas of developing countries is shown in Table 1.1. It indicates that the general pattern is to climb the ladder from traditional to modern fuels gradually. For cooking, wood dung and agricultural residues are the most common while some households use

[4] http://bioenergy.ornl.gov/papers/misc/switgrs.html.

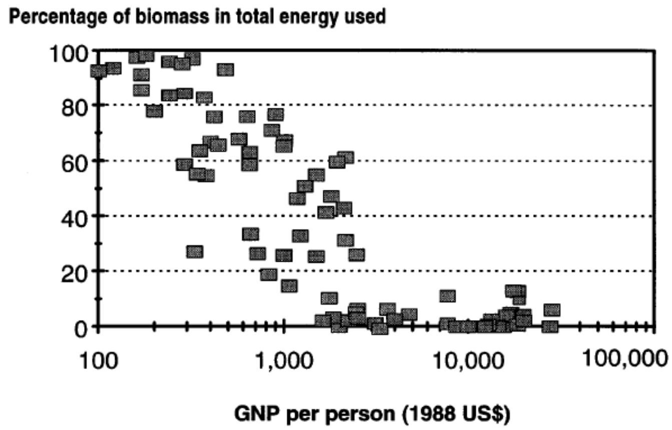

Fig. 1.7 Correlation between GDP and use of biomass energy for various countries (Barnes, 1996).

kerosene or charcoal. Biogas is also used in some cases. For lighting, the poor depend on candles or kerosene. For agriculture and rural industry, the general pattern is to move from human and animal power to mechanical power. For commercial and industrial heating, the trend is to move to more efficient use of biomass, as well as to modern fuels.

Modern fuel sources are still out of reach for poor people in those countries. The situation is acute with regard to access to clean cooking fuels and electricity. According to Bailis et al. (2005), in Africa about 94% of the rural population depends on wood, and 73% of the urban population depends on wood and charcoal as the primary source of energy. In India, less than 40% of rural households have connection to the electric grid and less than 10% of the rural households have access to clean burning fuels like liquefied petroleum gas or liquefied natural gas (Rajagopal, 2008). In China, despite rapid economic growth, 80% of households continue to rely on biomass or coal as their primary cooking and heating fuels (Smith and Mehta, 2003). Therefore, providing cleaner fuels for cooking and electricity, which can be produced from biomass, should also be an important area of focus for policy in such countries, along with producing modern biofuels for transportation.

Table 1.1 Sources of rural energy for various end-uses at different household incomes.

	Income stage		
End use	Low	Medium	High
Household			
Cooking	Wood, residues, and dung	Wood, residues, dung, kerosene, and biogas	Wood, kerosene, biogas, LPG, and coal
Lighting	Candles and kerosene (sometimes none)	Candles, kerosene, and gasoline	Kerosene, electricity, and gasoline
Space heating	Wood, residues, and dung (often none)	Wood, residues, and dung	Wood, residues, dung, and coal
Other appliances	None	Electricity and storage cells	Electricity and storage cells
Agriculture			
Tilling	Hand	Animal	Animal, gasoline, and diesel (tractors and small power tillers)
Irrigation	Hand	Animal	Diesel and electricity
Postharvest processing	Hand	Animal	Diesel and electricity
Industry			
Milling and mechanical	Hand	Hand and animal	Hand, animal, diesel, and electricity
Process heat	Wood and residues	Coal, charcoal, wood, and residues	Coal, charcoal, kerosene, wood, and residues

Source: Barnes and Floor (1996).

1.5 Biofuel Sources and Conversion Technologies

Most bioenergy systems can be explained using the schematic shown in Figure 1.8. Like any production system, inputs like fuel, capital, and labor are combined to produce the energy using a chemical conversion process. In the process pollution and other useful coproducts are also produced. Table 1.2 shows the key differences between traditional and modern bioenergy systems in terms of these inputs, conversion technology, and the outputs. Traditional forms of biomass use are characterized by low capital, low conversion efficiency, poor utilization of fuel, and poor emission controls whereas modern forms of biomass use

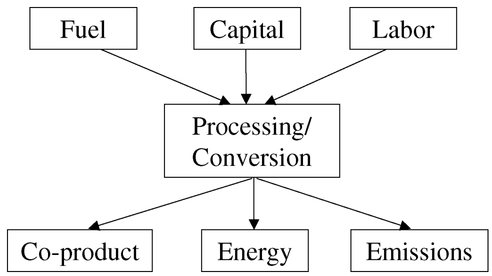

Fig. 1.8 Schematic of a bioenergy production system.

Table 1.2 Comparison of characteristics of traditional and modern biofuels.

Characteristic of technology	Traditional	Modern
Fuel	Mostly gathered or collected and in some cases purchased	Commercially procured
Capital	Low capital cost	High capital cost
Labor	High labor intensity at household level in collection of fuel	Low labor intensity at household level but overall high labor intensity compared to other energy sources
Conversion process	Low efficiency and poor utilization of biomass	Higher efficiency and higher utilization of biomass
Energy uses	Energy for cooking and heating in poor households in developing countries	Commercial heating, electricity and transportation
Emission controls	Poor emission controls	Controlled emissions
Co-product	No co-products	Commercially useful co-products

are characterized by higher capital, higher conversion efficiency, better utilization of fuel, and better emission controls. Let us consider these two types of biomass in more detail.

1.5.1 Traditional Biomass

Traditional biomass implies the use of sources like wood, crop residues, animal dung, and charcoal for cooking and heating at the household level. This is often done using three-stone stoves or in some cases using improved cook stoves or biogas stoves. Animal power for transportation or for farm use like tilling can also be considered a traditional form of use. Traditional use of biomass has the following characteristics. First, traditional biomass is usually gathered or collected (often by women and children) from common lands or privately owned lands and are, therefore, largely an informal activity. The only cost to users is the opportunity cost of time invested in collecting fuelwood. The informal nature of the market has been a reason for little private investment in research and development (R&D). Second, combustion of biomass is characterized by low efficiency due to poor design of stoves. As a result, biomass is overused and is associated with deforestation, fodder scarcity, and depletion of soil quality (due to nonavailability of animal manure and other residues for soil). Third, uncontrolled and open burning of biomass in traditional stoves in poorly ventilated chambers has serious health implications for women and children (Smith, 1987; Bailis et al., 2005). However, such attributes are not inherent to bioenergy and are the consequence of socioeconomic and political factors, which can be addressed with the aid of appropriate policies. For example, dissemination of improved cook stoves and biogas systems, better ventilation in the kitchen area, sustainable harvesting of wood, etc., can make traditional biomass more sustainable (Kammen, 2006). Investments in improving the efficiency and reducing emissions from traditional biomass use will have impacts as wide ranging as improving gender equity and halting environmental degradation given its high use of child and female labor and the high fuel use per unit of delivered energy.

1.5.2 Modern Biofuels

Although traditional biomass still comprises the major share of biobased energy, its share is declining relative to modern biomass. Liquid biofuels for transportation like ethanol and biodiesel are one of the fastest-growing sources of alternative energy in the world today and are poised to reverse the historical trend of decline in the share of biomass in the global primary energy supply. Like traditional biomass, modern biofuel systems also encompass a variety of feedstock, conversion technologies, and end uses as shown in Table 1.3. They are used mostly for generation of electricity or transportation as opposed to cooking and heating. The technological and commercial maturity and scalability of

Table 1.3 Biofuel technology matrix.

Feedstock type	Type of biofuel	Major end-use	Crops in temperate climes	Crops in tropical climes	Conversion technology	Technology maturity	Commercial maturity
Sugar and starch	Ethanol	Transportation	Corn, sugarbeet, wheat	Sugarcane, sorghum, cassava	Biochemical conversion (fermentation)	High	High
Oil seeds	Biodiesel	Transportation	Soy, rapeseed	Palm, *Jatropha**, Castor	Transesterification	High	High
Wood**	Fuelwood, Syn-gas	Cooking, heating, electricity	Willow, poplar	Eucalyptus, acacia, prosopis	Direct combustion, thermochemical conversion	High	Low
Municipal and agri-cultural waste**	Syn-gas or Biogas	Heating, electricity	na***	na	Direct combustion, thermochemical, anaerobic digestion	High	Low
Perennial grasses (cellulose)	Ethanol	Transportation	Switchgrass, Miscanthus		Biochemical (enzymatic) chemical (acid hydrolysis) conversion	Low	Nil

*Crop names in italics refer to those which are not commercial yet.
**Wood, municipal wastes and agricultural residues can also be converted to ethanol like perennial grasses using cellulosic technologies.
***Na — not applicable.

the various biofuel pathways are also diverse. Sugar and starch-based crops and the associated conversion technologies are the most mature for ethanol production today, while oilseed crops are the most mature sources of biodiesel. However, since they have low yield per hectare and are also used for food, they are not well suited for large-scale expansion. Cellulose-based fuels are considered the most promising for the future but are not commercially and technically mature today. The production of electricity from biomass, using wood and agricultural and municipal wastes while technologically mature, is not commercially widespread. The reasons for low commercial maturity are several including high cost, undercompensation for environmental benefits, etc. (Roos et al., 1999). Some of the technological aspects are described in more detail in the following sections.

A variety of biofuels are being produced today depending on the type of biomass source, the conversion technology, and end-use technology.

- Ethanol and biodiesel are the most widely used biofuels for transportation today. The former is blended with gasoline and the latter with diesel. Another prominent distinction is that ethanol is derived from starch- and sugar-based sources like cereals and sugarcane while biodiesel is produced from oil seeds. Biologically derived butanol and Fischer–Tropsch fuels could be two more types of future biofuels.
- Synthesis gas produced by gasification of wood is another type of biofuel used mainly for electricity generation.
- Fuelwood and biogas produced by anaerobic digestion of plant and animal wastes are used for cooking and heating at the household level.

Each of these biofuels can be produced from a variety of feedstocks using a variety of conversion technologies. A few major feedstocks and processes in commercial use today are described below.

1.5.2.1 Feedstock

The term feedstock refers to the raw material used in the conversion process, which can be a crop, crop residue, or agricultural and municipal waste. The main types of feedstock listed in Table 1.3 are described in detail below

1. *Sugar and starch-based crops*: Crops rich in sugar and starch like sugarcane and corn (maize), respectively, supply almost all the ethanol that is produced today. Other major crops being used include wheat, sorghum, sugar beet, and cassava. Technologies for conversion of sugar and starch are also the most technologically and commercially mature today. The major drawback of such crops is that they are important food crops, and their use for fuel can have adverse impacts on food supply. Another drawback is these crops are intensive in the use of one or more among inputs like land, water, fertilizer, and pesticides, which have other environmental implications (Giampietro et al., 1997; Ulgiati, 2001; Pimentel and Patzek, 2005; Farrell et al., 2006). Some characteristics like yield and water intensity of major sugar and starch crops are listed in Table 1.4. In the future cellulosic sources are expected to displace such crops as the major source of ethanol.
2. *Oilseed crops*: In contrast to ethanol, biodiesel is produced from oilseed crops like soybean, rapeseed, and oil palm (Sheehan et al., 2000; Demirbas, 2001). But like sugar and starch crops, oilseed crops are also characterized by low yield and high use of inputs. Some characteristics, e.g., yield and water intensity of major oilseed crops, are listed in Table 1.5. In the future nonedible crops like Jatropha curcas and Pongamia pinnata, which are considered to be low-input and suited to marginal lands, may become major sources of biodiesel, especially in the dry and semi-arid regions of Asia and Africa. But the economic viability of crops these crops under conditions of low inputs and poor land quality are considered highly uncertain (Prayas, 2007).
3. *Wood*: Wood is predominantly used for cooking and heating at the household level and to a lesser extent for producing electricity at a small scale. When used directly at the household level, it is often collected from forests or other

Table 1.4 Land and water intensity of potential sources for ethanol.

Ethanol feedstock	Global acreage (million hectares)*	Water required mm/yr (low)**	Water required mm/yr (high)**	Crop yield (tonnes per hectare)*	Ethanol conversion efficiency (liter/ton)***	Gasoline equivalent ethanol yield (liter/hec)	Ethanol yield per unit of water (liter/mm)	Growing season (months)
Wheat	215	450	650	2.8	340	600	1.09	4–5 months
Maize	145	500	800	4.9	400	450	0.69	4–5 months
Sorghum	45	450	650	1.3	390	450	0.82	4–5 months
Sugarcane	20	1500	1500	70	70	3300	1.65	10–12 month
Sugarbeet	5.4	550	750	100	110	7370	11.34	5–6 months
Sweet sorghum	insig.	450	650	40	70	1900	3.45	4–5 months
Bagasse*	na	na	na	18.9	280	3550	na	na

*Estimates that are typically cited, na — data not available or not applicable, insig. — not. significant; Data from FAO online statistical database.

**Data from FAO crop management database http://www.fao.org/ag/AGL/AGLW/watermanagement/default.stm.

***Data from various sources.

Source: Rajagopal (2008).

Table 1.5 Land and water intensity of major oilseed crops.

Oil seed crops	Oil content as % of seed wt	Water required mm/yr (low)	Water required mm/yr (high)	Trees per hectare	Average crop yield kg per hectare	Average oil yield in kg per hectare	Oil yield per unit of water (kg/mm)	Time to full maturity	Useful life (years)
Coconut	70	600	1200	100	na	4500	5.00	5 to 10 years	50
Oil palm	80	1800	2500	250	na	150	2.33	10 to 12 years	25
Groundnut	50	400	500	na	1015	508	1.13	100 to 120 days	na
Rapeseed	40	350	450	na	830	332	0.83	120 to 150 days	na
Castor	45	500	650	na	1100	495	0.86	150 to 280 days	na
Sunflower	40	600	750	na	540	216	0.32	100 to 120 days	na
Soybean	18	450	700	na	1105	199	0.35	100 to 150 days	na
Jatropha*	30	150	300	2000	2000	600	2.67	3 to 4 years	20
Pongamia*	30	150	300	1000	5000	1500	6.67	6 to 8 years	25

*Crops not commercially grown, calculations are based on estimates that are typically cited.

Source: Rajagopal (2008).

lands. Commercial plantations of woody trees like poplar and willow in temperate zones and eucalyptus and acacia exist today albeit on a small scale. The predominant use of commercial plantations today is for the supply of wood to paper and pulp industries (Ravindranath and Hall, 1995). Future cellulosic technologies, which permit the conversion of wood to ethanol, may compete with current uses of wood.

4. *Wastes and residues*: According to Kim and Dale (2004), there are about 73.9 million tonnes of dry wasted crops and about 1.5 billion tonnes of dry ligno-cellulosic biomass from seven crops, namely, maize, oats, barley, rice, sorghum, wheat, and sugarcane (Kim and Dale, 2004). These could potentially yield about 490 billion liters of ethanol or about 30% of global gasoline use today. Furthermore, lignin-rich fermentation residue, which is the coproduct of ethanol made from crop residues and sugarcane bagasse, can potentially generate both 458 TWh[5] of electricity (about 3.6% of world electricity production) and 2.6 EJ[6] of steam. The utilization of this feedstock is contingent upon the successful commercialization of cellulosic technologies. The economics of collection and processing of residues is also not clear. The low specific energy density of residues can imply high transportation costs that might render a large fraction of this resource uneconomical.
5. *Dedicated cellulosic crops*: Cellulose is the substance that makes up the cell walls of plant matter along with hemicellulose and lignin. It is the primary structural component of green plants comprising more than 50% of the phytomatter incorporated annually in plants. It is much more abundant than starch, sugar, and oil, which are concentrated only in seeds and fruits. Perennial grasses like switchgrass and Miscanthus are two crops considered having enormous potential for biofuel production in the next decade. Perennial crops

[5] TWh — terawatt hour (= 10^9 kilowatt hour).
[6] EJ — exajoule (= 10^{12} kilojoules).

also confer other advantages like lower rates of soil erosion and higher soil carbon sequestration. However, technologies for conversion of cellulose to biofuels are just emerging and not yet technically or commercially mature (described later). Cellulose conversion technologies will allow the utilization of nongrain parts of crops like corn stover, rice husk, sorghum stalk, bagasse from sugarcane, and the woody parts (Lynd, 1996; Wyman, 1999).

Theoretical estimates for global ethanol production from six potential crops, namely, sugarcane, corn (maize), wheat, sorghum, sugar beet, and cassava, based on global average yields are shown in Table 1.6. These six crops account for about 43% of the 1.4 billion hectare global acreage under crops (FAO, 2007). Utilization of the entire supply of these six crops for bioenergy would account for about 85% of global gasoline consumption in 2003, which was taken to be about 1,100 billion liters. Other calculations based on cropping patterns, yields, and conversion technologies suggest that, the United States, Canada, and European Union (EU)-15[7] would require between 30% and 70% of their respective current crop area if they are to replace even 10% of their transport fuel consumption with biofuels. The apparent discrepancy between the two calculations is because Europe and North America comprise a smaller portion of the production of crops relative to the rest of the world but a much larger portion of the demand for gasoline. Brazil on the other hand, would require only 3% of its current cropland to meet 10% of its gasoline demand (OECD, 2006). Obviously, it is hard to say anything about the feasibility of achieving this transition without consideration of the economic and environmental impacts.

1.5.2.2 Conversion Technologies

A number of conversion technologies are available today depending on the types of feedstock, fuel, and end use that are desired (Faaij, 2006;

[7] Fifteen countries in the European Union before the expansion on May 1, 2004: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom.

Table 1.6 Potential for ethanol production from major crops.

Crop	Global acreage (million hectares)*	Average yield (tons/ hectare)*	Global production (million tonnes)	Conversion efficiency (liters/ tonne)**	Land intensity (liters/ hectare)	Max. ethanol (billion liters)	Gasoline equivalent (billion liters)	Supply as % of 2003 global gasoline use***
Wheat	215	2.8	602	340	952	205	137	12
Rice	150	4.2	630	430	1806	271	182	16
Corn	145	4.9	711	402	1968	285	191	17
Sorghum	45	1.3	59	60	78	4	2	0
Sugarcane	20	65	1300	70	4550	91	61	6
Cassava	19	12	219	180	2070	39	26	2
Sugarbeet	5.4	46	248	110	5060	27	18	2
Wasted crops	—	—	74	660	—	49	33	3
Crop residues	—	—	1500	290	—	442	296	27
Total	599	—	—	—	—	1413	947	86

*Data from FAO online statistical database.

**Data from various sources.

***Global gasoline use in 2003 = 1,100 billion liters (Kim and Dale, 2004).

Farrell and Gopal, 2008). We will provide a brief review of each of these. Technologies that can be considered to be in the experimental stage are discussed in Section 1.6.

1. *Direct combustion*: This is the most common and oldest form of conversion that involves burning organic matter in an oxygen-rich environment mainly for the production of heat. The most common use of this heat is in the production of steam for industrial use or for electricity generation. In some cases, the goal of burning might simply be reduction in the volume of waste without energy recovery as is the case with disposal of agricultural or medical waste. Examples of applications of direct combustion include burning of biomass like wood, dung, and agricultural wastes in homes for cooking and heating, co-firing of biomass with coal in electricity production, the burning of wood for processed heat in chemical industries, etc. Typical flame temperatures for combustion and incineration range between $1,500^{\circ}$ F and $3,000^{\circ}$ F (Demirbas, 2001).
2. *Thermo-chemical conversion*: In contrast to direct combustion, thermo-chemical conversion utilizes heat and pressure in an oxygen-deficient environment to produce "synthesis gas." Syn-gas is composed mainly of carbon monoxide and hydrogen and can either be combusted to produce heat or converted to other fuels like ethanol and hydrogen. Thermo-chemical conversion is cleaner compared to other conversion pathways. Thermo-chemical conversion pathways include processes such as gasification, pyrolysis, plasma arc, and catalytic cracking. A detailed description of these technologies can be found in a report on conversion technologies by the California Integrated Waste Management Board (CIWMB). While gasification processes vary considerably, typical gasifiers operate from $1,300^{\circ}$ F and higher and from atmospheric pressure up to five atmospheres or higher (CIWMB, 2005).

3. *Biochemical conversion*: Unlike thermal and thermochemical processes, biochemical conversion processes occur at lower temperatures and have lower reaction rates. Higher moisture feedstock is more easily converted through biochemical processes. Fermentation and anaerobic digestion are two common types of biochemical conversion processes. The main use of fermentation is in conversion of sugar and starch, found in crops like sugarcane, corn, and wheat, to ethanol. The fermentation of alcohol yields coproducts like distiller dried grains, which can be used as feed for livestock. Anaerobic digestion involves the bacterial breakdown of biodegradable organic material in the absence of oxygen over a temperature range from about 50° to 160° F. The main end product of these processes is called biogas, which is mainly methane (CH_4), and carbon dioxide (CO_2) with some impurities such as hydrogen sulfide (H_2S). Biogas can be used as fuel for engines, gas turbines, fuel cells, boilers, and industrial heaters, and as a feedstock for chemicals (with emissions and impacts commensurate with those from natural gas feedstock) (Demirbas, 2001; CIWMB, 2005). Conversion of cellulosic feedstock using acid or enzymatic hydrolysis is another type of biochemical process, which is expected to become commercially very important in the future.
5. *Transesterification*: This is the most common method of producing biodiesel today. Transesterification is a chemical process by which vegetable oils (like soy, canola, and palm) can be converted to methyl or ethyl esters of fatty acids also called biodiesel. Biodiesel is physically and chemically similar to petro-diesel and hence substitutable in diesel engines. Transesterification also results in the production of glycerin, a chemical compound with diverse commercial uses. This process is carried out at a temperature of 60° C to 80° C (Sheehan et al., 2000; Crabbe et al., 2001; Demirbas, 2001, 2003).

1.6 Emerging Technologies

A variety of other technologies for conversion of biomass to fuels, or substitutes for fossil fuel-derived products like plastics, is being researched and developed.

1. *Cellulosic ethanol*: Cellulosic conversion implies the transformation of nongrain or nonfruit parts of phytomatter, which are mostly comprised of cellulose such as the stem, wood, grass, and leaves into ethanol. Switchgrass and Miscanthus are two perennial grasses that are undergoing trials as feedstock, while a variety of chemicals and biochemical processes including acid-based and enzymatic processes are being developed simultaneously for breaking down cellulose into ethanol. Similar to sugar refineries that utilize bagasse for cogeneration of electricity, cellulosic conversion can also be accompanied by the combustion of lignin to supply heat and steam for conversion. This will have the added benefit of offsetting electricity produced from fossil fuels (Lynd, 1996).
2. *Fischer-Tropsch fuels*: These are synthetic substitutes to gasoline and diesel, which are produced by a process in which carbon monoxide and hydrogen are catalytically transformed into liquid hydrocarbons (HC). Although coal and natural gas are considered as the main sources for carbon monoxide and hydrogen, gasification of biomass feedstock is considered a more environmentally benign conversion pathway for Fischer–Tropsch fuels (Hamelinck et al., 2004). Another line of research involves production of "biocrude" through high-temperature/pressure and chemical breakdown of biomass into liquids, using hydrothermal upgrading (HTU) or pyrolysis.
3. *Biobutanol*: Biobutanol is butanol (i.e., butyl alcohol), which is produced biologically from biomass through a process called acetone butanol ethanol (ABE) fermentation. As a result of low butanol yield, ABE fermentation was considered

uneconomical. However, it is expected to be viable at a gasoline price of $3.00 per gallon or greater (Ramey, 2004).

4. *Algae biodiesel*: Another novel technology is biodiesel production from algae perhaps similar to how they are used to produce food supplements such as spirulina. However, recent surveys suggest that there are major difficulties in finding an algal strain with a high lipid content and fast growth rate that is not too difficult to harvest, and has a cost-effective cultivation system (Farrell and Gopal, 2008).
5. *Biobased products and bioplastics*: Agricultural feedstock can also be used to produce other industrial products called bioproducts and bioplastics, which are substitutes to chemicals, plastics, hydraulic fluids, and pharmaceuticals produced from fossil fuels. Agricultural feedstock which are considered as candidates for making such products, include a variety of crops, wood and plant oils, and agricultural and forestry residues. Bioproducts are considered to require less energy to produce than the fossil and inorganic products they replace (USDA, 2007).

1.7 Estimates of Future Potentials for Bioenergy

There are several studies that estimate the global potential of biofuels in absolute units of energy and as percentages of global energy that they can supply. Estimates of such potential can be classified into three categories, namely, biophysical, technical, and economic. Each category in the list comprises the ones following it, so that the three categories are of decreasing magnitude. Biofuels can in principle supply a large fraction of global energy need, and this is called the theoretical potential. The biophysical potential is determined primarily by natural conditions and describes the amount of biomatter that could be harvested at a given time. The technical potential depends on the available technologies and therefore evolves as technology progresses. Estimates of biophysical and technical potential vary depending on assumptions about land availability, yield levels in energy crop production, future availability of forest wood and of residues from agriculture and forestry, etc. The economic potential depends on at least two additional factors, namely, energy prices and policies toward renewable and clean technologies. However, oil prices are uncertain with respect to time, while policies vary both with time and also from region to region (Fischer and Schrattenholzer, 2001). As a result, economic potential is hard to predict. For example, Brazilian ethanol is economically viable when oil sells at $35 per barrel whereas US ethanol is viable only at around $50 per barrel (OECD, 2006; Ugarte, 2006). These estimates are, however, sensitive to the cost of feedstock. But for the concomitant increase in oil price, the recent increase in corn prices would render several ethanol plants unprofitable.

Most studies report an increase in the supply of bioenergy over time. A review of 17 earlier studies on this subject by Berndes et al. (2003) reveals that estimates for potential contribution of biomass in the year 2050 range from below 100 EJ/yr to over 400 EJ/yr (Berndes et al., 2003). In comparison to the current level of bioenergy of 45 EJ/yr, this represents a doubling to a tenfold increase. A study by the International Institute of Applied Systems Analysis and the World Energy Council predicts that bioenergy would supply 15% of global primary energy by 2050 (Fischer and Schrattenholzer, 2001). In comparison the share of bioenergy is about 10.6% (see Figure 1.2). A study by the Natural Resources Defense Council predicts that an aggressive plan to develop cellulosic biofuels between now and 2015, could help the United States produce the equivalent of nearly 7.9 million barrels of oil per day by 2050. This is equal to more than 50% of the current total oil use in the transportation sector in the US (Greene et al., 2004). A majority of the increase is accounted by cellulosic biomass like switchgrass.

However, it is also possible to envision scenarios that involve reduction in cropland while meeting the future food needs for a larger and wealthier population. One of the drawbacks of the above assessment is that it is static and does not take into account future changes in technologies and the demand for food. An analysis of the demand for cropland based on fundamental forces responsible for expansion of cropland by Waggoner and Ausubel (2001) suggests that sustained technological progress in crop production could meet the recommended nutritional requirements for a population of 9 billion and simultaneously reduce cropland by 200 million hectares by the year 2050. It is even claimed that under the best-case scenario the land withdrawn from agriculture could be as high as 400 million hectares. At the same time, they warn that such improvements would come about only through sustained investments in productivity, experimentation, and deployment of better technologies (Waggoner, 1996; Waggoner and Ausubel, 2001). Extending on their analysis, we depict in Table 1.7 a hypothetical scenario in which the 200 million hectares of freed cropland is allocated equally to switchgrass and Miscanthus for producing lingo-cellulosic biomass. Assuming a conversion efficiency of 330 liters per ton, about 1,100 billion liters of gasoline-equivalent ethanol could be produced, which at today's consumption levels can offset about 64% of the global demand for gasoline.

1.8 Diverse Solutions for a Diverse World

Biofuels have played a vital role in meeting the energy needs of human beings. There is reason to believe that they will continue to do so in the future albeit in a different manner. Traditional forms of biomass energy are still prevalent among the rural poor in developing countries that use it for cooking and heating (Figure 1.9). Modern forms of bioenergy are expanding in the developed countries largely for use in automobiles and electricity generation. With economic growth, the share of traditional biomass will decline while that of modern energy sources will increase so that transportation and electricity production may be the dominant end uses one day as opposed to cooking and heating. However, given the slow pace of expansion of rural electrification and access to clean cooking fuels in developing countries, such a change may be a long while coming. Traditional or modern, biofuels can make a positive contribution to all three pillars of sustainable development — economic, social, and environmental. But the diversity in the social, economic, and environmental impacts proscribes a "one size fits all" approach. Most people contend that no single source of biomass or conversion technology or type of biofuel will suffice because of the disparate agro-climatic, ecological, technological, and socioeconomic and political economic factors that need consideration. Modern biofuels can in some cases be more

Table 1.7 Potential for ethanol from perennial grasses in future based on predictions.

Crop	Global acreage in 2005 (million hectares)*	Average yield (tons/ hectare)**	Global production (million tonnes)	Conversion efficiency (liters/ tonne)***	Land intensity (liters/ hectare)	Max. ethanol (billion liters)	Gasoline equivalent (billion liters)	Supply as % of 2003 global gasoline use****
Switchgrass	100	10	1000	330	3300	330	220	20
Miscanthus	100	22	2200	330	7260	726	490	44
Total	200					1056	710	64

*A hypothetical scenario in which about 100 million hectares each are under switchgrass and miscanthus.
**Yield reported in Heaton et al. (2004).
***Predicted conversion efficiencies reported in Khanna et al. (2007).
****Global gasoline use in 2003 = 1,100 billion liters (Kim and Dale, 2004).

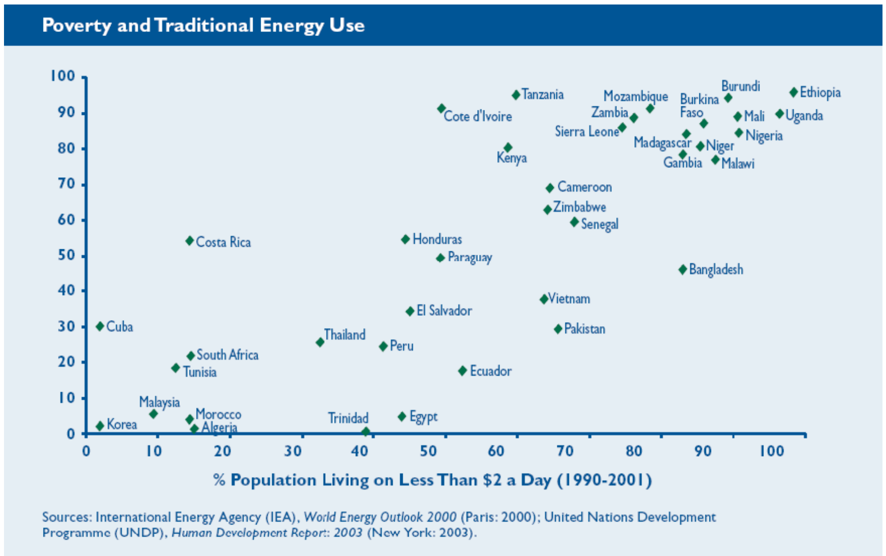

Fig. 1.9 Poverty and biomass energy use (Karekezi and Kithyoma, 2006).

detrimental to the poor than traditional biofuels. The appropriation of food crops for ethanol production may have adverse impacts of food prices (FAPRI, 2005; Msangi et al., 2006; OECD, 2006; Runge and Senauer, 2007). The commercialization of cellulosic technologies may result in conversion of fodder resources for livestock or conversion of wood used by household into fuel for automobiles. The use of marginal lands for biofuel plantations can also worsen the energy poverty of the landless poor who may stand to lose access to fuelwood and fodder from such lands (Gundimeda, 2004; Karekezi and Kithyoma, 2006; Rajagopal, 2008). In the case of poor rural households in developing countries, the use of biomass for providing cleaner energy for cooking and providing electricity may be more beneficial overall rather than using them to produce transportation fuels (see Table 1.8).[8] Along with

[8] Table 1.8 shows a-back-of-the-envelope calculation, which estimates the amount of land required to produce enough oil for electricity generation using diesel generators for a single village of 100 households. The most striking conclusion that emerges from this table is that providing an average supply of 100 watts of electricity for 8 hours per day to the approximately 90 million rural households without electricity access today can be achieved using less land than it would require to meet 20% of India's demand for diesel.

Table 1.8 Estimate of land needed to electrify rural homes in India using biodiesel.

Number of households per village	100
Maximum demand per household (watts)	100
Number of hours of supply per day	8
Energy supplied per household per day (watt hour/day)	800
Total energy supplied to village per year (kilo watt hours /year)	30000
Specific fuel consumption of diesel generator (gms/kWhr)*	300
Oil required to generate electricity (tonnes/year)	9
Oil yield per hectare (kgs/hec.)	0.6
Total land required to produce the needed oil per village (hec.)	15
Number of village households in India	150,000,000
% of households with no electricity access	60%
Number of unelectrified households	90,000,000
Total land required to electricity rural homes (million hec)	13
Annual consumption of diesel in India (million tonnes)	42
Total land required to meet 20% of diesel demand (million hec)	14

*Specific fuel consumption refers to the amount of oil (gms) needed to produce one kilo watt hour of electricity.
Source: Rajagopal (2008).

technological progress, innovative policies will be necessary to ensure a smooth transition to a future where modern biofuels can be a significant supplier of energy. This section has provided a historical and technological perspective. In the following sections, we will discuss the environmental, economic, and political aspects of biofuels.

And given the rate of growth in transportation fuel demand in India, an increasingly larger area will need to be converted to energy plantations to meet a given percentage of the demand using biofuels. A comparison of social impact of providing electricity access versus providing marginally better transportation fuel for cars would make this comparison even more useful.

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