

# Review of Environmental, Economic and Policy Aspects of Biofuels

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## Abstract

The world is witnessing a sudden growth in production of biofuels, especially those suited for replacing oil like ethanol and biodiesel. This paper synthesizes what the environmental, economic, and policy literature predicts about the possible effects of these types of biofuels. Another motivation is to identify gaps in understanding and recommend areas for future work. The analysis finds three key conclusions. First, the current generation of biofuels, which is derived from food crops, is intensive in land, water, energy, and chemical inputs. Second, the environmental literature is dominated by a discussion of net carbon offset and net energy gain, while indicators relating to impact on human health, soil quality, biodiversity, water depletion, etc., have received much less attention. Third, there is a fast expanding economic and policy literature that analyzes the various effects of

biofuels from both micro and macro perspectives, but there are several gaps.

A bewildering array of policies – including energy, transportation, agricultural, trade, and environmental policies – is influencing the evolution of biofuels. But the policies and the level of subsidies do not reflect the marginal impact on welfare or the environment. In summary, all biofuels are not created equal. They exhibit considerable spatial and temporal heterogeneity in production. The impact of biofuels will also be heterogeneous, creating winners and losers. The findings of the paper suggest the importance of the role biomass plays in rural areas of developing countries. Furthermore, the use of biomass for producing fuel for cars can affect access to energy and fodder and not just access to food.

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This paper—a product of the Sustainable Rural and Urban Development Division, Development Economics Research Group Department—is part of a larger effort in the department to mainstream economic research on climate change. Policy Research Working Papers are also posted on the Web at <http://econ.worldbank.org>. The authors may be contacted at [zilber@are.berkeley.edu](mailto:zilber@are.berkeley.edu) and [deepak@berkeley.edu](mailto:deepak@berkeley.edu).

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## List of acronyms

ABE - acetone butanol ethanol

ASM - Agricultural Sector Model

FBDS - Brazilian Foundation for Sustainable Development

Btu - British thermal unit

CIWMB - California Integrated Waste Management Board

CGE - computable general equilibrium

CRP - Conservation Reserve Program

CGF - corn gluten feed

CGM - corn gluten meal

DDG - distiller's dried grain

DDGS - distiller's dried grain with solubles

EPPA - Emissions Prediction and Policy Analysis

EJ - exajoule

FFV - flexible fuel vehicles

FAPRI - Food and Agricultural Policy Research Institute

FAO - Food and Agriculture Organization of the United Nations

FASOM - Forest and Agricultural Sector Optimization Model

GHG – greenhouse gas

HC - hydrocarbon

IFRPI - International Food Policy Research Institute

IMPACT -International Model for Policy Analysis of Agricultural Commodities and Trade

LCA – life-cycle assessment

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

# **1 Biofuels - Sources, Production, and Uses**

## **1.1 Motivation behind the survey**

The last few years have witnessed both a dramatic increase in the price of oil and an increase in the production of biofuels like ethanol and biodiesel (Martinot 2005, EIA 2007). There have been such developments in the past too, the most notable being during the 1970s in the aftermath of the energy crisis, but these were short lived. The perception this time around, however, is that these trends will persist for a much longer time frame. One reason for this is that supply of oil is not expected to keep up with demand in future (Campbell and Laherrere 1998). The large energy-consuming nations are all setting ambitious long-term targets for biofuels and for reduction in carbon emission (Kojima and Johnson 2005; Fulton, Howes, Hardy 2004). Therefore, it is becoming increasingly certain that in the future agriculture will become a significant supplier of energy along with food. This presents both opportunities and risks especially in a developing country context. The main contribution of biofuels will be in providing energy that is renewable, less carbon intensive than oil, and can be produced domestically by most countries. But 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, increase in use of agrichemicals, etc. 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. A related motivation is to identify areas for future work that are critical from a public policy standpoint. Since this is a review of literature, it has not been our aim to present new analysis. There are five chapters in this report. The first chapter describes the drivers for biofuels, the various types of biofuels, and some of the emerging technologies. It also provides a historical perspective on biofuels. The second chapter surveys the environmental literature on biofuels. The third chapter is a review of the studies of economic impacts of biofuels. The fourth chapter is a review of the various policies that are influencing the evolution of



biofuels and their economic implications. The fifth chapter 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 (Runge 2007, Hazell and Pachauri 2006). 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). Transportation is expected to account for about one-half of the total projected increase in global oil use between 2003 and 2030 (EIA 2007). Transportation also accounts for 21% of global annual greenhouse gas (GHG) emissions (Watson, Zinyowera, and Moss 1996). While a range of technologies including renewable sources like wind and solar photovoltaics and carbon-free technologies like nuclear are poised to challenge coal and natural gas in the electricity sector, there seemed to exist no alternative 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 are replenishable:** Biofuels are an inexhaustible resource since the stock can be replenished through agriculture. Technologies like fuel cells and electric vehicles depend on hydrogen and the electric grid, respectively, and are effectively dependent on depletable sources like natural gas and coal, respectively.
2. **Biofuels can reduce carbon emissions:** Biofuels are sometimes considered as a solution to climate change. While this may be too optimistic, it is true that direct carbon emissions from combustion of biofuels are insignificant compared to fossil fuels. That said, it is hard to generalize about indirect carbon emissions (from agriculture and processing) and emissions of other harmful pollutants, which can be significant.

3. **Biofuels can increase farm income:** Today decline in farm income is 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 need for subsidies for income support (Hazell and Pachauri 2006).
4. **Biofuels can improve energy security:** The above fact also means that countries can produce their own fuel, and reduce their dependence on foreign sources for energy (Hazell and Pachauri 2006).
5. **Biofuels can create new jobs:** Biofuels are more labor intensive than other energy technologies on per unit of energy delivered basis (Kammen, Kapadia, and Fripp 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 are 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:** Several physical and chemical characteristics of biofuels such as their liquid state, specific energy density, viscosity, and combustion characteristics are more similar to gasoline or diesel than for alternatives. They are combustible in existing internal combustion engines with minor modifications. 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 (Ugarte 2006; Fulton, Howes, Hardy 2004).
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 used as an additive or as a blend with gasoline in several countries for over two decades. In fact, Henry Ford and Rudolph Diesel who are considered the grandfathers of the automobile assembly line and the diesel engine, respectively,

are said to have prophesized a future for transportation based on fuels derived from plant-based sources.<sup>1</sup>

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; the technology is not without costs. Biofuels may mean filling the fuel tank at the cost of emptying the stomach of the poor (Runge 2007, Msangi 2006). Biofuels are also feared for the impact they will have on the natural environment (Runge 2007, van Dam 2006, Fearnside 2002, Giampietro 1997). 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 like fertilizers, pesticides, etc., which have negative environmental externalities. By increasing energy supply, biofuels can also undermine efforts at improving energy efficiency and energy conservation. We defer a more detailed discussion on the environmental and economic implications on biofuels to later chapters. The emphasis in this chapter is on the sources, technologies and uses of bioenergy systems.

Although the term biofuels is being appropriated to refer just to 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, fermentation, etc. Traditional biomass accounts for 80% of the global 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

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<sup>1</sup> <http://news.bbc.co.uk/2/hi/science/nature/6294133.stm>

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 and 2003; Ravindranath and Hall 1995; Barnes and Floor 1996; and Bailis, Ezzati and Kammen 2005).

The rest of the chapter is organized as follows. Section 2 provides some basic statistics on global energy use and the share of biofuels. Section 3 provides a historical perspective on biofuel use. Section 4 describes the various biofuel technologies in use today. Section 5 summarizes the findings of several studies that estimate the future potential of biofuels. Section 6 describes cutting edge research in biofuel technologies. Section 7 concludes the chapter.

### **1.3 Global energy situation and the share of bioenergy**

The global energy production in 2004 was about 440 quadrillion Btu<sup>2</sup>(11000 mtoe<sup>3</sup>) (EIA 2007) (figure 1). In terms of end-use consumption, transportation, and electricity accounted for 21% and 30%, respectively (Watson, Xinyowera, and Moss 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 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 2). Combustible renewables and waste are consumed mainly in non-OECD countries while hydro and other modern renewables are consumed largely in OECD countries (Figure 3). Overall Africa, non-OECD (Organization for Economic and Development) Asia, and China combined for 67% of the global renewable energy (figure 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 (figure 3 and 4). From an end-use energy perspective, 58% of the renewable energy is consumed by the residential, commercial, and public sector (figure 5). We can

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<sup>2</sup> Btu –British thermal unit

<sup>3</sup> mtoe – million tonnes of oil equivalent

also safely assume that a majority of the combustible renewables and waste is consumed for cooking and heating purposes especially in developing countries.

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 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 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, Howes, Hardy 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 U.S. land—land that had been used to grow grass and other feed for the millions of animals used by humans.<sup>4</sup> With the advent of coal and petroleum in the middle and late 19<sup>th</sup> 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,

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<sup>4</sup> <http://bioenergy.ornl.gov/papers/misc/switgrs.html>

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 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. 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 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, Ezzati, and Kammen (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 (Pachauri 2004). In China, despite rapid economic growth, 80% of households continue to rely on biomass or coal as their primary cooking and heating fuels (Smith 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.

## **1.5 Biofuel sources and conversion technologies**

### **Conceptual framework for understanding bioenergy**

Most bioenergy systems can be explained using the schematic shown in figure 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 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 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.

### **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. Firstly, 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, Ezzati, and Kammen 2005). But 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 women labor and the high fuel use per unit of delivered energy.

### **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 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 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. But 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 1999). Some of the technological aspects are described in more detail in the following sections.

### **Major types of biofuels**

A variety of biofuels can be derived from biomass.



- Ethanol and biodiesel are the most widely used biofuels for transportation today. In the future, butanol and Fischer-Tropsch fuels have the potential to become competitive as liquid fuels.
- Synthesis gas produced by gasification of wood is 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.

## **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 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, pesticides, etc., which have other environmental implications (Pimentel and Patzek 2005; Ulgiati 2001; Giamipietro, Ulgiati, and Pimentel 1997; Farrell 2006). Some characteristics like yield and water intensity of major sugar and starch crops are listed in table 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 (Demirbas 2001, Sheehan 2000). But like sugar and starch crops, oilseed crops are also characterized by low yield and high use of inputs. Some characteristics like yield and water intensity of major oilseed crops are listed in table 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 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<sup>5</sup> of electricity (about 3.6% of world electricity production) and 2.6 EJ<sup>6</sup> 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 phyto-matter 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 to hold enormous potential for ethanol production. Perennial crops also confer other advantages like lower rates of soil

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<sup>5</sup> TWh – terawatt hour (= 10<sup>9</sup> kilowatt hour)

<sup>6</sup> EJ – exajoule (= 10<sup>12</sup> kilojoules)

erosion and higher soil carbon sequestration. However, technologies for conversion of cellulose to ethanol 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 (Wyman 1999, Lynd 1996).

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 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 production accounted for about 85% of global gasoline consumption in 2003, which was taken to be about 1,100 billion liters. A more plausible scenario in which 25% of the current annual production of such crops is used for ethanol production would result in a 21% reduction in gasoline demand. Similar calculations based on cropping patterns, yields, and conversion technologies suggest that, the United States, Canada, and EU-15<sup>7</sup> 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. But only 3% of Brazil's current cropland would be required to meet 10% of its 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.

### ***Conversion technologies***

A number of conversion technologies are available depending on the types of feedstock, fuel, and end use that are desired (Faaij 2006). We will provide a brief review of each of these.

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<sup>7</sup> 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.

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 process heat in chemical industries, etc. Typical flame temperatures for combustion and incineration range between 1,500° F and 3,000° 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° F and higher and from atmospheric pressure up to five atmospheres or higher (CIWMB 2005).
3. **Biochemical conversion:** Unlike thermal and thermo-chemical 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, wheat, etc., 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<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) with some impurities such as hydrogen sulfide (H<sub>2</sub>S). 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.

4. **Transesterification:** This is the most common method of producing biodiesel today. Transesterification is a chemical process by which vegetable oils (like soy, canola, palm, etc.) 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 (Demirbas 2001, 2003; Sheehan 2000; Crabbe 2001).

In this section we have reviewed briefly only some of the common conversion processes in use today. R&D underway today are expected to lead to the commercialization of several new conversion technologies in the future. Some of these are reviewed briefly below.

## 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.

- **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, leaves, etc., into ethanol. Switchgrass and Miscanthus are two perennial grasses that are undergoing trials as feedstock while a variety of chemical 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).

- **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 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. All these pathways are currently expensive and technically immature (Fulton 2005).
- **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).
- **Algae biodiesel:** Biodiesel production from algal oil is another technology, which is considered to have significant potential to replace diesel use. However, the major difficulties are in finding an algal strain with a high lipid content and fast growth rate that isn't too difficult to harvest, and has a cost-effective cultivation system (Sheehan 1998).

- **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 U.S. ethanol is viable only at around \$50 per barrel (Ugarte 2006, OECD 2006).

Most studies report an increase in the supply of bioenergy over time. A review of 17 earlier studies on this subject by Berndes, Hoogwijk, and van den Broek (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, Hoogwijk, and van den Broek 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). 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 (Greene 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 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 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. 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 detrimental to the poor than traditional biofuels. The appropriation of food crops for ethanol production may have adverse impacts of food prices (Runge 2007, Msangi 2006, OECD 2006, FAPRI 2005). 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 would lose access to fuelwood and fodder from such lands (Gundimeda 2004, Rajagopal 2007, Karekezi and Kithyoma 2006). 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<sup>8</sup>. Along with 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 chapter has provided a historical and technological perspective. In the following chapters, we will discuss the environmental, economic, and political aspects of biofuels.

## **2 Environmental Footprint of Biofuels**

### **2.1 Introduction**

One of the major arguments behind support for biofuels is the perception that they are more climate friendly than oil. Biofuels are sometimes even claimed as being carbon neutral and fossil free. But serious concerns about the carbon benefits of current biofuels have been raised in the literature (Pimentel and Patzek 2005, Farrell 2006). In reality, biofuels consume a significant amount of energy that is derived from fossil fuels. Inputs to production include tillage, fertilizers, pesticides, irrigation, operation of machinery for harvesting and transport, steam and electricity for processing, etc., all of which embody fossil energy, leading to a significant net carbon addition to the atmosphere by the time the biofuel is ultimately consumed (Giampietro 1997, Lal 2004, Pimentel and Patzek 2005, Farrell 2006). Equally important is the fact that production of biofuels has other nonclimate-related environmental impacts such as soil erosion due to tilling, eutrophication due to fertilizer runoffs, impacts of exposure to pesticides, habitat, and biodiversity loss due to land-use change, etc., which have not received the same attention as GHG emissions. The adverse changes taking place in the Cerrado region of Brazil or the rainforests in Indonesian Borneo, which are biodiverse regions, have been associated with expansion of soybean and oil palm plantations, respectively (Fearnside 2002, Curran

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<sup>8</sup> Table 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 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. And given the rate of growth in transportation fuel demand in India 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

2004). In fact, already the fear of rainforest destruction due to the EU's biofuel mandate led commissioner Peter Mandelson to recently declare, "Europeans won't pay a premium for biofuels if the ethanol in their car is produced unsustainably by systematically burning fields after harvests, or if it comes at the expense of rainforests. We can't allow the switch to biofuels to become an environmentally unsustainable stampede in the developing world."<sup>9</sup> Given these trade-offs, characterizing the overall environmental impact of biofuels is complex and challenging. The aim of this chapter is to summarize some prominent works that measure the environmental impacts of biofuel. The literature is dominated by studies that use a technique called life-cycle assessment (LCA) to compare the environmental indicators of biofuels, vis-à-vis fossil fuels. This is a purely engineering technique today. We think environmental assessments should involve a broader set of tools, which would include economic tools like general equilibrium models and also tools used by ecologists and agronomists for impact assessment in their domain. We defer a discussion on these to the chapter on future work. The rest of the chapter is organized as follows. Section 2.2 describes briefly some of the life-cycle analysis terminology. Section 2.3 lists some of the caveats of this methodology. Section 2.4 describes some case studies. Section 2.5 is a summary of the LCA studies. Section 2.6 concludes the chapter.

## **2.2 LCA models**

One approach to estimating the environmental burden of an activity is to estimate its resource footprint, and one way to characterize this is in terms of the intensity of consumption or emission of polluting substances. For example, greater emission of GHG is associated with greater contribution to global warming, and greater emission of criteria pollutants or toxic chemicals can be associated with greater human health impact. Similarly, more intensive use of surface water for irrigation can reduce its availability of environmental purposes. Thus, by measuring the net emission or net consumption of a resource, one can compare the environmental footprint of competing products and processes. The most widely used model today to perform such calculations is an LCA

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<sup>9</sup> <http://news.bbc.co.uk/2/hi/business/6273626.stm>

model. An LCA model aggregates the material (quantity of fuel, electricity, water, chemicals, pollutants, etc.) and the embodied energy flow associated with the production and/or consumption of a particular commodity. In the case of fuels, LCAs look at the whole picture of how a fuel is made beginning with farming, followed by harvesting, processing and distribution, and end use.

The essential theory behind LCA is the principle of conservation of mass and energy inflow through a controlled system in which inputs are combined to produce one or more outputs. For a given state of technology, the inputs are combined in a fixed proportion. This proportion is invariant across space and time so long as the technology is held constant. In other words, it should require almost identical quantities of corn grain, calories of heat, and liters of water to produce a liter of ethanol in the United States and China so long as the same chemical technology is in use. Therefore, knowing the distribution of technology across firms (which are discrete and estimable at least in theory), we can aggregate impacts from a micro- to macro level and thereby estimate the overall level of emissions, etc. (of course, aggregation would have to be done recursively for estimating the flows during production of inputs themselves and so on). But such aggregation can be more complex for agricultural processes since the production function varies from farm to farm. For example, the level of use of fertilizer can vary with land quality or the level use of labor and machinery may vary etc.

An LCA does not per se measure the environmental impact resulting from an activity, but it measures the indicators that can be used to estimate the ultimate impacts. In some cases the indicator can be directly associated with an environmental impact such as global warming potential but for impacts on human health, biodiversity loss, etc., this is unclear yet. Some of the common indicators LCAs that have been used to measure include:

- ***Net energy value*** (NEV): A simple definition of NEV is “energy contained in a liter of ethanol minus the fossil energy used to produce that liter of ethanol.” It is measured in units of megajoules per liter of biofuel (MJ/lit). There are two important things to remember here: (1) NEV does not measure the net energy created in the process of producing biofuel, which by the first law of

thermodynamics is obviously zero, and (2) NEV calculations are meaningful when only fossil energy inputs are considered. Therefore, solar energy utilized during photosynthesis is not considered. However, wind, hydro, nuclear, and other renewable energy contained in the electricity supply may or may not be considered. A possible justification for exclusion of energy used for photosynthesis is that it has no opportunity cost. But such justification is not tenable for energy delivered from other nonfossil sources especially if the marginal resource is nonrenewable. In our opinion a meaningful indicator should include all energy sources with an opportunity cost. Mathematically,

$$\begin{aligned}
 NEV = & \text{energy contained in the fuel} + \\
 & \text{energy contained in the coproduct energy} - \\
 & \text{energy consumed in the agriculture phase} - \\
 & \text{energy consumed in the conversion phase} - \\
 & \text{energy consumed in transportation of crops and finished fuel}
 \end{aligned}$$

In some cases the NEV is calculated as the net energy ratio (NER), i.e., the ratio of energy content of ethanol and the fossil energy used to produce ethanol. Sometimes it is also called the fossil energy intensity, i.e., amount of fossil energy needed to produce one unit of fuel. The main drawback of net energy indicators is that they carry little economic or environmental intuition.

- **Net petroleum offset:** This refers to the reduction in petroleum consumption that can be achieved by using biofuel. One way to measure the net petroleum offset is to calculate the number of gallons of gasoline displaced by one gallon of ethanol. This indicator can be useful for studying the implications of biofuel for oil depletion, oil imports, etc.
- **Net carbon reduction:** This refers to the net reduction in carbon emissions resulting from the consumption of a unit of biofuel. Biofuels are generally expected to result in lower net addition of carbon to the atmosphere because the carbon emitted on combustion is eventually sequestered during recultivation, whereas carbon emitted during combustion of fossil fuels is not. But because

inputs used during the fuel production process are made with fossil energy there is a net addition of carbon to the atmosphere.

Detailed mathematical definition of the metrics can be found in Farrell et al. (2006). In reality, all metrics are dynamic because technological change and equilibrium effects can affect such metrics. However, we are not aware of any studies that perform such an analysis in the context of biofuels.

### 2.3 Case studies

In this section we review some prominent studies that analyze some physical and environmental indicators of biofuels. A tabulated summary of these studies is in table 9.

- **Ethanol from corn:** The LCA of corn ethanol produced in the United States is one of the most studied among all biofuel pathways. Through a meta-analysis of several studies, Farrell et al. (2006) conclude that although current corn ethanol technologies will result in reduction in crude oil use, the GHG are, however, only marginally lower than for gasoline. They report a net energy gain of 4.6 MJ<sup>10</sup>/liter (or a energy ratio of 1.2, i.e., 20% energy more than is consumed in production). Cellulosic technologies are estimated to be capable of delivering an energy gain of 23 MJ/liter (or an energy ratio of 8.1) (figure 9). The most prominent critique of corn ethanol is a study by Pimentel and Patzek (2005), which estimates both a net energy loss and net carbon emission increase from all forms of biofuels including cellulosic sources. However, the consensus view is that such studies find negative net benefits either ignored coproduct benefits or used obsolete data (Pimentel and Patzek, 2005). But almost all studies conclude that other important environmental effects of biofuel production like increase in soil erosion, eutrophication, land-use changes and its impact on biodiversity and habitat loss, etc., are poorly understood.
- **Ethanol from sugarcane and cassava:** The other most prominently discussed LCA of biofuels in the literature concerns the production of ethanol from sugarcane. Macedo, Leal, and de Silva (2004) analyze two scenarios for the case

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<sup>10</sup> MJ – Mega joule (= 10<sup>6</sup> joule)

of Brazil, one based on the average values of energy and material consumption and a second based on the best practices in the sugarcane sector. The ratios of output energy (renewable) to input energy (fossil) per ton of sugarcane are 8.3 and 10.2, for the two scenarios, respectively. The emissions avoided due to the substitution of ethanol for gasoline and surplus bagasse for fuel oil for electricity, deducting the above values, give a net result of 2.6 and 2.7 tonnes of CO<sub>2</sub> equivalent /cubic meter anhydrous ethanol and 1.7 and 1.9 tonnes of CO<sub>2</sub> equivalent /cubic meter of hydrous ethanol, for the two scenarios, respectively. Based on this study, it is generally concluded that sugarcane ethanol is more efficient from a net energy perspective. Nguyen, Gheewala, and Garivait (2007) in a net energy analysis of ethanol from cassava in Thailand find a NEV of 9.15 MJ/L, which is almost twice that of ethanol. Notably, their calculations do not include any coproduct credits and yet find a higher NEV than corn ethanol in the United States. Mrini, Senhaji, and Pimentel (2001) in an energy assessment of the cultivation of sugarcane in Morocco find that irrigation accounted for 50% of the input energy requirements.

- **Ethanol from sugarcane byproducts:** A comparison of the environmental benefits of converting sugarcane bagasse, the fibrous residue after cane is crushed, to ethanol production as opposed to disposing it through the current practice of open-field burning revealed lower net values of carbon dioxide, carbon monoxide, hydrocarbons, SO<sub>x</sub>, NO<sub>x</sub>, particulates, carbon dioxide, methane, and fossil energy consumption (Kadam 2000). Additional drivers are the lower values observed for the following impact assessment categories for the ethanol scenario: depletion of natural resources, air acidification potential, eutrophication potential, human toxicity potential, and air odor potential. Prakash, Henham, and Bhat (2005) estimate a net energy ratio of 2 for ethanol made from sugarcane molasses in India.
- **Biodiesel from oilseeds:** Sheehan et al. (2000) find that substituting B100 for petroleum diesel in buses was found to reduce the life-cycle consumption of petroleum by 95%. Biodiesel is also claimed to yield 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle. With regard to

emissions, biodiesel reduces net CO<sub>2</sub> emissions by 78.45%, particulate matter by 32%, CO by 35%, and SO<sub>x</sub> by 8%, relative to petroleum diesel life cycle, while NO<sub>x</sub> and unburnt HC emissions increase by 13.35% and 35%, respectively. Tailpipe emissions of particulates smaller than 10 microns are 68% lower for buses that run on biodiesel (compared to petroleum diesel). Tailpipe CO emissions are 46% lower, while biodiesel completely eliminates tailpipe SO<sub>x</sub> emissions. LCA of rapeseed biodiesel and petro-diesel in Europe found that replacing ultra low sulphur diesel with rapeseed biodiesel yields up to 83% reductions in fossil fuel use, 86% net savings in carbon dioxide emissions, and 80% net savings in GHG emissions (Janulis 2004; Mortimer, Elsayed, and Horne 2003).

- **Electricity from wood:** The production of electricity through gasification and combustion of purpose-grown wood in the United States was found to have a net energy ratio of 15 (Mann and Spath 1997); see figure 10 for details. Again the input energy calculations do not include energy content of the biomass i.e., photosynthetic energy harvested by the plant and includes only the energy input fossil fuels for farm operations, transportation, and processing of biomass in the power plant. The power plant was found to have a 95% carbon closure rate, i.e., 95% of the carbon emitted upon combustion was recycled through the system. An LCA of electricity production from short rotation coppice wood chips in the UK showed a 91% reduction in fossil fuel use, and a 78% net saving in GHG emissions (Mortimer, Elsayed, and Horne 2003). The high net energy and carbon savings from electricity production using biomass present some interesting options for policy especially in developing countries, which we discuss later.
- **Electricity from municipal solid waste:** A comparison of various options for disposal of municipal solid waste (MSW) showed that producing electricity using thermo-chemical and biochemical conversion technologies would yield higher energy and lower emissions of carbon dioxide criteria air pollutants (oxides of nitrogen and sulphur) than land filling and incineration (direct burning) of MSW



(CIWMB 2005). There were limited data available to adequately assess the impacts of dioxins, furans, and other hazardous air pollutants, which are released by municipal wastes. However, since these are theoretical estimates and there are no conversion technology facilities in commercial operation in the United States, there is a high level of uncertainty towards their actual environmental performance.

- **LCA of agriculture:** Tilman, Hill, and Lehman (2006), through a decade-long experiment in which they compare different combinations of perennial herbaceous grassland species that can be used for producing biomass, conclude that high-diversity grasslands had increasingly higher bioenergy yield, higher carbon sequestration, and lower agrichemical pollution than monoculture crops in the long run. Moreover, since their experiment was conducted on degraded and abandoned nitrogen-poor sandy soils, this lends credence to claims that biofuels can be produced without displacing food production or causing habitat destruction. Kim and Dale (2005) perform a comparison of four different crop rotation systems: (1) corn-soybean rotation with no winter crop, (2) continuous corn with no winter crop, (3) continuous corn with no winter crop and 50% removal of stover, and (4) continuous corn with 70% stover removal and winter wheat rotation, for assessing impacts like nonrenewable energy consumption, global warming impact, acidification, and eutrophication. They found that all the cropping systems studied offered environmental benefits in terms of nonrenewable energy consumption and global warming impact, but planting cover crops was necessary to prevent acidification and eutrophication, primarily because large nitrogen (and phosphorus)-related environmental burdens are released from the soil during cultivation. Planting winter cover crops can also compensate for loss in soil organic carbon levels and soil erosion due to removal of corn stover. Cover crops also permit more corn stover to be harvested. Thus, utilization of corn stover and winter cover crops can improve the eco-efficiency of the cropping systems. But when water is scarce, the main environmental impact may be depletion of water resources. Mattson, Cederberg, and Blix (2000) outline a

method for environmental assessment of agricultural land use, which has not been considered in most LCAs. Environmental objectives and indicators of the land-use quality are defined. The method is tested in case studies of cultivated vegetable oil crops: Swedish rapeseed, Brazilian soybean, and Malaysian oil palm. They conclude that soil erosion, soil organic matter, soil structure, soil pH, phosphorus and potassium status of the soil, and the impact on biodiversity are a good choice of indicators of long-term soil fertility and biodiversity impacts of land-use impacts of various cropping systems. Land-use assessment performed in this way includes not only quantitative results but also qualitative descriptions. Lal (2004) provides a comprehensive survey in which he compares the carbon intensity of various agricultural activities and finds plowing, fertilizers, pesticides, and irrigation to be the most carbon-intensive operations. Improved practices like no-till agriculture, improving nitrogen-use efficiency, integrated pest management, and drip irrigation are all found to have lower carbon intensities.

## **2.4 Summary of current literature**

We summarize some of the main findings from the reviewed studies below.

1. The life cycle of ethanol and sugarcane has been the most widely studied. Ethanol from sugarcane offers the highest energy and CO<sub>2</sub> benefits, followed by cassava, while ethanol from corn offers relatively modest energy and environmental benefits. Cellulosic ethanol, however, is expected to deliver higher future net energy gains and reduced future GHG.
2. Coproducts have an important bearing on the net energy and environmental benefits. However, there is considerable debate about the most suitable technique for the valuation of coproduct credit.
3. Crop rotation and intercropping are better than monocropping, while perennial crops are better than annual crops for achieving soil carbon sequestration, reducing soil erosion and use of agri-chemicals in the production of biomass.
4. Electricity production from biomass also has the potential to offer significant reductions in fossil-fuel use and GHG. In recognition of the fact that multiple

- options exist for producing energy from biomass, LCA studies should adopt a double-difference approach, i.e., differencing the reduction in emissions when biomass is used to displace both gasoline and grid electricity. The utilization of biomass for provision of electricity or clean cooking fuels like biogas in rural and remote areas of developing countries will also have other important social impacts.
5. The literature on crops and production conditions in developing countries is scarce with the exception of a few studies on sugarcane in Brazil, India, Thailand, and Morocco. Therefore, if much of the demand for biofuels in the EU is going to be met through imports from developing countries, then there is little basis to conclude about the climate or other benefits of biofuels.
  6. Lastly, studies seem to focus largely on carbon and energy intensity, while ignoring other indicators such as those related to human health, soil erosion, nutrient loading in rivers, the health of the ecosystem, etc. These are important environmental impacts that need to be considered in evaluating the environmental impacts of biofuels (Andrews 2006). A recent study comparing the impact of gasoline and E85 (85% ethanol fuel, 15% gasoline) on cancer risk and ozone-related health consequences found a scenario that includes projected improvements in gasoline and E85 vehicle emission controls may increase ozone-related mortality, hospitalization, and asthma by about 9% in Los Angeles and 4% in the United States as a whole (relative to 100% gasoline), while it was estimated to cause little change in cancer risk. As a result, the study concluded that E85 might be a greater overall public health risk than gasoline (Jacobson 2007).

## **2.5 Caveats of LCA**

Several aspects of LCA, including the choice and definition of indicators and the methodology itself have been controversial and the subject of intense debate (Pimentel and Patzek 2005; Farrell 2006; Macedo, Leal, and de Silva 2004; Mattsson, Cederberg, and Blix 2000; Delucchi 2004).

1. **Differences in system boundaries:** LCA can include multiple levels of analyses. For example, Macedo, Leal, and de Silva (2004) describe three levels of LCA for net energy gain from sugarcane ethanol.
  - a. Level 1 – Direct energy consumption for operation of farm machinery, harvest and transportation of feedstock, electricity and heat for processing, distribution of biofuel, etc.
  - b. Level 2 – Energy required to produce the material inputs used like fertilizers, chemicals, seeds, water, etc. These are typically variable inputs to production.
  - c. Level 3 – Energy required in the construction and maintenance of equipment, buildings, etc. These are the fixed inputs to production whose lifetime far exceeds that of the fuel itself.

In the above example, the net energy gain based on Level 1 LCA would exceed the net energy gain based on Level 2 LCA. This is because a Level 2 analysis would include indirect energy inputs necessary for the production of fertilizers, which are significantly large. Similarly, a Level 3 analysis would predict an even lower net energy gain. Studies suggest that given the energy intensity of the agricultural inputs, especially fertilizer, a level 2 analysis is warranted, while the marginal gain in accuracy from a level 3 may be less than the marginal effort expended in collecting the data. Therefore, depending on the definition of the system boundary, the net energy gain or any environmental indicator for that matter can vary.

2. **Accounting of coproduct credits:** Biofuel production yields several coproducts. For example, ethanol production from corn also yields distiller's dried grains with solubles (DDGS) or corn oil, corn gluten feed, and/or corn gluten meal depending on whether dry- or wet wet-milling is used. Ethanol production from sugarcane yields bagasse, which can be used to generate electricity. Some of these coproducts will displace feed products for livestock, while others have other industrial and human use. Such displacement saves energy and materials that would have been consumed if the coproducts were produced exclusively. Hence,

it is reasonable for such savings to be credited to ethanol. Several approaches to estimating this displacement effect have been suggested, including:

- a. **Process-based credit:** The process method typically uses a process simulation model to model the actual mass and energy flows through a production sequence, allocating coproduct energy according to estimated process requirements.
- b. **Market-based credit:** The market-based method allocates total input energy to the various products according to the relative market value of each.
- c. **Displacement-based credit:** The displacement method credits the coproduct with the energy required to produce a functionally equivalent quantity of the nearest substitute, e.g., distillers dried grains with solubles (DDGS, a coproduct of dry-mill corn ethanol production) or electricity from coal in the case of sugarcane bagasse cogeneration.

While the most appropriate method is still a matter of debate, it is clear credits should not be assigned to the marginal units of coproducts as supply begins to exceed market demand for coproducts. For example, the current utilization of coarse grains for livestock feed is about 150 million tonnes while the utilization of corn for ethanol is about 45 million tonnes, which results in about 14 million tonnes of DDGS (Ferris and Joshi 2007). An elevenfold increase in corn ethanol would result in more DDGS than the demand for raw corn.

3. **Heterogeneity:** The results of LCA are often relevant only in a specific geographic, temporal, and technological context. For example, in the case of biofuel crops, production conditions vary from farm to farm. Differences in land quality and the economic conditions of the farm can give rise to differences in tilling practices, levels of use of inputs like irrigation, fertilizer, pesticides, etc. Fertilizers, one of the most energy-intensive inputs in the life cycle of a crop, can be produced using coal, natural gas, or naphtha, which have varying energy and carbon intensities. Similarly, the process heat necessary for ethanol production can be supplied by either coal or natural gas. The mix of electricity can also vary

depending on the location. For example, electricity in India and China is dominated by coal, in France by nuclear energy, in Brazil by hydropower, and in California by natural gas. Water used in cultivation of biomass can also vary widely. For instance, more than 98% of sugarcane grown in Brazil is rain fed (Moreira 2007), while sugarcane grown in India is almost entirely irrigated. In the United States, corn grown in Nebraska uses an average of 7 inches (186,000 gallons) of irrigation water per acre of crop, while corn grown in Minnesota is rain fed (Turner 2007). Thus, extrapolation of LCA results without considering the distribution of such variations will give biased estimates.

## 2.6 Chapter summary

Biofuels will have a mixed impact on the environment. They may reduce carbon emissions but contribute to other environmental problems. There are numerous ways to assess the efficiency of a production system. Economists may prefer to use productivity or total factor productivity, soil scientists may prefer to use soil quality, ecologists may prefer to use indicators that measure the health of an ecosystem while engineers assess the thermodynamic or material use efficiency. LCA is an engineer's framework that measures the efficiency of use of energy and materials. LCA in its current form is a useful tool for benchmarking various technologies and identifying areas where the design and processing can be improved to make the product less resource intensive. However, future research should give consideration to the following.

1. **Develop a broader set of indicators.** Environmental performance indicators are confined to measurement of net emissions of carbon or other air pollutants. Indicators of several other important environmental impacts like eutrophication, pesticide exposure, habitat and biodiversity loss, etc., as a result of biofuel production should be developed. The accounting and impacts of water withdrawals for cultivation and processing are other aspects that have not been adequately researched. Overall, the effects of the agricultural phase of biofuel production need more research

2. **Incorporate general equilibrium effects.** The conclusion of studies in the literature is typically that “Fuel *X* on average consumes (or emits) *Y*% more (or less) of material *Z*.” But it says little about whether such gains can be captured in the real world. An economist will argue that changes in prices would induce input substitution or behavioral change in such a way to eliminate the benefits of technological change. Higher price for natural gas will induce a shift to the use of coal in production of fertilizer or in processing. More efficient cars may reduce the effective cost of transportation inducing people to drive more. In fact, fuel-efficiency improvements along with land zoning regulations have paved the way for bigger cars that are driven more today than in the past. The net result would be that total emissions are higher than before. In the case of agricultural systems, agricultural prices are the main determinant of whether a parcel of land is under native vegetation, agricultural production, conservation program, or is idle. This matters a great deal in the analyses of life-cycle GHG, because of the different carbon-storage characteristics of these ecosystems (Delucchi 2004).
3. **Include dynamics and uncertainty.** Real-world systems are evolving under circumstances that are technologically and economically dynamic. For example, cellulosic technology will improve the net energy of ethanol while future oil supplies will come from resources that are dirtier like tar sands or coal. A rise in the price of natural gas in the absence of carbon regulation could cause power plants, fertilizer industry, and biorefineries to shift to dirtier fuels like naphtha or coal. Energy used in transportation of feedstock to processing facilities and to demand centers is another parameter, which can vary depending on the type and distance of transportation. Any such change alters the net energy and net carbon benefits of ethanol. Life-cycle accounting is a snapshot of technological conditions at a given instant of time and not equipped to handle, dynamics and uncertainty.

## **3 Economic Studies of the Impact of Biofuels**

### **3.1 Introduction**

The economic motivation for biofuels is that they are a convenient, low-cost, domestically producible substitute for oil, a fuel that is getting costlier by the day and is also imported from politically volatile regions. The increased demand for agriculture from biofuels can also address the worldwide problem of declining farm income. But negative effects on food and the environment are threatening to offset the positive effects on welfare as an energy source. This, however, should not be surprising. As the previous chapter explained, biofuels are intensive in the use of inputs, which include land, water, crops, and fossil energy, all of which have opportunity cost. Understanding how biofuels will affect resource allocation, energy and food prices, technology adoption, and income distribution, etc., is essential at this very early stage of development. A variety of economic modeling techniques are being used to model the impacts from different angles. Microlevel models like cost accounting models and models of technology adoption and resource allocation are useful for calculating the economics of biofuels from the perspective of an individual economic agent. Sector models, general equilibrium, and international trade models on the other hand are useful for studying the aggregate impacts of biofuels. But nonmarket effects like the impact on the informal economy, which is important in developing countries, and environmental spillovers like loss of natural habitats as a result of agricultural expansion are unlikely to be captured in standard neoclassical approaches and new techniques will be needed here. Our aim in this chapter is to review the modeling literature and to develop recommendations for future work in modeling these impacts. The rest of the chapter is organized as follows. Section 3.2 is a survey of the various types of economic studies and their predictions. Section 3.3 provides both a summary of findings and also possible hypotheses for future work. Section 3.4 concludes the chapter.

### **3.2 Economic studies of biofuels**

The biofuel production chain can be divided into four stages.



1. **Production of biomass feedstock through cultivation:** This is mainly an agricultural activity in which a biofuel crop is grown, harvested and transported to a conversion facility. The biofuel crop can be a food crop like corn or a dedicated energy crop like switchgrass.
2. **Conversion of the feedstock to fuel (or electricity):** This is an industrial activity in which the raw biomass is converted into biofuel along with one or more coproducts.
3. **Distribution and retailing of finished fuels:** This involves distribution of finished fuel for blending with fossil fuels. In the case of electricity, this involves the transmission and distribution of electricity to demand centers.
4. **Consumption of bioenergy:** This refers to the ultimate end use in which the biofuel enters the fuel tank of a vehicle or provides electricity.

From a private standpoint, a variety of economic questions arise at each stage, which relates to if and when a producer or consumer will adopt biofuel. From a societal standpoint, questions like what incentives are needed and what are the aggregate impacts of biofuels on welfare are the most important. We discuss the existing economic literature under four broad categories. These are:

1. Cost accounting models
2. Micromodels of technology adoption and resource allocation
3. Sector models
4. General equilibrium and international trade models.

The key features of each type of model and the findings of some studies based on these techniques are discussed below.

### **3.2.1 Cost accounting models**

These are simple, spreadsheet-style budgeting models that are used to estimate profitability of an activity for a single price-taking agent, such as an individual farmer or processor. The production function is typically assumed as fixed proportion. Crop budget models have been used to estimate the profitability of cultivation of energy crops based

on assumptions about yield, output price, and cost of production. Hallam, Anderson, and Buxton (2001) perform a comparison of economic potential of several high-yielding annual and perennial crops for biomass production on prime and marginal, sloping land in the state of Iowa in the United States. They compare perennials like reed canarygrass, switchgrass, big bluestem, and alfalfa with annuals like sweet sorghum, forage sorghum, and maize. Cost of production varies between these two sets of crops because of differences in establishment, production period, and harvesting procedures and frequency. Monocropped sorghums had the lowest cost per ton of biomass compared to monocropped perennials and intercropped species. Among the perennials, switchgrass was the most economical but they also found sorghums had high potential for erosion on sloping soils which preclude their use on such soils. Khanna, Dhungana, and Clifton-Brown (2007) examine the cost of production of ethanol from *Miscanthus* and switchgrass in Illinois. They find considerable spatial variability in break-even farm gate price due to variations in land quality and transportation costs. The Graham et al. (1995) model estimates the potential supply of biomass from crops like poplar, willow, and switchgrass for use in electricity generation in the United States. Here the supply price of biomass on an acre of land was determined by calculating the present value of estimated revenue and costs over the life of the plantation of energy crop. They estimate the break-even farm gate price and a supply curve for biomass at different energy prices.

Tiffany and Eidman (2003) predict the financial performance of a representative dry-mill ethanol plant based on a range of corn prices, ethanol prices, prices of coproducts (DDGS), natural gas prices, and interest rates in comparison to the rates of return on equity compiled in the last decade for a group of 200 farmers in southwestern Minnesota. This model predicted that dry-mill ethanol plants have experienced great volatility in their net returns over the last decade of operations and that ethanol prices, corn prices, natural gas prices, and ethanol yields can each drastically affect net margins for ethanol plants. Tyner and Taheripour (2007a) study the sensitivity of profitability of ethanol production in the United States as a function of oil prices and subsidies. They predict that with crude oil at \$60/bbl., the break-even corn price is \$4.72/bushel including both an additive premium and the fixed federal subsidy of 51 cent per gallon assuming a 12%

return on equity and 8% interest on debt (figure 12). These studies indicate that biofuel producers must strive to utilize risk-management techniques, especially with respect to procuring their feedstock, and purchasing their natural gas and marketing the biofuel and the coproducts. But the fact that corn prices have traditionally hovered around \$2.00 per bushel means competition from an industry that can afford more than twice that price bodes ominously for the food sector. Gnansounou, Dauriat, and Wyman (2005) compare the trade-offs in using sweet sorghum to produce a combination of sugar, cane ethanol, cellulosic ethanol, and electricity in North China. They found that the production of ethanol from the hemi cellulose and cellulose in bagasse was more favorable than burning it to make power, but the relative merits of making ethanol or sugar from the juice was very sensitive to the price of sugar in China. Table 10, lists the average cost in 2004 of producing biodiesel and ethanol in select countries based on the cost of feedstock, energy, the revenue from sale of by-products, etc. We can see that sugarcane ethanol in Brazil is the cheapest at \$0.33 per liter of gasoline equivalent, while ethanol from wheat and sugar beets in the EU is more than double the cost of Brazilian ethanol on account of higher feedstock and conversion costs. Ethanol from maize in the United States is cheaper than European ethanol but costlier than Brazilian ethanol because of higher cost of conversion.

Budgeting models have both advantages and disadvantages. They can help identify the key economic variables in the production chain. They are also used to analyze the sensitivity to factors such as oil price, cost of feedstock, energy costs, and price of by-products. It has been reported that feedstock costs account for as much as 60 to 70% of the cost of production of biofuel (OECD 2006). Yet, budgeting models should be viewed with skepticism for policy purposes because they are based on accounting rather than economic principles. The prices used in calculations may not be the real social value of resources given the distortions induced by national and international policies and the various externalities associated with production and use (Kojima and Johnson 2005). Moreover, such models do not consider the role of market structure and risk, which are important in explaining the actual level of investment that will take place. Then there are dynamic considerations too. When there are economic incentives for sequestering carbon

in addition to producing biomass, static models such as the above will become inadequate. In such cases one requires dynamic analysis that determines the optimal harvesting period based on the growth function of biomass and the dynamics of carbon accumulation. In the case of wood, the harvest date can be adjusted depending on the market situation as farmers may choose to leave the stock standing until prices increase. This may either not be possible or require expensive postharvest storage in the case of annual crops. Another drawback is that they ignore general equilibrium effects of bioenergy crop production. Large-scale shifts in the order of millions of acres would raise land price, eventually affecting the cost of production and the profitability. Therefore, the supply estimates using such a methodology is appropriate for low levels of production compared to the size of the market.

### **3.2.2 Micromodels of resource allocation and decision making**

Even from an individual decision maker's perspective, farm planning problems are much more complex, with farmers having to choose from multiple crops and multiple ways of producing them. For example, farmers have to decide how much to grow of each crop, on which lands should they grow them if they have plots of varying quality, how much inputs to use on each, whether they should increase their fixed resources by renting or purchasing, what are their risk preferences, etc. With biofuels, new crops, new farm practices, new types of marketing arrangements, new fuel production technologies, and new vehicles will all have to be adopted by a wide range of economic actors. A

microlevel analysis of biofuels requires analysis of adoption at different levels, namely:

- (1) Farmer: This involves a decision by the farmer to cultivate new kinds of energy crops like switchgrass , Miscanthus, or oilseed crops like Jatropha and Pongamia.
- (2) Industry: This involves a decision to invest in biorefineries that convert the biomass into ethanol, biodiesel, or electricity. It also involves a decision by retailers to invest in distribution outlets.
- (3) Consumer: This involves a decision to purchase flexible fuel vehicles (FFV) and indeed operating them on biofuels.

Traditionally, adoption decisions by farmers were analyzed within the context of markets and existing institutional setups, namely, a seed manufacturer or a dealer introduces a new variety or a new product, extension provides some demonstration, and farmers may or may not adopt the new product (Feder, Just, and Zilberman 1985). The literature on adoption has expanded from simple models that saw adoption as a process of imitation, to more complex models that recognize heterogeneity among potential adopters and uncertainty about technology performance, and emphasize the role of profitability and risk considerations in an integrated framework to explain patterns of adoption (Just and Zilberman 1983, Caswell and Zilberman 1985). Khanna and Zilberman (1996) explain how distortionary regulatory policies, which do not result in prices that do not reflect the scarcity of resource and the lack of institutional mechanisms for efficient allocation of inputs and outputs, can slow down the rate of diffusion of precision technologies. Furthermore, the theoretical literature on adoption was accompanied by empirical studies using discrete choice modeling (Besley and Case 1993), but all these models have not focused on what happens above the farm level. When it comes to biofuels and related technologies, adoption is more complex. Adoption of farm technology in this case should not merely emphasize farmer behavior but also the behavior of the suppliers of seed and other genetic materials, processors (biofuel refiners), and the end users of those technologies (consumers of ethanol). In case of biofuels, farmer decisions to switch to crops like switchgrass or *Miscanthus* (in temperate climates), or crops like sweet sorghum or *Jatropha* (in tropical climates) will depend on whether they have a contract or a market for their product, which will depend on decisions to erect a processing facility, which in turn depends on infrastructure and other factors that effect potential profitability and risks associated with the facility and the behavior of the owners of the facility. Whether the crop is perennial or annual, will also have a bearing on the farmer's decision. Perennial crops like switchgrass, *Miscanthus*, and *Jatropha* may have high establishment costs but may have lower annual operating costs due to reduced input requirements (low quality land, reduced tillage, lower fertilizer, and irrigation demand) compared to annuals. Small and poor farmers who are constrained by credit or require short payback may not be able to adopt them. Risk aversion may also prevent investment

in perennials by many farmers. The emergence of new institutional setups has also not received much emphasis in this literature. These are all, however, areas of future work.

### 3.2.3 Sector models

From a policymaker's perspective, the problem is often one of finding the best way to allocate public resources towards achieving a specified end, say, reduction of oil imports, creation of rural jobs, etc. Thus, developing good policy prescriptions requires good understanding of what will be the aggregate response of the entire sector to a policy, such as pollution taxes and standards, blending mandates, trade regulations, etc. The emphasis in such cases is on a sectorwide model, which includes all producers and consumers that are likely to be affected by the policy.

A simple conceptual model of supply and demand for a crop that has two uses, say, food and biofuel, is shown in figure 11. The initial state (figure a) represents a period of little demand for biofuel either due to low price of oil or no environmental regulation; therefore, at the equilibrium  $(P_0, Q_0)$  there is no biofuel production. In the short run (figure b), changes in economic conditions such as increase in energy price result in upward shift in biofuel demand. Assuming no change in supply in the short run  $(P_S, Q_S)$  denotes the new equilibrium in the short run. There is both an increase in the price of food and a decrease in the supply of food ( $Q_{SF} < Q_0$ ), although total agricultural production increases ( $Q_S > Q_0$ ). In the long run (figure c), supply shifts outward ( $Q_L > Q_S$ ) resulting in an equilibrium  $(P_L, Q_L)$ , which implies both lower price ( $P_L < P_S$ ) and larger supply of fuel without a reduction in supply of food compared to the short run. Expansion of agriculture, productivity enhancement through greater use of yield-augmenting inputs, and agricultural biotechnology could be responsible for the increase in supply. Although this model is very simplistic, it explains the essential idea underlying the more sophisticated mathematical programming models of the whole agricultural sector of a region or an economy. Several such models have been augmented to study the effects of biofuels. Below we discuss three categories of such models.

- 1. Models that analyze outcomes of biofuel mandates at a global level:** The first category of models describes the impacts of biofuel demand in certain major regions on the global price of food. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is a global partial equilibrium trade model originally developed by the International Food Policy Research Institute (IFPRI) for projection of future demand and supply for agricultural commodities. The model predicts that when there is aggressive growth in ethanol and biodiesel supply with no accompanying increase in crop productivity compared to current levels, there is likely to be a drastic increase in food prices. Results for calorie availability and child malnutrition portend a decline up to 194 kilocalories per person, while the number of malnourished children increases by 11 million children with the worst impacts being felt in sub-Saharan Africa followed by South Asia. However, in a scenario in which cellulosic ethanol technologies are adopted and productivity improvements are realized, the model predicts a softening of the impact on prices and on malnutrition (Msangi 2006) (figure 13). There is, nevertheless, an increase in the price of food crops under all scenarios. AGLINK-COSIMO is another dynamic partial equilibrium model of agricultural product markets developed by OECD and FAO for developing medium-term projections of supply, demand, trade and prices, as well as for the forward-looking analysis of policy changes and other factors. A special emphasis is given to domestic and trade policies, which are represented in detail. Nonagricultural markets are not modeled and are treated exogenously to the models. The model predicts crop prices in 2014 could increase by 2% in the case of oilseeds and almost 60% in the case of sugar. One major drawback of this model is that projections are based on assumptions of unchanged conditions in terms of technology, feedstock mix, and area use since 2004. In addition, neither the potential use of currently unproductive land nor the implications of trade in biofuels are taken into account (OECD 2006).
- 2. Models that analyze outcomes of biofuel mandates at a national level:** The second category of models simulates the impacts of biofuel mandates at the

national level. Simulations with the Food and Agricultural Policy Research Institute (FAPRI) stochastic model of the U. S. agricultural sector indicate that additional ethanol production capacity results in an increase in corn prices but reduced prices for ethanol, corn by-products, and soybean meal. Corn production also increases, while corn exports, feed consumption, and stocks decline. Increased ethanol production results in more production and lower prices of corn by-products. Soybean meal prices are reduced by 10%. Livestock and poultry sector effects are relatively small in aggregate. Producers who can take advantage of lower corn by-products and soybean meal prices benefit, while those feeding rations heavily dependent on grain face higher costs. The taxpayer cost of farm programs is reduced by an average of \$1.0 billion per year between 2011 and 2015. Increases in ethanol consumption could reduce tax revenue, given differences in the tax treatment of ethanol and regular gasoline. Net farm income exceeds baseline levels by an average of \$298 million per year over 2011-2015. Higher corn receipts are partially offset by lower government payments. Rental payments increase, as do other production costs (FAPRI 2005). POLYSYS is another partial-equilibrium model of the U. S. agricultural sector that is used to simulate changes in crop and livestock supply and demand, farm gate prices, cash receipts, government payments, and net realized income in response to changes in policy, economic, or resource conditions. This model has been expanded to include markets for switchgrass, residues from corn and wheat and woody feedstock such as forest trimmings, and wood and mill wastes; and it also includes possibilities for conversion of pastureland and Conservation Reserve Program (CRP) land to cropland. This model was used to predict commodity prices in the production scenario of 86 billion gallons of ethanol in the United States by the year 2025 under certain assumption of yield for major food crops (corn, 195 bushels/acre; soybeans, 51 bushels/acre; and wheat, 53 bushels/acre) and energy crops (6 to 12 dry tonnes/acre) as well as assumptions of improved conversion efficiencies (89 gallons of ethanol per ton of cellulose and 3 gallons of ethanol per bushel of corn). This model predicts an increase of 13%, 6%, and 30% in the price of corn, wheat, and soybeans, respectively, in the year 2025. Major acreage



changes include conversion of 33 million acres in pastureland and 15 million acres of CRP land into cropland (Walsh 2003).

- 3. Models that analyze outcomes of policies to sequester carbon through agriculture:** The third category of models simulates the impact of policies aimed at sequestering carbon through agriculture. The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States. The FASOM model initially was developed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees but also has been applied to a wider range of forest and agricultural sector policy scenarios. Prices for agricultural and forest sector commodities and land are endogenously determined given demand functions and supply processes. Through an optimization approach, the FASOM model maximizes the net present value of the sum of consumers' and producers' surpluses (for each sector), with producers' surplus interpreted as the net returns from forest and agricultural sector activities. Farmers and private timberland owners are assumed to have perfect foresight regarding the consequences of their behavior; that is, expected future prices and the prices realized are identical. The model provides estimates of economic welfare disaggregated by agricultural producers, timberland owners, consumers of agricultural products, and purchasers of stumpage (Adams 1996). Schneider and McCarl (2003) develop a supply curve for carbon mitigation via agriculture. They compare the economic potential of various carbon mitigation options such as soil carbon sequestration, afforestation, production of biomass for electricity production, and production of biofuels like ethanol from traditional crops. At each carbon price level, the Agricultural Sector Model (ASM) computes the new market equilibrium, revealing agricultural commodity prices, regionally specific production, input use and welfare levels, environmental impacts, and adoption of alternative management practices such as biofuel production. Results indicate no role for corn-based ethanol below carbon prices of \$40 per ton of carbon equivalent. At these incentive levels, emission reductions via reduced soil tillage and afforestation are more cost efficient. For

carbon prices above \$70, producing switchgrass and woody biomass for electricity dominate all other agricultural mitigation strategies (Schneider and McCarl 2003; figure 14).

To summarize the partial equilibrium literature, the typical approach has been to extend existing models of the agricultural sector by incorporating the demand for biofuels in the form of an exogenous increase in demand for feedstock like maize, sugarcane, wheat, sugar beet, oilseeds, etc., to determine the changes in long-run equilibrium prices and its implications for welfare. Another use for such models could be in generating aggregate supply functions for general equilibrium analyses. But the current literature is lacking in many respects. One, the models are static and do not capture the dynamic interactions between agricultural markets and energy markets, which will be important in explaining the timing of adoption and diffusion of biofuels. In fact, in many models there is not even an explicit use of oil prices, and they only model biofuel mandates. Ujjayant, Magne, and Moreaux (2006) use the Hotelling model to derive the conditions (range of energy prices and environmental regulation) under which land is allocated to biofuels. Another gap is the lack of consideration of risk and uncertainty. Ignoring risk-averse behavior can lead to overstatements of output levels, especially since we are talking about energy prices, perennial crops, low-income agriculture, etc., where risk and uncertainty play a crucial role in production. Thus, contrary to the prediction of these models, despite high oil prices, investment in biofuels may not be forthcoming, and food price effects may be overstated.

### **3.2.4 General equilibrium models**

Biofuels affect not only farmers, but also affect agro-industries, the well-being of consumers, balance of trade, and the government budget. Understanding the impacts of biofuel on the overall economy requires a modeling framework that accounts for all the feedback mechanisms between biofuels and other markets. The technique that would allow for assessment of such effects is a computable general equilibrium (CGE) analysis. (Sadoulet and de Janvry 1995). A CGE model can be loosely defined as one in which all

the markets in an economy equilibrate. The dramatic impact of the 1970s' oil crises on the national economies spurred the use of CGE models for understanding the energy-economy interactions. The main purpose of these efforts was to measure the overall economic impact of changes in energy prices on employment, government payments, total economic activity, and balance of trade (Manne, Richels, and Weyant 1979; Bhattacharyya 1996). With the passing of the oil crisis by the mid-1980s, the interest shifted to the analysis of impacts of policies aimed at controlling emissions and pollutants like CO<sub>2</sub>, ozone, etc., on the economy. CGE models have since been used to compare the costs and benefits of several alternative policies for abatement of emissions (Nordhaus 1991; Manne and Richels 2004; Bovenberg and Goulder 2000). But now there is a growing emphasis on modeling the impact of biofuel policies on the economy. We discuss the CGE literature on biofuels under two categories.

1. **Models that analyze impact of biofuel and carbon targets on the national economy:** One set of models studies the impact of biofuel mandates and achieving carbon reduction targets on the national economy. Dixon, Osborne, and Rimmer (2007) use a dynamic CGE model called USAGE to investigate the economywide implications of a policy that aims to replace 2 % of the crude oil consumption in the United States with ethanol by 2020. The main conclusion of this study is that the United States can benefit from multiple developments resulting from substitution of oil with biofuels, namely, (1) biomass fuels would be cheaper than oil whose price is likely to rise; (2) simultaneous reduction in the world price of crude petroleum because of decrease in demand in the United States which consumes about 25% of the world's oil; (3) increased employment; and (4) an increase in export prices due to reduction in crop exports. But McDonald, Robinson, and Thierfelder (2007) using the GTAP model predict that the net effect of decline in crude oil price and an increase in world price of cereals as a result of switchgrass production in the United States would be a general decline in economic welfare. They also predict a proportionately greater decline in welfare for developing countries that stand to benefit less from a fall in oil price but lose more from an increase in price of cereals. Steininger and

Voraberger (2003) and Breuss and Steininger (1998) use a CGE model of the Austrian economy to compare the relative macroeconomic and GHG impacts of policies that support the production heat, electricity, and/or fuels from biomass. They find that the impact on gross domestic product (GDP) and employment differs widely for different biomass technologies. But the more interesting conclusion that arises from their analysis is that a combination of policies like recycling revenues from taxation of fuel as a subsidy for biomass technologies has better impact than a policy based purely on either subsidies or taxes. Reilly and Paltsev (2007) use a model called MIT Emissions Prediction and Policy Analysis (EPPA) model to simulate the demand for land necessary for achieving different stabilization levels of GHG concentrations in the coming decades. Their main conclusion is that large increase in domestic biofuel production would result in the United States becoming a net importer of food as opposed to an importer of oil.

2. **Models that emphasize international trade:** A second set of models focus on the impacts of trade liberalization in agriculture and its impact on the production and prices of agricultural commodities. Elobid and Tokgoz (2006) simulate the impact of the removal of trade tariffs and federal tax credit in the United States on production, consumption, and trade using a multimarket international model for ethanol. Their model is calibrated on 2005 market data. They find that with the removal of trade distortions, the world ethanol price increases as demand for ethanol, and therefore imports, increases in the United States. Brazil would benefit in a big way from the removal of the U.S. duties. As more sugarcane is diverted toward the production of ethanol, the price of raw sugar increases. But the marginal effect of removal of the federal tax credit for refiners blending ethanol is a reduction in the refiners' demand for ethanol, prompting a reduction in imports and a corresponding decline in the world ethanol price. Thus, the net effect of the removal of both the tariff and the tax credit is to temper the increase in imports and the increase in demand for ethanol. Gohin and Moschini (2007) perform a numerical simulation of the EU biofuel directive using a farm-detailed

CGE model. Simulations suggest that most of the biodiesel demand will be satisfied by (marginally taxed) imports while the bioethanol demand is met mostly by domestic production (due to significant import tariffs on wheat and sugar beets). There is no negative impact on livestock sector, while there is definite positive impact on farm income. The findings are robust to assumptions about land set-aside rates, mobility of capital, and labor to and from farm sectors. Since like fossil fuels most of biofuel demand is met through imports, this questions the justification of the policy on energy security grounds. The transfer efficiency of the policy is also quite low, given that much of budgetary support is transferred to foreign agents and in costs of processing. Similarly, in simulating the impact of the EU biofuels directive using the GTAP CGE model, Banse et al. (2007) also predict an increase in imports into the EU.

There are several gaps in the existing CGE literature. The international trade models are very thin in the treatment of developing countries, which are expected to be a big supplier of biofuels in the future. CGE models treat everyone within a sector as identical and ignore heterogeneity. There is little emphasis on distribution of impacts within a sector. But depending on whether one is a landowner or landless, rural or urban poor, the impacts will be different. The models also do not take into account that the utility consumers may derive from a cleaner environment, which may offset some of the costs. Another drawback of such models is that there is no comparison of biofuel policies with alternative policies that could achieve the stated goals.

### **3.3 Summary of literature and hypotheses for further research**

Several hypotheses for further testing of the anticipated effects can be gleaned from the current literature and also from what has been said and written in the nonacademic literature and the popular press. While simulation-based efforts to quantify these effects are gathering momentum, econometric testing of these effects is an important area of future research.

- **Energy:** The biofuel sector is both a consumer and supplier of energy. As a supplier of energy, biofuels displace oil or electricity while they consume coal, natural gas, and electricity during production. The impact on price of these commodities at least in the near term should be minimal if biofuel production remains at low levels compared to world or regional demand for those commodities. (Of course, in the electricity sector cost of marginal supply determines the market-clearing price; but the same is not true of oil, coal, and gas markets since these goods are storable.) However, a scenario in which a major oil-consuming region such as the United States or the EU meets a significant portion of its demand from biofuel can cause a reduction in world oil prices. That said, environmental regulation like carbon taxes may dwarf the effect of biofuels on the price of fossil fuels. However, this effect has not been investigated by past studies.
- **Food:** Biofuels will increase the price of food either because food crops are converted to fuel or because energy crops displace food crops on agricultural lands. The ultimate impact on a region will depend on several factors including the intensity of cultivation of biofuel crops and the extent of trade in food-related commodities. One can envision several scenarios. Developed regions such as the EU and the United States will experience price increase but may be able to absorb the price rise more easily than developing countries. One reason for this could be that since food-processing costs comprise a large share of the total cost, there will be a lesser impact on the final consumer price. The food processing industry will, however, be negatively affected due to higher input costs and lower demand for food. Developing countries that are net importers of food will be negatively affected due to higher food prices irrespective of whether they adopt biofuels or not. A region that is autarkic and does not adopt biofuel crops should, however, be isolated from such developments. If biofuel crops are cultivated exclusively on set-aside lands or marginal lands, with little competition with food crops, the impacts on food prices can be theoretically minimal. But in reality biofuels may still compete for other resources like water or labor and thus impact food production. This effect needs to be investigated further.

- **Livestock:** Biofuels will have a mixed effect on the livestock sector. In cases where crops used for feed are diverted to ethanol, higher feed prices and higher livestock prices will result. The U. S. Department of Agriculture also predicts higher price of crops like soy, sorghum, alfalfa, and hay which are displaced due to greater planting of corn to meet biofuel demand. However, higher feed prices will be partially offset by increased supplies of DDGS, which is a coproduct of ethanol production and is a substitute for corn. The response by the livestock sector to changes in feed prices depends on the relative importance of protein (primarily soybean meal) versus energy (primarily corn) and the size of the price changes associated with these feed components. Since these production and price adjustments are small, increases in biofuels production over the near term is not expected to have a major effect on the livestock sector. In the future livestock facilities may relocate near biofuel refineries or vice-versa in order to lower transportation costs. In developing countries where the livestock depends more on agricultural wastes than on feed, the effects will be much smaller. However commercialization of cellulosic technologies that can convert agricultural wastes into ethanol can increase fodder scarcity.
- **Land:** Allocating land to biofuels means taking land away from other uses like food or environmental preservation. The demand for agricultural land will benefit landowners. In fact, it has been hypothesized tenant farmers may end up losing much of the benefits to landowners in the form of increased rent. Increased demand for land for farming could lead to expansion of the agricultural land base. This might result in marginal and environmentally sensitive lands being brought under production such as CRP lands in the United States, set-aside lands in Europe, and tropical rainforests in Indonesia (Ogg 2007, Curran 2004). In other cases biofuel plantations may come up at the expense of pastureland rather than cropland or forestland. It is estimated that in Brazil about 30 million hectares out of the 220 million hectares could migrate to crops with little impact on meat production due to technological advance (FBDS 2007). The conversion of such lands to crop production will release carbon sequestered in the soil into the atmosphere, which will offset some of the carbon benefits. One concern that has

been raised by critics of biofuels in this regard is that governments tend to reclassify forestlands as pasturelands in order facilitate their conversion to biofuel plantations. In India, biofuel plantations are planned for wastelands, which are considered not suited to cultivation of food crops. Here again, the categorization of such lands as wastelands has been disputed given the dependence of the rural poor on those lands for grazing and fuelwood collection (Gundimeda 2004, Rajagopal 2007).

- **Water:** Agricultural water demand will also increase either due to expansion of agriculture or if biofuel crops are more water intensive than traditional crops. The increased demand for water will lead to higher optimal price. This might lead to reduced availability of water for food crops lowering yield and affecting food supply. Because the demand for food is inelastic, the demand for water for food production is inelastic. It also has a steeper slope than the demand for water for energy production, since the demand for energy has a relatively more elastic demand, reflecting that a small change in price may lead to a relatively large increase in quantity demanded.
- **Labor:** Biofuels are more labor intensive than other energy technologies per unit of energy-delivered basis. Therefore, biofuels should result in a net creation of new jobs related to energy production with the bulk of the increase occurring in the agricultural and processing phase. Of course, there will be a reduction in the rate of increase that would have otherwise occurred in the oil processing industry to meet future demand. There will also be movement of labor within the agricultural and the food processing sector. But these effects can be captured only in an equilibrium framework. One study that focuses on the impacts of the EU biofuels directive on France concludes that the impacts of a massive development of biofuels on the farmers' incomes and on jobs will remain quite modest (Treguer and Sourie 2006).
- **Farm income:** The impact on farm income will depend on several factors. In general net food producers will benefit from increase in food prices. However, energy is also an input to agriculture and, to the extent that energy prices are a



significant part of the costs of production, it will dampen the net increase in profits. Similarly, increase in water prices can also affect productivity and income of farmers. In places like the EU, where farmers are already granted higher than market prices through price supports, it seems unlikely that the farmers will be granted an even higher price as a result of the competition from biofuels. Such farmers will not experience an additional increase in rent. In the absence of such supports however, the volatility of the energy situation will mean a risk of major losses from shocks that may lower energy prices. Dumping of oil by the Organization of Petroleum Exporting Countries is an example of such a shock. Although subsidies and standards requiring use of biofuels can reduce such uncertainties, market power by agribusiness firms involved in seed and processing can reduce the benefit of such subsidies to farmers. Also when land is scarce, landowners will capture most of the benefits going to farmers. Economic studies should emphasize the role of market structure to determine the likely distribution of benefits of biofuels along the supply chain.

- **Agribusiness:** Modern biofuels have major implications for agribusiness. The conversion of energy crops into modern biofuels requires sophisticated processing technology. If energy prices are expected to remain high or if subsidies are likely to remain in place, there will be major investments made in crop production and processing. The result is likely to be strategic alliances between farmer cooperative agribusiness and energy sector merger and acquisition of agribusiness by energy firms. Vertical integration in new fuels from agriculture to processing and distribution is also likely in the case of new fuels like cellulosic ethanol. The food processing industry will be negatively affected due to increase in cost of inputs like grains, sugar, oil, and meat.
- **International trade:** Biofuels are expected to reduce a nation's dependence on imports for oil. While this is likely to be true, it however may not reduce the dependence on imports for energy unless the biofuel feedstock is produced locally. This has led some to question the effectiveness of biofuels in improving energy security. Simulations for the EU and the United States suggest that these regions are likely to become net importers for agricultural commodities especially

in scenarios at levels of substitution (Elobeid and Tokgoz 2006, Banse 2007). Thus, they could have negative impact on the balance of trade, and at the same time developing countries will experience a reduction in imports and an increase in exports.

### **3.4 Chapter summary**

While the models reviewed here are not exhaustive, they are surveys of representative works on the economic impacts of biofuels. The literature has two types of models. One type is budgeting models, which provide point estimates of average costs and profitability of biofuel production under static conditions of technology and market prices. But predicting the profitability based on point estimates of oil prices, cost of feedstock, etc., should be avoided since such parameters are uncertain. Moreover, these models use market prices as opposed to economic values, and so should be viewed with skepticism given the embodied distortions due to government policies. They also ignore feedback effects of large-scale production of biofuels such as rising land, input costs, etc.

The second type of models is macro or aggregate models that analyze the impacts at the sector or economywide level. These models are concerned with predicting the impact of biofuel policies like mandates on the price of food, farm income, trade, and overall welfare. Most of the models focus on the economies of the United States and the EU and have not considered in detail the conditions in developing countries. They also do not emphasize the distribution of the impacts within a given sector of the economy.

In terms of results the various models are hard to compare with each other because the predictions are sensitive to the modeling assumptions, which vary widely. Different models analyze different future scenarios. The economic driver is modeled differently across different models. In some cases oil prices are the explicit main economic driver while some use government dictates on biofuel production as the main driver. Models also differ in the representation of future technology, elasticity of supply and demand, and representation of agricultural and trade policies. The models are sometimes opaque

about these assumptions. For example, it is not clear how the stock of land available for agriculture in the future is modeled and whether it is exogenous or endogenous. Most models also assume a competitive market structure and ignore market power in the processing market or market power in international trade markets. But there are some definite trends to be gleaned from the simulations. Most models predict an increase in the price of food, decrease in exports of cereals from EU and the United States, a positive effect on farm income, a decrease in demand for farm support program, an ambiguous effect on livestock sector, and an increase in rural jobs.

There remain several gaps in our understanding of the economic impacts of biofuels that need to be addressed in future research. First, the literature is very thin on the treatment of developing countries other than Brazil, where both the supply of biofuels and demand for energy and agricultural commodities are likely to be vastly different than in the developed countries. Even a small increase in food prices will be felt more by the population in such regions. Second, at a microlevel, there is a need for studies that focus on the factors that would lead to the adoption of biofuel technologies by farmers, processors, and consumers. While some macromodels incorporate switchgrass as a future commodity, there is little actual understanding of the timing, location, and extent of adoption. The implications for small versus large farmer, landowning farmer versus tenant farmer, food grower versus cash cropper are all not yet well understood. Third, there is also a need for better understanding of the dynamics and international trade aspects of biofuels. Fourth, the distribution of cost and benefits of biofuels is another important area of research that needs a lot of attention of economists. Biofuels have been described as carrying the risk of filling the gas tank at the cost of emptying the stomach. Fifth, there is little or no treatment of the economic cost of environmental externalities in these models. They also ignore the private utility of cleaner environment in the estimation of welfare. Lastly, the modeling of impacts has thus far been confined mostly to conceptual and simulation-based models. Rigorous econometric analysis of impacts of biofuels should be undertaken in the future. In the next chapter we will survey the literature that describes the major policies influencing the evolution of biofuels and their implication for economic welfare and the environment.

## **4 Policies and Policy Implications**

### **4.1 Introduction**

There is a history of dependence of alternative energy technologies on government support to compete with fossil fuels at the marketplace. Biofuels are no exception. A spectrum of policies which include explicit biofuel policies like excise tax exemptions, mandatory blending requirements, and renewable portfolio standards in transportation fuels and electricity, and other indirect policies such as carbon policies, agriculture and trade policies, vehicle policies, etc., have influenced the evolution of biofuels. Indications are that they will continue to do so. A variety of justifications have been provided for government support. While a variety of policy tools exist that could be used to achieve a desired economic or environmental goal, the cost effectiveness and the distributional implications of each will vary. In fact, the latter may dictate the selection of the winning policy. The aim of this chapter is to explain the motivation for policy, the essential features of the various policies that are in effect around the world, and to survey the theoretical and empirical literature that predicts the implications of these policies for economic welfare and the environment. The rest of the chapter is organized as follows. Section 4.2 discusses the rationale behind government support for biofuels. Section 4.3 briefly describes the various policy tools that can be used in theory to address externalities. Section 4.4 describes the spectrum policies actually in effect today that directly or indirectly affect the evolution of biofuels. Section 4.5 surveys studies that describe the impact of such policies. Section 4.6 concludes the chapter.

### **4.2 The rationale for intervention**

There are two ways to explain the rationale for policy. One is using normative welfare analysis, and the other is using political economic theory. The welfare maximization argument is that if there is market failure government intervention can correct this and improve allocative efficiency. There can be several reasons for such failure. Externalities like environmental impacts of energy use and cost incurred in ensuring security of oil

supply is an example of such failure. A second reason for market failure is public goods. R&D investments in production and processing of biofuels entail knowledge spillovers, which are public goods and thus lead to underinvestment by private sector. A third justification could be infant industry argument and the need for special incentives to build skills and capacity. A fourth reason could be the element of uncertainty. Investors may be risk averse but government may be risk neutral. Government policies that provide subsidies and assure a market can affect both quantity and timing of production. According to the normative school, the observed divergence between the neoclassical prescription and actual practice is attributable either to a lack of knowledge or poor management. The second way to explain the rationale for policy is the political economic view, which explains public intervention as a manifestation of the rent-seeking behavior of politicians, voters, lobby groups, and bureaucrats. One difference between the two is that the welfare maximization approach implicitly assigns equal weight to all the different groups while the political economic approach assigns different weights for different economic groups. Whatever the real motivation for government intervention in biofuel markets, the existence of market failure in energy markets is indisputable. The goal of a good policy should be to internalize the externality efficiently and, with due consideration to distributional aspects, the fact that externalities are diverse and often not easily quantified in monetary units makes the design of policies complex and challenging.

### **4.3 Policy tools**

A variety of policy tools exist in theory to overcome the “missing market” problem. A list of several different types of instruments that are in use is in table 11. However, there is no single tool that is the first best under all circumstances. The theoretical efficiency of any particular approach also depends on pre-existing distortions (Lichtenberg and Zilberman 1986). Experience suggests that the actual policy will, however, depend on various factors like budget and resource availability, the availability of information, transaction costs, and political economic considerations.

Theoretically the first-best instrument is a Pigouvian tax equal to marginal social cost of the externality. But in several cases imposition of tax can prove to be infeasible because it may be difficult to estimate the social damage or because of political economic considerations. One popular policy response has been to subsidize benign alternatives. Theoretically both a tax and subsidy can result in the same level of emissions, but they have different distributional effects. Another response is to impose direct controls on quantity of pollution through quotas, targets, and standards. In cases where pollutants pose a grave risk to the human health such as emissions of dioxins, mercury, or lead from industrial facilities, this type of regulation is common. Mandatory installation of emission control devices like scrubbers or catalytic converters in automobiles are also examples of direct controls. But no matter whether a price or quantity-based instrument is used, there is always a corresponding way to set the other in such a way that the same result is obtained (Weitzman 1976). In addition to price-based incentives and direct controls, other policy tools like enforcement of property rights and trading mechanisms (sulphur and nitric oxide emissions from electric power plants), informational programs (energy star labels for electric appliances), compensation schemes (Mexico's program on payments for hydrological services), etc., have been used in other contexts. While a complete survey of the vast literature on the relative merits and demerits of these tools is beyond the scope of this report, we would like to highlight one major difference between a tax on pollution and a subsidy for clean technology. The outcome of a policy based on subsidies will be capital augmentation in benign technologies and a reallocation of resources from more polluting to less polluting technologies. But it would do little to induce demand management through conservation and resource efficiency, whereas a policy based on taxation can achieve all of those. This is a subtle yet important difference since demand management is often more cost effective than augmenting supply through clean technology (Hawken and Lovins 1999, Lovins 1985). It has been argued by several economists that environmental externalities should be corrected for by taxing polluting goods, not by subsidizing nonpolluting alternatives.

## 4.4 The biofuel policy spectrum

This section describes the essential features of some widely used policies, the various forms in which they exist, and the implications of such policies for economic welfare and the environment.

### 4.4.1 Energy and carbon policies

- **Excise tax credit for biofuels:** Fuel excise tax reduction is the most direct and widely used instrument to help biofuels compete with fossil fuels. Most nations levy a tax on the consumption of gasoline and diesel, and a fuel tax reduction for biofuel aims to lower the cost of biofuel relative to gasoline or diesel. Biofuel tax policies vary widely in the level of reduction, the cap on production that is subject to reduction, the sunset clause, etc., across countries. For example, in the United States, the volumetric ethanol excise tax credit provides a fixed tax credit of \$0.51 per gallon of ethanol blended with motor gasoline (and \$1.00 per gallon for biodiesel). The level of exemption does not adjust to changes in oil prices and has no cap on production and no sunset clause. However, Germany, which also has similar tax credits, has begun phasing out tax reductions for biodiesel starting in 2007. In France and Italy biofuel tax policies are being reviewed each year. Spain has granted a full excise tax exemption for biofuels until the end of 2012, amounting to €0.42 (US \$0.57) per liter for ethanol and €0.29 (US \$0.39) per liter for biodiesel (Kojima, Mitchell, and Ward 2007). A tax credit is a subsidy to the processor (some of which is passed on to the farmer) and, therefore, raises their surplus whereas it is neutral from a consumer's standpoint. It also has a negative impact on government revenues. The ability to use this instrument depends on the level of excise taxes levied on petroleum fuels. Countries with low levels of taxation are not in a position to provide adequate reduction. In countries where fuel taxes are high because they are primarily for revenue generation, a fuel tax reduction will adversely affect the fiscal situation (Koplow 2006; Kojima, Mitchell, and Ward 2007). Tax credits, which are invariant with changes in oil price and have no caps on production level or do not have a sunset clause, can

result in a large increase in subsidy burden if there is a structural break resulting in lower oil prices or a large increase in biofuel production.

- **Direct controls – renewable fuel standards and mandatory blending:** While a tax or a subsidy is an incentive-based approach, several national and state governments exert more direct control over fuel markets. Renewable fuel standards and mandatory blending requirements for biofuels are two examples of direct control over fuel markets. The U. S. Energy Policy Act of 2005 mandates the production of 12 billion gallons by 2010 while the Renewable Transport Fuel Obligation in the United Kingdom requires oil companies to blend 2.5% biofuel in motor fuel by 2008 and 5% in 2010-11. The European Union Biofuels Directive issued in 2003 requires member states to set national targets to ensure a minimum proportion of biofuels and other renewable fuel use in their domestic market. A reference target value for end-2005 was set at 2%, calculated on the basis of energy content, of all gasoline and diesel for transportation purposes, and 5.75% by end-2010 (Kojima, Mitchell, and Ward 2007; EU 2003). In India, China, and Thailand mandatory blend ratios range from 5% to 10% while it varies from 20% to 25% in Brazil depending on the supply of ethanol. Unlike a tax credit, the effect of regulating the market share through direct control is to drive up the price of fuel. From the government's perspective, a blending standard is revenue neutral, while consumer surplus is reduced and producer surplus increases like in the case of a subsidy. In fact, theoretically speaking, an ethanol mandate can be made to exactly duplicate the effect of a subsidy such as a tax credit on the producer (Gardner 2003).
- **Energy tax or carbon tax:** In a few countries fossil fuels are taxed to tip the scale in favor of biomass as an energy source. For example, in Finland and Sweden taxation of oil has have been in use since the 1970s as one of the means of reducing oil dependence. Finland is considered the first country to introduce a carbon-based tax in 1990 while Sweden introduced it in 1991. As a result of such taxes, biomass became less expensive than coal in 1991 in Sweden and in 1997 in



Finland. The general carbon tax in 2002 in Finland was 17.2 €/tonne CO<sub>2</sub>, except for natural gas where it was half of this, and in Sweden 70 €/tonne CO<sub>2</sub>. Peat in Sweden is taxed only for its sulphur content at 4.4 €/tonne of peat (40 SEK), or about 1.7 €/MWh (15 SEK/MWh). Peat in Finland is subject to an energy tax of about 1.5 €/MWh (Bohlin 1998, Ericsson 2004). Several economists have argued that environmental externalities should be corrected through taxes such as these that penalize polluting goods rather than subsidies for nonpolluting alternatives because it violates the polluter-pays principle (Jaffee, Newell, and Stavins 1999; Popp 2006). Therefore, carbon taxes are considered more appropriate to counter global warming than subsidies to biofuels. Taxes also have dynamic effects such as encouraging investment, a broader set of technologies including energy efficiency, and inducing behavioral changes such as energy and resource conservation. However, unless other countries impose taxes, unilateral action can have several disadvantages. One of these might be that polluting industries might relocate to places with poorer environmental laws and more polluting energy sources, and the result might be a loss of jobs with no real gain for the environment. Similar to a fuel standard or a blending mandate, the effect of a tax is to drive up the price of the fuel, but taxes have a different distributional effect on the welfare of producers and consumers than a subsidy. Moreover, due to political economic reasons, taxes are highly unpopular and replaced by subsidies. Taxes result in an increase in government revenues, but the effect on consumer and producer surplus depends on the elasticity of demand. If demand is inelastic, the tax is passed on to the consumer by the producer.

- **Policies for flex vehicles:** Government policies have aimed to stimulate supply and demand for ethanol vehicles, through direct subsidies in the form of tax credits and indirectly through energy-efficiency credits to manufacturers of automobiles. State and federal policies in the United States and Brazil have given preference to alternative fuel vehicles, including FFV that can run on ethanol-blended gasoline. In the United States the Alternative Motor Fuels Act of 1998 has provided credits to automakers in meeting their Corporate Average Fuel

Economy standards when they produced cars fueled by alternative fuels, including E85 (Leiby and Rubin 2001). However, the credits were not contingent upon achieving any particular efficiency of operation or actual use of ethanol-blended gasoline. In Brazil vehicle tax policies have been tinkered with to adjust the supply of vehicles in accordance with the supply of ethanol (Geller 1985, Geller 2004). Between the two types of policies mentioned above, a vehicle tax credit has similar effect as a fuel tax credit. It stimulates demand for FFVs and has a negative impact on tax revenues from the government's perspective. While a policy that provides efficiency credits seems to have no apparent implications for government budget, it is in fact claimed to have enabled a number of U.S. automobile manufacturers to avoid penalties they would have otherwise had to pay on inefficient fleets. Estimates suggest that automakers have, as result of this dual-fuel vehicle loophole, avoided nearly \$1.6 billion in penalties for falling short of federal fuel economy targets (MacKenzie, Bedsworth, and Friedman 2005). The ultimate impact of such a policy is that automakers avoid investments in fuel efficiency and consumers spend more on transportation.

#### **4.4.2 Farm policies**

Bioenergy is produced mainly from agricultural crops and crop residues. Since feedstock accounts for more than half the cost of production, agricultural and trade policies that affect supply, demand, and prices of agricultural commodities are important determinants of biofuel economics. Contrary to energy policies which have relied by and large on tax subsidies and mandates, agricultural policies have focused on either enhancing or controlling supply, through price supports, land-use regulation, regulation of imports and exports, etc. Historically, agricultural policies have tended to protect producers in industrial countries from imports from lower-cost producers, while policies in developing countries have tended to tax exports to fund government budgets (Kojima, Mitchell, and Ward 2007; Binswanger and Deininger 2005; Swinnen and van der Zee 1993). Price supports coupled with deficiency payment have helped increase output and lower market price of commodities. Through the farm commodity program, the U. S. government pays farmers who participate in feed grain, wheat, rice, and upland cotton programs a

deficiency payment for the eligible level of production. The deficiency payment is the difference between a target price and the market price or a loan rate, whichever (difference) is smaller. In order to be eligible for deficiency payments, participating farmers must idle land as required by the acreage reduction program. The effect in the biofuel market is to reduce the cost of biofuel feedstock and hence the cost of biofuel and by-products. Through the Common Agricultural Policy, the EU supports the biofuel sector by allowing growing biofuel crops on set-aside land and furthermore by granting an area-constrained 45€/ha direct payment to energy crops grown on nonset-aside land. In developing countries subsidies in investment of public goods (for example, irrigation) have increasingly given way to inputs (for example, fertilizer, water, and electricity).

#### **4.4.3 Trade policies**

Most countries impose several forms of trade restrictions on both feedstock and biofuel, with preferential waivers of tariffs and quotas for certain countries. For example, import tariffs (and quotas) are omnipresent in most biofuel-producing countries (table 12). Import tariffs and quotas have the effect of protecting the interests of domestic producers and also restricting benefits to selected countries (Kojima, Mitchell, and Ward 2007). Another barrier is taxation of exports. Argentina, for example, levies an export tax of 27.5% and 24% on soybean seeds and soybean oil, respectively, while biodiesel is assessed a lower tax of 5%. This policy is aimed at promoting the export of value-added finished products rather than raw materials. Export subsidies for agricultural and industrial products are on the other hand aimed at helping high cost domestic producers compete with low cost producers in international markets. Since such trade barriers are erected with little consideration of the environmental impacts, they can either diminish the environmental benefits of biofuels or even have a net negative impact compared to fossil fuels. Import tariffs on Brazilian sugarcane ethanol in order to protect corn ethanol producers in the United States despite the well-documented evidence that the former has higher net energy and carbon benefits is a case in point. In general, trade liberalization and lowering of trade barriers increases global welfare in the long run. Reforms in biofuel trade should be no exception. Reduction of barriers should increase competition leading to improvement in average efficiency of production. Removal of high tariffs in highly

protected markets will lead to lower prices and increase in consumption, such as decrease in cost of ethanol in the United States and EU due to cheaper imports of sugarcane ethanol from Brazil. It would also lead to higher world price of sugar and sugar products as cane gets increasingly diverted to ethanol production. Consumers in exporting countries would also be negatively affected by such price rise. At the same time some barriers by reducing the volume of trade can actually enhance welfare. For instance, given the grave concerns about the sustainability of biofuels that are produced at the cost of destruction of rainforests or starvation in poor biofuel exporting countries barriers to trade may be legitimate (Kojima, Mitchell, and Ward 2007). Thus, barriers to Brazilian ethanol or Malaysia palm biodiesel may be welfare enhancing. A complete review of the trade policies is contained in Kojima, Mitchell, and Ward (2007). In any case, one can easily see that analyzing the net impact of trade policies on the environment can be very complex and challenging task. Modeling the impacts of global trade in biofuels for the environment under various scenarios of trade restrictions and trade liberalization should be an important area of future research.

#### **4.4.4 Government funding for R&D**

R&D on biofuel technologies has the potential to increase productivity and reduce costs. However, since investments in R&D have public good characteristics the private sector is likely to under invest in such ventures. Knowledge spillovers, which make it difficult for inventors to reap the full social benefits of their innovations, are one such characteristic. There is consequently little controversy among economists about the desirability of governmental support for R&D investments (Klette, Moen, and Griliches 2000). The Biomass Research and Development Program is operated jointly by the U. S. Department of Agriculture and the Department of Energy, which offer \$12 million in support for R&D of biomass-based products, bioenergy, biofuels, and related processes. Federal spending on biofuels R&D in the United States is claimed to have hovered between \$50 and \$100 million a year between 1978 and 1998 (Gielecki, Mayes, and Prete 2001). Several governments of the EU including Germany, France, and Sweden also fund R&D in biofuels.

#### **4.4.5 Other policies**

Investment incentives such as grants, loans and loan guarantees, tax-related incentives (tax holidays, accelerated depreciation, tax reductions), etc., are being provided in almost all countries to biofuel refineries (Koplow 2006; Kojima, Mitchell, and Ward 2007). However, policies like trading mechanisms, certification of biofuels, and compensation schemes like payments for environmental services are yet to achieve prominence in the context of biofuels. This should be one area for future policy work as they have important implications for biofuels. For example, there are increasing calls for certification of biofuels in order to ensure sustainability in production practices and preventing loss of ecologically sensitive areas like tropical rainforests (van Dam 2007).<sup>11</sup>

#### **4.5 Summary of policies and some implications**

It's amply clear that the biofuel sector is being promoted through an intricate web of policies. Table 12 lists these major policies. The U. S. and EU policies are a blend of fuel excise tax subsidies, mandatory blending standards, and vehicle subsidies along with the indirect influence of deficiency payments, acreage control, and import and export regulations (Koplow and Johnson 2005; Kojima, Mitchell, and Ward 2007). In Brazil too the government has underwritten the ethanol program by providing highly subsidized financing for producers, a guaranteed market, support prices for producers, and subsidies for consumers (Geller 1985, Geller 2004). Similarly in Malaysia and Indonesia, the government has encouraged the development of the palm oil sector through a variety of concessions at every step from planting to export (Casson 2000, Pletcher 1991). In India and Thailand the government is promoting the production of ethanol from sugarcane and cassava, respectively, through mandates for blending of ethanol (GoI 2003, Nguyen 2007).

From a profit-maximization perspective, one can conjecture the likely effects of these policies on economic welfare and environment. However, we would like to point out that

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<sup>11</sup> <http://news.bbc.co.uk/2/hi/business/6273626.stm>

if when there are pre-existing distortions and there is stacking of policies, the following conjectures may become invalid. In such cases general equilibrium analysis will be needed. Table 13 lists the expected impact of a policy on some indicators of interest. (1) In general almost all policies result in a reduction in the consumption of oil at a national level either because they increase the supply of biofuel or reduce the demand for oil. The possible exceptions would be acreage controls and export subsidies, which discourage domestic production and domestic consumption of biofuel, respectively. But export subsidies may increase the global supply of biofuel and, hence, cause global reduction in use of oil. (2) On the contrary, we surmise net GHG offsets from most policies are uncertain with the exception of carbon taxes and fuel efficiency standards, which reduce the demand for oil. The net GHG gas offsets are uncertain because they depend on the crop, the intensity of use of fossil fuel-based inputs in production and processing of feedstock, and the nature of land-use change resulting from cultivation of biofuel crops, each of which varies with location and with time (refer to chapter 2 for more detail). (3) All policies that encourage the production of biofuel will have a positive impact on farm income. (4) The ethanol processing industry is likely to either gain or be unaffected by most policies with the exception of acreage controls which increase the price of feedstock and have a negative effect on producer surplus. On the contrary, the food processing industry will suffer due to higher prices of the raw inputs. The impact on the livestock industry will also be varied. Livestock producers that can utilize the coproducts from corn or rapeseed will benefit, while those that use fresh grains or oilseeds will suffer. (5) The impact on consumer surplus will also vary. Taxes and mandates, which increase the overall energy price, rather than lower the cost of clean energy lower consumer surplus along with policies that restrict the production of feedstock. Efficiency standards, price supports for biofuel crops and export quotas increase consumer surplus either by lowering the cost of energy service or lowering the cost of feedstock which comprises a large share of biofuel production cost. The impact of agricultural and trade policies on consumer surplus for food is similar to the impact of the policy of consumer surplus for energy. (6) From the taxpayer's perspective, naturally taxes and tariffs are superior since they raise revenue, while tax credits, price supports, acreage controls, and trade subsidies result in loss of revenue or increase in spending. (7) In general most

agricultural and trade policies tend to benefit farmers while the energy policies are suited to addressing the problems arising out of oil consumption. It is also worth reiterating that the above hypotheses are for the case of a single isolated policy and do not apply when there are multiple policies in effect simultaneously. Assessing the marginal impact on welfare of any one of these policies under such circumstances is a complex task.

#### **4.6 Theoretical and empirical literature on policy impacts**

Our separation of the economic and policy literature into two different groups is somewhat artificial. In the previous chapter we had described several general and partial equilibrium models, which are no doubt policy relevant. But we find that most of those models focused on simulating the impact of just one policy, namely, a renewable fuel mandate. There was neither much detail on the agricultural policies nor on oil prices. They also did not compare various types of policies based on efficiency and distributional aspects. In this section, we summarize some more theoretical and simulation-based studies, which consider these aspects in a little more detail. Gardner (2003) performs a theoretical comparison of the effect of three different policies—target price, acreage controls, and ethanol subsidy—on the welfare of corn producers, ethanol producers, and taxpayers, and the efficiency of transfer using a simple supply and demand model of the market for single commodity. The analysis indicates that both corn producers and ethanol manufacturers gain from either an ethanol subsidy or corn-deficiency payment. Acreage controls on the other hand make farmers better off and ethanol producers worse off because it reduces supply and raises corn price. But from a distributional perspective, corn producers gain relatively more from deficiency payments and ethanol producers gain relatively more from an ethanol subsidy. From a taxpayer's perspective, acreage controls are the least costly while mandates are costly for the consumer. However, all policies result in a net transfer from consumer and taxpayer to corn producer and ethanol producers. The efficiency of such transfer is dependent on assumptions of elasticity of supply and demand for corn, ethanol, and by-products. One drawback of this study is that it does not take into account pre-existing distortions in determining the efficiency of a policy. Lichtenberg and Zilberman (1986) show that ignoring such pre-existing

distortions can give rise to biased welfare estimates. Tyner and Taheripour (2007b) develop a stylized analytical partial equilibrium model to investigate distributional impacts of an excise tax subsidy for ethanol. Their model is motivated by the theory of tax incidence, which states that the statutory incidence of a tax (or a subsidy) is different from its economic incidence. The main conclusions that emerge are that the distribution of the tax credit given at the point of blending between the ethanol industry and gasoline industry varies with the elasticity of substitution and the supply elasticities of ethanol and gasoline. As the elasticity of substitution tends to infinity, the entire subsidy goes to the ethanol producer. The share of the subsidy passed on to the farmer by the ethanol industry increases with corn prices and ethanol production. In turn, the farmers pass a large portion of their share to landowners.

Tyner and Taheripour (2007a) simulate the impact of various alternatives to the current fixed 51 cent-per-gallon subsidy that could reduce the upward pressure on corn prices. Under the current policy, ethanol producers could still invest profitably in new production with corn price as high as \$4.72/bu (at oil price of \$60 per barrel). This leaves the burden of adjusting to higher corn prices on livestock producers and exporters. A policy that provides no subsidy for crude oil price above \$60 per barrel, and a subsidy that increased 2.5 cents per gallon for each \$1.00 crude price below it yields a break-even corn price of \$3.12/bu (at oil price of \$60 per barrel) compared with \$4.72/bu under the current policy. Alternatively, a policy that combines a renewable fuel mandate combined with a variable subsidy that kicks in only at low oil prices can further reduce the subsidy burden while limiting the risk of high prices at the pump. To summarize again, a majority of the studies we encountered analyze the impact of biofuel mandates. Some studies analyze the effects of achieving a certain level of carbon reductions. Some studies considered trade liberalization while others did not. All studies predict a decrease in surplus for food buyers and an increase in surplus for farmers and the ethanol refining industry. Some studies also predict a decrease in demand for farm support programs.

In general we find that the literature on the impact of policies is at a nascent stage. The studies are all either theoretical or simulation based. The general emphasis seems to be



on predicting the impact of achieving a certain biofuel target on a small set of indicators like prices of agricultural commodities, farm income, and balance of trade. One major gap is the lack of econometric assessments of biofuel policies. We recognize this task is challenging for several reasons. First, except for Brazil, the time series of ethanol has been short with the result longitudinal data sets are unavailable. Second, given that there is a stacking of policies, it is hard to isolate the effect of any single policy. Ignoring the effects pre-existing distortions can produce biased welfare estimates (Lichtenberg and Zilberman 1986; Goulder 1995; and Goulder, Parry, and Burtraw 1997). Third, since the treatment assignment is nonrandom, it is hard to determine causality. Another shortcoming in current studies is that with the exception of studies that evaluate the cost of achieving GHG reductions, the others do not analyze the actual implications of these policies for the environment. It is also difficult to gauge the cost effectiveness of these policies for achieving carbon emission reduction. There is also little discussion of the infrastructure costs of adjustment to biofuels.

One important environmental policy, which will have major implications for biofuels, is the regulation of biotechnology. Biotechnology offers opportunities for enhancing productivity while at the same time reducing intensity in the use of inputs that are scarce such as land and water or inputs that have environmental externalities like fertilizers and pesticides. But growth of agricultural biotechnology is constrained by regulation and bans. While the motivation for these bans is claimed both to be political and scientific, uncertainties about impacts and the regulatory barriers no doubt slow the development of this technology. Identifying the optimal level of regulation, which retains sufficient incentives for the development of biotech innovations that are welfare enhancing, should be an important area of research (Cooper 2005).

## **4.7 Chapter summary**

Biofuels, like all energy sources, have relied heavily on government support to compete with fossil fuels. A complex web of policies that includes policies towards energy, transportation, environment, agriculture and international trade, and national security are

simultaneously influencing the evolution of biofuels. The orthodox neoclassical explanation is that government intervention can maximize social welfare by correcting the sources of market failure and achieving allocative efficiency while political economic theory questions the assumption of government as a benevolent dictator that aims to maximize social welfare. Market failure considerations seem to carry more weight in the case of energy and environmental policy while political economy considerations seem more powerful when it comes to explaining agricultural and trade policies. Our aim has been to steer clear of this debate and focus on what can be predicted based on economic theory and modeling as to what the implications of certain types of policies are likely to be for economic welfare and the environment.

Among the specific policy instruments tax subsidies, renewable fuel standards, and mandatory blending are omnipresent. Trade policies such as tariffs and quotas on imports and exports have also been crucial in helping countries develop a domestic biofuel sector. Subsidies are effective in stimulating supply, but unconditional subsidies carry the risk of transferring too much income to producers especially under a regime of high oil prices. A mandatory fuel standard is also effective but may be inefficient under a regime of low oil price. Carbon taxes appear to be less popular, which we surmise is due to reasons of political economy. Since there is stacking of subsidies at multiple levels ignoring pre-existing or accompanying distortions can give biased estimates of welfare impacts under a given policy. In general rigid policies that are not dynamically linked to economic and environmental indicators such as shadow price of energy security, oil prices, etc., create the risk of “technological lock-in” into costly technologies.

Theoretical analysis and simulations suggest that the impact of current generation of policies will be heterogeneous creating both winners and losers among economic agents. For example, it is clear that net food producers will generally gain while net food buyers will lose. The impact on the environment is uncertain or at least cannot be deciphered from the current literature. From an environmental standpoint, while carbon intensity of energy in transportation will decrease, there will be other negative externalities due to land-use change. There is also little analysis of the impact of biofuels on energy price. In

fact, the imprecise definition of policy goals (as energy security, rural development, etc.) itself renders such an analysis impossible. The current set of policies seems to suggest that they are designed to benefit political constituencies (farm lobby, agribusiness, voters, etc.) rather than maximize economic welfare or environmental goals.

Policies are mostly national in scope with the exception of the common agricultural policy of the EU, which is continental in scope. There is a need for coordination of policies at a global level if biofuels are to be effective in combating global climate change. For example, policies that subsidize domestic but carbon-intensive feedstock and discriminate against imported low-carbon feedstock can nullify or even worsen the net carbon emissions. That said, import of oil palm from EU is being blamed as a cause for deforestation in Malaysia. An important area for future policy research, therefore, is to design policies that prevent such collateral damages. In developing countries, policies should also focus on biofuel technologies for alternative uses such as cooking and electricity from biomass, which can be grown on the same lands that are planned for cultivation of feedstock for ethanol and biodiesel.

## **5 Conclusion and Areas for Future Work**

Concerns about climate change, security, and reliability of energy supply and the growing demand for oil are likely to make biofuels ever more attractive. This will trigger competition for agricultural land; therefore, it is imperative to analyze the impact on agricultural markets, trade, and the environment along with the analysis of impact on energy markets. As far as energy is concerned, the main contribution of biofuel will be in augmenting the supply of fuels for transportation. It may also in certain situations be a source for electricity and heat but those will be confined to places with either an abundance of biomass or with little access to the electric grid. For the most part, the future of biofuels will depend on energy policies and technologies that will affect demand for liquid fuels. Increase in fuel efficiency, hybrid and fuel cell vehicles, and carbon taxes will reduce the demand for fuel, while increase in income and highways will increase the demand for fuel. Such increases are more certain in developing countries.

The production of biofuel involves at least two major stages, production of an agricultural crop and conversion of the crop to fuel. There are three types of crops, which can be used, namely, sugar and starch, oilseeds, and cellulose. Ethanol and biodiesel are the two main types of liquid biofuels today. (Of course, this is in addition to other types of biofuels which are suited for electricity production or for household purposes.) Production of biofuel from sugar and starch and oilseeds is relatively cheap and commercially mature, while that from cellulose is costly and not economical today. But from a social standpoint, the cost per unit of fuel is an incomplete indicator for comparison of fuels. This is because the cost per unit of fuel does not include the cost (or benefit) with respect to carbon and other nonclimate externalities from using a particular fuel, which should ideally be the case. Although techniques like LCAs are being used to quantify the physical impacts of using biofuel, they are not ready for economic comparisons yet. We also believe other indicators, which quantify the impact on poverty, rural development, balance of trade, the price of energy, and price of food should be considered when comparing fuels. Therefore, one area of future work is to expand the engineering life-cycle framework to include the market effects of biofuels using a CGE-type approach. Current partial and general equilibrium models have several drawbacks in this context. They focus on today's commercial crops, on OECD countries, on a limited set of economic indicators like the price of food and energy, and only on climate-related carbon emissions. This gap should also be addressed in future work by expanding the geographic, economic, and environmental scope of equilibrium models. They are also thin on the treatment of dynamics, risk, and uncertainty.

When we look at agriculture, the main impacts of biofuels will be to increase the demand for land, water, and other inputs. Current research throws up several interesting hypotheses for future research in this area. Biofuels may displace forestland or pastureland and shift production of food and livestock to marginal land. Biofuels have been universally hypothesized to raise the price of food over the long term; have negative impact on the landless, especially the urban poor; and have a positive impact on landowners. But in some instances the landless poor may be better off if the benefit from increased employment opportunities and higher wages as a result of higher biofuel

production may exceed the increased cost of purchased foods. There will also be several technological changes in agriculture because biofuels will necessitate improvements in agricultural productivity. This will lead to the adoption of new types of crops, biotechnologies, water conserving technologies, etc. Switchgrass, Miscanthus, Jatropha curcas, and sweet sorghum are some crops that are being investigated in different countries. One of the key elements then is to understand the adoption of new crops and technologies. Adoption of biofuels will have to be analyzed at several levels, namely, the farm level, the processing and distribution industry, and the consumer. But production of biofuels represents substantial risks. A positive oil supply shock such as that witnessed in 1980s or a negative biofuel supply shock due to crop failure will render biofuels uncompetitive. Because of these risks, adoption is being and will continue to be triggered by policies that maintain demand for biofuels. At the same time rigid policies such as those, which provide a fixed subsidy irrespective of oil prices, present a fiscal risk to the exchequer in the event of negative oil supply shock. Policy research should focus on developing policies that are dynamic and also reflect the marginal impact of biofuels on the environment, which is not the case with today's policies. Adoption of biofuels may also result in the emergence of contracting and cooperatives in the processing sector. The impact on farmers will be contingent of a host of factors like the market structure, the type of contracts, protection against risk, etc. This is another area that has not been addressed in the current literature.

Related to agriculture is the relationship between biofuels and international trade. A major motivation for biofuel is that they will raise farm income, which will have attendant political and economic benefits. But such gains may not be realized when domestic production competes with imports that are cheaper. This is the reason biofuel crops like other agricultural goods are also subject to barriers in the form of duties, quotas, and bans on imports. The rationale for such protection can be several such as the need to support domestic farmers, enable the development of a domestic infant industry, keeping food prices low, and environmental regulation. An obvious effect of trade barriers is to prevent the best biofuel from entering the market. The example of tariffs imposed by the United States on ethanol or sugarcane from Brazil is a case in point since

sugarcane is considered economically and environmentally superior to using corn. But by reducing the volume of trade, some barriers actually enhance welfare. One instance where this can be true is when biofuel production has environmental externalities that are not taken into account. Biofuels will also affect trade by reducing food surpluses in developed countries, which will reduce both food exports and food aid. This will allow farmers in poor importing countries to receive higher prices, which can be an opportunity to increase productivity especially in those countries. The literature on linkages between biofuels and international trade is at a nascent stage and needs to be expanded further.

Given the spectrum of agricultural and trade effects, the only conclusive statement one could make about the environmental impact of biofuels is that it is hard to generalize. Biofuels will have both environmental benefits and costs, and these are difficult to compare. They may reduce carbon emissions, but there will be negative impacts from increased agricultural activity, which will be important on a local if not global scale. The current literature has focused too much on carbon offsets to the exclusion of other environmental effects. Depending on whether forestland is converted to agricultural land, whether a perennial or annual crop is grown, whether the crops are grown as a monoculture or polyculture, whether they are irrigated or rain fed, whether they are grown organically, etc., the impacts will vary too. Existing tools like LCA provide aggregate information for a limited set of environmental indicators, but future research will need to estimate both a broader set of indicators and also differentiate them with location and time. A related area of future work should be in monitoring and evaluation of production practices. Ensuring adherence to sustainable practices will require development of labeling and certification procedures. Economists and policymakers will have to consider the costs of implementing such procedures and its impact on the competitiveness of biofuels.

In addition to the above themes, there are several others we think should be part of the future research agenda. For instance, formal economic models predict the impact on the poor solely based on market price of food or other commodities. While this may be sufficient in the context of fully developed market economies, the importance of informal

economy in developing countries renders such models inadequate in those contexts. The use of marginal lands or the utilization of crop residues for biofuel production will deny access to fuelwood and fodder, which can hurt the poor. In such cases the production of biomass suited to local needs may be socially more optimal than the production of biofuels for cars in cities. Demand-side policies that discourage the consumption of fossil fuels or carbon emissions as a way of improving energy security or protecting the environment seem should also be given greater attention by researchers and policymakers despite the political economic barriers to such policies. From a formal modeling perspective, the dynamic relationship of food price in relation to energy price as they become increasingly correlated is an area of future research. Most of the models that exist today are simulation based but, as the time series of biofuels grows, econometric verification of the impacts should also be accorded priority. There should also be an effort to develop tools that would allow assessments of the impacts of biofuels at a country-specific level.

We believe this report is a broad and comprehensive survey given that the emphasis is on liquid biofuels. We are aware that the use of biomass for household heating or electricity production is very important especially among the poor in developing countries, while demand for liquid biofuels is largely from the richer sections of society. But in terms of the potential for impact on the broader economy and the environment, we think ethanol and biodiesel warrant greater attention given the scale of the commitments in terms of investments and policies that are being made in these countries today. Even at low levels of production of biofuels, rising food prices are already being evidenced in many countries. In terms of future impact on poverty and the environment, modern biofuels may dwarf the impacts of traditional biomass. Because of international trade possibilities, actions of rich nations assume equal or greater significance for the poorer nations, which are bound to feel both positive and negative effects from the rising demand for agriculture.

The most important conclusion of our survey is that not all biofuels are created equal. Biofuels exhibit considerable spatial and temporal heterogeneity in production. The

impact of biofuels on welfare will be heterogeneous, creating winners and losers. The fact that the likely losers are poor net food buyers raises serious concerns about the distributional impacts of biofuels. It will also result in environmental tradeoffs such as reduction in carbon emissions versus increase in local pollution and/or loss of natural habitats. There seems to be an exclusive emphasis on climate change to the detriment of other environmental problems in making the case for biofuels as an environmentally benign technology. The reality is that the overall impact of biofuels on energy security, environment, and economic welfare is hard to conjecture. Finally in the words of Vaclav Smil (2003), “Long-term historical perspectives are truly invaluable; energy transitions are protracted, generations-long affairs; dubious claims made on behalf of small-scale, experimental and demonstration-size techniques are no substitutes for mercilessly critical appraisals based on the first principles; biased promotions of grand theoretical solutions rarely survive brutal encounters with scaling up for large-scale, reliable operations in the real world.”



## 6 References

- Adams, D. M., R. J. Alig, J. M. Callaway, B. A. McCarl, and S. M. Winnett. *The Forest and Agricultural Sector Optimization Model (FASOM:) Model Structure and Policy Applications*. Portland, Oregon: U. S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station, 1996.
- Andrews, S. S. "Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations," White paper, USDA Natural Resources Conservation Service, 2006.
- Bailis, R., M. Ezzati, and D. M. Kammen. "Mortality and Greenhouse Gas Impacts of Biomass and Petroleum Energy Futures in Africa," *Science* 308, 5718 (2005):98-103.
- Banse, M., A. Tabeau, G. Woltjer, and H. van Meijl. "Impact of EU Biofuel Policies on World Agricultural and Food Markets," paper submitted for the GTAP Conference, Purdue University, Indiana, 2007.
- Barnes, D. F., and W. M. Floor. "Rural Energy in Developing Countries: A Challenge for Economic Development," *Annual Review of Energy and the Environment* 21, 1 (1996):497-530.
- Berndes, G., M. Hoogwijk, and R. van den Broek. "The Contribution of Biomass in the Future Global Energy Supply: A Review of 17 Studies," *Biomass and Bioenergy* 25, 1 (2003):1-28.
- Besley, T., and A. Case. "Modeling Technology Adoption in Developing Countries," *The American Economic Review* 83, 2 (1993):396-402.
- Bhattacharyya, S. "Applied General Equilibrium Models For Energy Studies: A Survey," *Energy Economics* 18, 3 (1996):145-164.
- Binswanger, H., and K. Deininger. "Explaining Agricultural and Agrarian Policies in Developing Countries," *Journal of Economic Literature* 35, 4 (1997):1958-2005.
- Bohlin, F. "The Swedish Carbon Dioxide Tax: Effects on Biofuel Use and Carbon Dioxide Emissions," *Biomass and Bioenergy* 15, 4/5 (1998):213-291.

- Bovenberg, A. L., and L. H. Goulder. "Neutralizing the Adverse Industry Impacts of CO<sub>2</sub> Abatement Policies: What Does It Cost?" National Bureau of Economic Research (NBER) Working Paper Series, Cambridge, Massachusetts, 2000.
- Brazilian Foundation for Sustainable Development (FBDS). "Outcomes and Recommendations of Workshop on Agro-energy Expansion and Its Impact on Brazilian Natural Ecosystems," 2007.
- Breuss, F., and K. Steininger. "Biomass Energy Use to Reduce Climate Change—A General Equilibrium Analysis for Austria," *Journal of Policy Modeling* 20, 4 (1998):513-535.
- California Integrated Waste Management Board (CIWMB). *Conversion Technologies*, report to California Legislature by California Integrated Waste Management Board, 2005.
- Campbell, C., and J. Laherrere. "The End of Cheap Oil, " *Scientific American* 278, 3 (1998):60-5.
- Casson, A. "The Hesitant Boom: Indonesia's Oil Palm Sub-Sector in an Era of Economic Crisis and Political Change," report prepared for the Program on the Underlying Causes of Deforestation, Centre for International Forestry Research (CIFOR), Bogor, Indonesia, 2000.
- Caswell, M., and D. Zilberman. "The Choices of Irrigation Technologies in California," *American Journal of Agricultural Economics* 67, 2 (1985):224-234.
- Chakravorty, U., B. Magne, and M. Moreaux. "A Dynamic Model of Food and Clean Energy," IDEI Working Papers 403, Institut d'Économie Industrielle (IDEI), Toulouse (2006).
- Cooper, J., L. M. Lipper, and D. Zilberman. *Agricultural Biodiversity and Biotechnology in Economic Development*, Norwell Massachusetts: Springer, 2005.
- Crabbe, E., C. Nolasco-Hipolito, G. Kobayshi, K. Sonomoto, and A. Ishizaki. "Biodiesel Production from Crude Palm Oil and Evaluation of Butanol Extraction and Fuel Properties," *Process Biochemistry* 37, 1 (2001):65-71.
- Curran, L., S. N. Trigg, A. K. McDonald, D. Astiani, Y. M. Hardiono, P. Siregar, I. Caniango, and E. Kasischke. "Lowland Forest Loss in Protected Areas of Indonesian Borneo," *Science* 313, 5660 (2004):1000-1003.

- Delucchi, M. A. "Conceptual and Methodological Issues in Lifecycle Analyses of Transportation Fuels," report prepared for the U. S. Environmental Protection Agency Office of Transportation and Air Quality, Institute of Transportation Studies, University of California, Davis, 2004.
- Demirbas, A. "Biomass Resource Facilities and Biomass Conversion Processing for Fuels and Chemicals," *Energy Conversion and Management* 42,11 (2001):1357-1378.
- Demirbas, A. "Biodiesel Fuels from Vegetable Oils via Catalytic and Non-Catalytic Supercritical Alcohol Transesterifications and Other Methods: A Survey. " *Energy Conversion and Management* 44, 13 (2003):2093-2109.
- Dixon, P. B., S. Osborne, M. T. Rimmer. "The Economy-Wide Effects in the United States of Replacing Crude Petroleum with Biomass," paper submitted for the GTAP Conference, Purdue University, Indiana, 2007.
- EIA. *US Energy Information Administration World Outlook*, Report #:DOE/EIA-0484, 2007
- Elobeid, A., and S. Tokgoz. "Removal of U. S. Ethanol Domestic and Trade Distortions: Impact on U. S. and Brazilian Ethanol Markets," Working Paper 06-WP 427, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa, 2006.
- Ericsson, K., S. Huttunen, L. J. Lars, J. Nilsson, and P. Svenningsson. "Bioenergy Policy and Market Development in Finland and Sweden," *Energy Policy* 32, 15 (2004):1707-1721.
- European Union (EU). "Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the Promotion of the Use of Biofuels or Other Renewable Fuels for Transport," *Official Journal of the European Union*, L 123/42. [http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l\\_123/l\\_12320030517en00420046.pdf](http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_123/l_12320030517en00420046.pdf), 2003.
- Faaij, A. "Modern Biomass Conversion Technologies." *Mitigation and Adaptation Strategies for Global Change* 11, 2 (2006):335-367.

- Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. "Ethanol Can Contribute to Energy and Environmental Goals," *Science* 311, 5760 (2006):506-508.
- Fearnside, P. "Soybean Cultivation as a Threat to the Environment in Brazil," *Environmental Conservation* 28, 01 (2002):23-38.
- Feder, G., R. Just, and D. Zilberman. "Adoption of Agricultural Innovations in Developing Countries: A Survey," *Economic Development and Cultural Change* 33, 2 (1985):255-298.
- Ferris, J., and S. V. Joshi. "Agriculture as a Source of Fuel—Prospects and Impacts, 2007 to 2017," presented at the Biofuels, Food & Feed Tradeoffs Conference Organized by the Farm Foundation and USDA, St. Louis, Missouri, April 12-13, 2007.
- Fischer, G., and L. Schrattenholzer. "Global Bioenergy Potentials Through 2050," *Biomass and Bioenergy* 20, 3 (2001):151-159.
- Food and Agricultural Policy Research Institute (FAPRI). "Implications of Increased Ethanol Production for US Agriculture," FAPRI-UMC Report #10-05, August 22, 2005.
- Food and Agriculture Organization of the United Nations (FAO). *FAOSTAT, FAO Statistical Database*. <http://faostat.fao.org>, 2007.
- Fulton, L., T. Howes, and J. Hardy. *Biofuels for Transport: An International Perspective*, Paris: International Energy Agency, 2004.
- Gardner, B. "Fuel Ethanol Subsidies and Farm Price Support: Boon or Boondoggle?" working paper, Department of Agricultural and Resource Economics, University of Maryland, 2003.
- Gardner, B., and G. Raussler. *Handbook of Agricultural Economics*, Amsterdam: Elsevier, 2002.
- Geller, H. "Ethanol Fuel from Sugar Cane in Brazil," *Annual Review of Energy* 10, 1 (1985):135-164.
- Geller, H., R. Schaeffer, A. Szklo, and M. Tolmasequin. "Policies for Advancing Energy Efficiency and Renewable Energy Use in Brazil," *Energy Policy* 32, 12 (2004): 1437-1450.

- Giampietro, M., S. Ulgiati, and D. Pimentel. "Feasibility of Large-Scale Biofuel Production," *BioScience* 47, 9 (1997): 587-600.
- Gielecki, M., F. Mayes, and L. Prete. *Incentives, Mandates, and Government Programs for Promoting Renewable Energy*. Washington, D.C.: Energy Information Administration, U.S. Department of Energy, 2001.
- Gnansounou, E., A. Dauriat, and C. Wyman. "Refining Sweet Sorghum to Ethanol and Sugar: Economic Trade-Offs in the Context of North China," *Bioresource Technology* 96, 9 (2005):985-1002.
- Gohin, A., and G. Moschini. "Impacts of the European Biofuel Policy on the Farm Sector: A General Equilibrium Assessment," draft prepared for Biofuels, Food & Feed Tradeoffs Conference organized by Farm Foundation and the USDA, St. Louis, Missouri, April 12-13, 2007.
- GoI. Government of India Planning Commission Report of the Committee on Development of Biofuel, 2003
- Goulder, L. H. "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis," *Journal of Environmental Economics and Management* 29, 3 (1995):271-297.
- Goulder, L., I. Parry, and D. Burtraw. "Revenue-Raising versus Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions," *The RAND Journal of Economics* 28, 4 (1997):708-731.
- Greene, N., F. E. Celik, B. Dale, M. Jackson, K. Jayawardhana, H. Jin, E. Larson. M. Laser, K. Lynd, D. MacKenzie, M. Jason, J. McBride, S. McLaughlin, and D. Saccardi. "Growing Energy: How Biofuels Can Help End America's Oil Dependence," National Resource Defense Council (NRDC) Report, 2004.
- Gundimeda, H. "How 'Sustainable' Is the 'Sustainable Development Objective' of CDM in Developing Countries like India?" *Forest Policy and Economics* 6, 3/4 (2004): 329-343.
- Hallam, A., I. C. Anderson, and D. R. Buxton. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production," *Biomass and Bioenergy* 21(2001): 407-424.

- Hamelinck, C. N., P. C. A. P. C. Faaija, H. den Uilb, and H. Boerrigteret. "Production of FT Transportation Fuels From Biomass; Technical Options, Process Analysis and Optimisation, and Development Potential," *Energy* 29, 11(2004):1743-1771.
- Hawken, P., A. Lovins, and L. H. Lovins. *Natural Capitalism: Creating the Next Industrial Revolution*, New York: Little, Brown and Company, 1999.
- Hazell, P., and R. K. Pachauri (eds.). *Bioenergy and Agriculture: Promises and Challenges*. International Food Policy Research Institute 2020 Focus No. 14, 2006.
- International Energy Agency (IEA). *IEA Global Renewable Fact Sheet 2006*.
- Jacobson, M. Z. "Effects of Ethanol (E85) Versus Gasoline Vehicles on Cancer and Mortality in the United States. *Environmental Science and Technology*," *Environmental Science and Technology*, forthcoming, 2007.
- Jaffe, A. B., R. G. Newell, and R. N. Stavins. "Energy-Efficient Technologies and Climate Change Policies: Issues and Evidence," Climate Issue Brief 19, report prepared for the Resources for the Future, 1999.
- Janulis, P. "Reduction of Energy Consumption in Biodiesel Fuel Life Cycle," *Renewable Energy* 29, 6 (2004):861-871.
- Just, R. E., and D. Zilberman. "Stochastic Structure, Farm Size and Technology Adoption in Developing Agriculture," *Oxford Economic Papers* 35, 2 (1983):307.
- Kadam, K. *Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay)*. NREL/TP-580-28705, National Renewable Energy Lab., Golden, Colorado, 2000.
- Kammen, D. M. "Bioenergy in Developing Countries: Experiences and Prospects," in *Bioenergy and Agriculture: Promises and Challenges*, International Food Policy Research Institute 2020 Focus No. 14, 2006.
- Kammen, D., K. Kapadia, and M. Fripp. "Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate," report of the Renewable and Appropriate Energy Laboratory, Energy and Resources Group/Goldman School of Public Policy at University of California, Berkeley, April, 2004.

- Karekezi, S., and W. Kithyoma. "Bioenergy and the Poor," in *Bioenergy and Agriculture: Promises and Challenges*, International Food Policy Research Institute 2020 Focus No. 14, 2006.
- Khanna, M., B. Dhungana, and J. Clifton-Brown. "Costs of Perennial Grasses for Bio-Energy in Illinois," working paper, Department of Agricultural and Consumer Economics University of Illinois, Urbana-Champaign, 2007.
- Kim, S., and B. Dale. "Global Potential Bioethanol Production from Wasted Crops and Crop Residues," *Biomass and Bioenergy* 26, 4 (2004):361-375.
- Kim, S., and B. Dale. "Life Cycle Assessment of Various Cropping Systems Utilized for Producing Biofuels: Bioethanol and Biodiesel," *Biomass and Bioenergy* 29, 6 (2005):426-439.
- Klette, T., J. Moen, and Z. Griliches. "Do Subsidies to Commercial R&D Reduce Market Failures? Microeconomic Evaluation Studies," *Research Policy* 29, 4-5 (2000):471-95.
- Kojima, M. J., and T. Johnson. *Potential for Biofuels for Transport in Developing Countries*, Washington, D. C.: Energy Sector Management Assistance Programme World Bank, 2005.
- Kojima, M., D. Mitchell, and W. Ward. "Considering Trade Policies for Liquid Biofuels," Energy Sector Management Assistance Program (ESPM), World Bank, 2007.
- Koplow, D. "Biofuels—At What Cost? Government Support for Ethanol and Biodiesel in the United States," report prepared for the Global Subsidies Initiative, International Institution for Sustainable Development, 2006.
- Lal, R. "Carbon Emission from Farm Operations," *Environment International* 30, 7 (2004):981-990.
- Leiby, P., and J. Rubin. "Effectiveness and Efficiency of Policies to Promote Alternative Fuel Vehicles," *Transportation Research Record* 1750 (2001):84-91.
- Lichtenberg, E., and D. Zilberman. "The Welfare Economics of Price Supports in US Agriculture," *The American Economic Review* 76, 5(1986):1135-1141.
- Lovins, A. "Saving Gigabucks with Negawatts," *Public Utilities Fortnightly* 115, 6 (1985):19-26.

- Lynd, L. "Overview and Evaluation of Fuel Ethanol from Cellulosic Biomass: Technology, Economics, the Environment, and Policy," *Annual Review of Energy and the Environment* 21, 1(1996):403-465.
- Macedo, I. C., M. R. L. V. Leal, and J. E. A. R. da Silva. "Assessment of Greenhouse Gas Emissions in the Production and Use of Fuel Ethanol in Brazil," report to the Government of the State of São Paulo, 2004.
- MacKenzie, D., L. Bedsworth, and D. Friedman. *Fuel Economy Fraud: Closing the Loopholes that Increase U.S. Oil Dependence*. Cambridge, Massachusetts: Union of Concerned Scientists, 2005.
- Mann, M. K., and P. L. Spath. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System*, Technical Report, National Renewable Energy Lab., Golden, Colorado, 1997.
- Manne, A., and R. Richels. "The Impact of Learning-By-Doing on the Timing and Costs of CO<sub>2</sub> Abatement," *Energy Economics* 26, 4 (2004):603–619.
- Manne, A., R. Richels, and J. Weyant. "Energy Policy Modeling: A Survey," *Operations Research* 27, 1 (1979):1-36.
- Martinot, E. *Renewables 2005: Global Status Report*. Worldwatch Institute, 2005.
- Mattsson, B., C. Cederberg, and L. Blix. "Agricultural Land Use in Life Cycle Assessment (LCA): Case Studies of Three Vegetable Oil Crops," *Journal of Cleaner Production* 8, 4 (2000):283-292.
- McDonald, S., S. Robinson, and K. Thierfelder. "Impact of Switching Production to Bioenergy Crops: The Switchgrass Example," *Energy Economics* 28, 2 (2006):243-265.
- Moreira, J. "Water Use and Impacts Due Ethanol Production in Brazil," International Conference on Linkages in Energy and Water Use in Agriculture in Developing Countries, Organized by IWMI and FAO, ICRISAT, India, January 2007.
- Mortimer, P. C., M. A. Elsayed, and R. E. Horne. "Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel," Report to the Department for Environment, Food and Rural Affairs Contract Reference No. CSA 5982/NF0422, Report No. 20/1, 2003.



- Mrini, M., F. Senhaji, and D. Pimentel. "Energy Analysis of Sugarcane Production in Morocco," *Environment, Development and Sustainability* 3, 2 (2001):109-126.
- Msangi, S., T. Sulser, M. Rosegrant, R. Valmonte-Santos, and C. Ringler. *Global Scenarios for Biofuels: Impacts and Implications*, International Food Policy Research Institute (IFPRI), 2006.
- Nguyen, T., S. H. Gheewala, and S. Garivait. "Full Chain Energy Analysis of Fuel Ethanol from Cassava in Thailand," *Environmental Science and Technology* 41, 11 (2007):4135-4142.
- Nordhaus, W. "To Slow or Not to Slow: The Economics of The Greenhouse Effect," *The Economic Journal* 101, 407 (1991):920-937.
- Ogg, C. "Environmental Challenges Associated with Corn Ethanol Production," presented at the Biofuels, Food, and Feed Tradeoffs Conference organized by the Farm Foundation, St. Louis, Missouri, April 12-13, 2007.
- Organization for Economic Cooperation and Development (OECD). "Agricultural Market Impacts of Future Growth in the Production of Biofuels." *OECD Papers* 6, 1 (2006):1-57.
- Pimentel, D., and T. Patzek. "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower," *Natural Resources Research* 14, 1 (2005):65-76.
- Pletcher, J. "Regulation With Growth: The Political Economy of Palm Oil in Malaysia," *World Development* 19, 6 (1991):623-636.
- Popp, D. "R&D Subsidies and Climate Policy: Is There a Free Lunch?" *Climatic Change* 77, 3 (2006):311-341.
- Prakash, R., A. Henham, and I. K. Bhat. "Gross Carbon Emissions from Alternative Transport Fuels in India," *Energy* 10 (2005).
- Prayas (Initiatives in Health, Energy, Learning and Parenthood). "Jatropha in Horticulture Program of Employment Guarantee Scheme. An Assessment from Small Farmer's Perspective," report by Resources and Livelihoods Group, Prayas, Pune, India, 2007.
- Rajagopal, D. "Rethinking Current Strategies for Biofuel Production in India," presented at the International Conference on Linkages in Water and Energy in Developing

- Countries Organized by IWMI and FAO, ICRISAT, Hyderabad, India, January 29-30, 2007.
- Ramey, D.S.-T.Y. "Production of Butyric Acid and Butanol from Biomass," final report to the U. S. Department of Energy, Contract No.: DE-F-G02-00ER86106, 2004.
- Ravindranath, N. H., and D. O. Hall. *Biomass, Energy, and Environment: A Developing Country Perspective from India*, Oxford: Oxford University Press, 1995.
- Reilly, J., and S. Paltsev. "Biomass Energy and Competition for Land," report of MIT Joint Program on the Science and Policy of Global Change, No. 145, 2007.
- Roos, A., R. L. Graham, B. Hektor, and C. Rakos. "Critical Factors to Bioenergy Implementation," *Biomass and Bioenergy* 17, 2 (1999):113-126.
- Runge, C., and B. Senauer. "How Biofuels Could Starve the Poor," *Foreign Affairs*, (2007).
- Sadoulet, E., and A. de Janvry. *Quantitative Development Policy Analysis*, Baltimore, Maryland: The Johns Hopkins University Press, 1995.
- Schneider, U., and B. McCarl. "Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation," *Environmental and Resource Economics* 24, 4 (2003):291-312.
- Sheehan, J., T. Dunahay, J. Benemann, and P. Roessler. "A Look Back at the U. S. Department of Energy's Aquatic Species Program: Biodiesel from Algae," Report No. NREL/TP-580-24190, National Renewable Energy Laboratory, Golden, Colorado, 1998.
- Sheehan, J, V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. "An Overview of Biodiesel and Petroleum Diesel Life Cycles," Report No. NREL/TP-580-24772, National Renewable Energy Laboratory, Golden, Colorado, 2000.
- Smil, V. *Energy at the Crossroads*, Cambridge, Massachusetts: MIT Press, 2003.
- Smith, K. R. *Biofuels, Air Pollution, and Health: A Global Review*, New York: Plenum, 1987.
- Smith, K., and S. Mehta. "The Burden of Disease from Indoor Air Pollution in Developing Countries: Comparison of Estimates," *International Journal of Hygiene and Environmental Health* 206, 4 (2003):279-289.

- Steininger, K., and H. Voraberger. "Exploiting the Medium Term Biomass Energy Potentials in Austria," *Environmental and Resource Economics* 24, 4 (2003):359-377.
- Swallow, S., and R. Sedjo. "Eco-Labeling Consequences in General Equilibrium: A Graphical Assessment," *Land Economics* 76, 1 (2000):28-36.
- Swinnen, J., and F. van der Zee. "The Political Economy of Agricultural Policies: A Survey," *European Review of Agricultural Economics* 20, 3 (1993):261-290.
- Tiffany, D. G., and V. R. Eidman. "Factors Associated with Success of Fuel Ethanol Producers," Department of Applied Economics, College of Agricultural, Food, and Environmental Sciences, University of Minnesota, Staff Paper Series P03-07, 2003.
- Tilman, D., J. Hill, and C. Lehman. "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass," *Science* 314, 5805 (2006):1598-1600.
- Turner, B. T., R. J. Plevin, M. O'Hare, and A. E. Farrell. "Creating Markets for Green Biofuels: Measuring and Improving Environmental Performance," Transportation Sustainability Research Center, Paper UCB-ITS-TSRC-RR-2007-1, 2007.
- Tyner, W. E., and F. Taheripour. "Ethanol Subsidies, Who Gets the Benefits?" paper presented at Biofuels, Food, & Feed Tradeoffs Conference Organized by the Farm Foundation and USDA, St. Louis, Missouri, April 12-13, 2007a.
- Tyner, W. E., and F. Taheripour. "Future Biofuels Policy Alternatives," paper presented at Biofuels, Food, & Feed Tradeoffs Conference Organized by the Farm Foundation and USDA, St. Louis, Missouri, April 12-13, 2007b.
- Treguer, D., and J. Sourie. "The Impact of Biofuel Production on Farm Jobs and Income: The French Case," article presented at the 96th EAAE seminar in Tanikon, Switzerland, January 2006.
- Ugarte, D. G. de la Torre. "Developing Bioenergy: Economic and Social Issues," in *Bioenergy and Agriculture: Promises and Challenges*, International Food Policy Research Institute 2020 Focus No. 14, 2006.
- Ulgiati, S. "A Comprehensive Energy and Economic Assessment of Biofuels: When 'Green' Is Not Enough," *Critical Reviews in Plant Sciences* 20, 1 (2001):71-106.

- United States Department of Agriculture (USDA). "USDA Farm Bill 2007"  
<http://www.usda.gov/documents/Farmbill07energy.pdf>, 2007.
- van Dam, J., M. Junginger, A. Faaij, I. Jürgens, G. Best, and U. Fritsche. "Overview of Recent Developments in Sustainable Biomass Certification," Working Paper for IEA Bioenergy Task 40, 2007.
- Waggoner, P. E. "How Much Land Can Ten Billion People Spare for Nature?" *Daedalus* 125 3 (Summer 1996).
- Waggoner, P., and J. Ausubel. "How Much Will Feeding More and Wealthier People Encroach on Forests?" *Population and Development Review* 27, 2 (2001):239-257.
- Walsh, M., D. G. de la Torre Ugarte, H. Shapouri, and S. P. Slinsky. "Bioenergy Crop Production in the United States: Potential Quantities, Land Use Changes, and Economic Impacts on the Agricultural Sector," *Environmental and Resource Economics* 24, 4 (2003):313-333.
- Watson, R. T., M. C. Zinyowera, and R. H. Moss. *Technologies, Policies and Measures for Mitigating Climate Change*. Technical Paper Series No. 1, Geneva, 1996.
- Weitzman, M. "Prices vs. Quantities," *The Review of Economic Studies* 41, 4 (1974): 477-491.
- Wyman, C. "Biomass Ethanol: Technical Progress, Opportunities, and Commercial Challenges," *Annual Review of Energy and the Environment* 24, 1 (1999):189-226.

## 7 Appendix: Definition of Terms

**Renewable energy:** Energy derived from resources that can either cannot be depleted or can be regenerated.

**Fossil energy:** Energy derived from sources like coal and petroleum (crude oil and natural gas), which are formed from the fossilized remains of dead plants and animals over millions of years.

**Biomass:** Plant matter that can be used as fuel or for other commercial and industrial uses. The source of biomass can either be purpose-grown crops or crop wastes and residues, which are generated by agricultural or forestry activities.

**Bioenergy:** Energy derived from biomass.

**Biofuel:** Fuels derived from biomass, which can be in solid, liquid or gaseous states. In our context it is taken to refer to liquid or gaseous transportation fuel derived from biomass.

## **Figures and Tables**

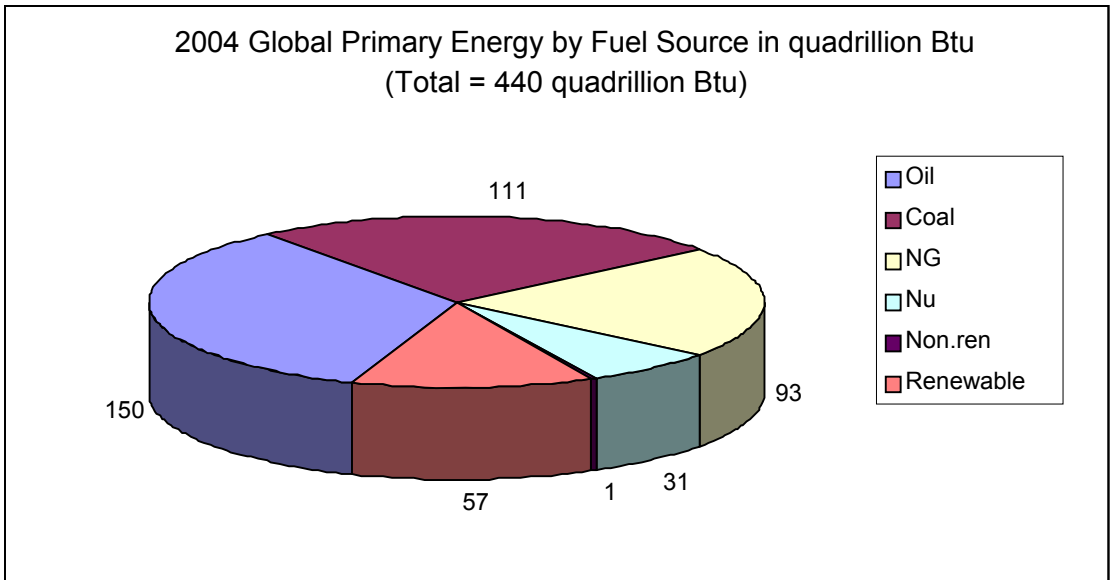


Figure 1: Fuel shares in global primary energy supply (EIA 2007)

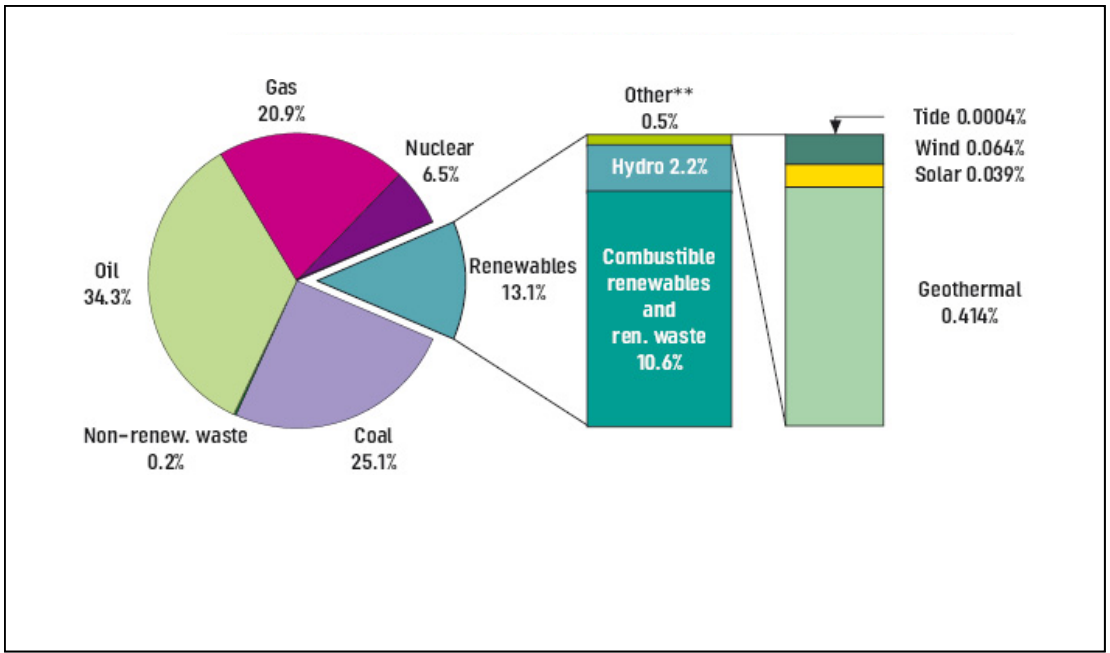


Figure 2: Share of renewables in global energy supply (IEA 2006)

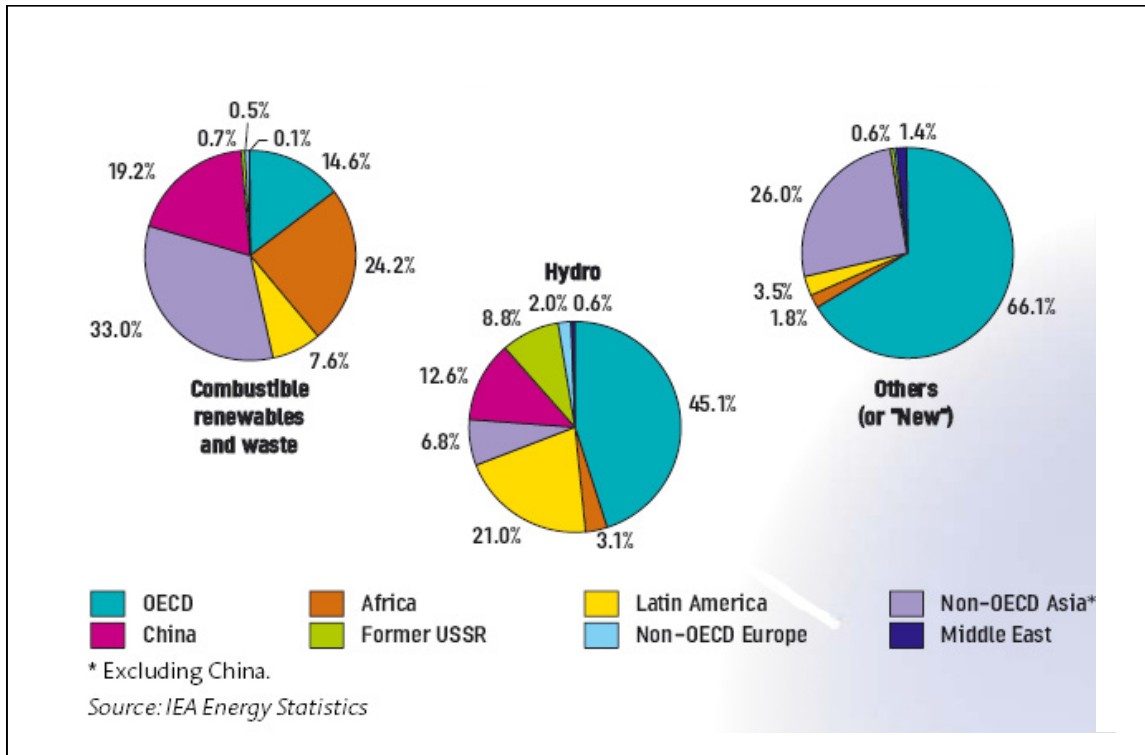


Figure 3: Regional distribution for each renewable source (IEA 2006)

	TPES*	Of which Renewables	Share of Renewables in TPES	Share of the main fuel categories in total renewables					
				Mtoe	Mtoe	%	Hydro	Geothermal, Solar, Wind, etc.	Combustible Renewables and Waste
							%	%	%
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			
<b>World</b>	<b>11,059</b>	<b>1,404</b>	<b>13.1</b>	<b>16.7</b>	<b>4.0</b>	<b>79.4</b>			

\* 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.

Figure 4: Share of various sources of renewable in each region (IEA 2006)



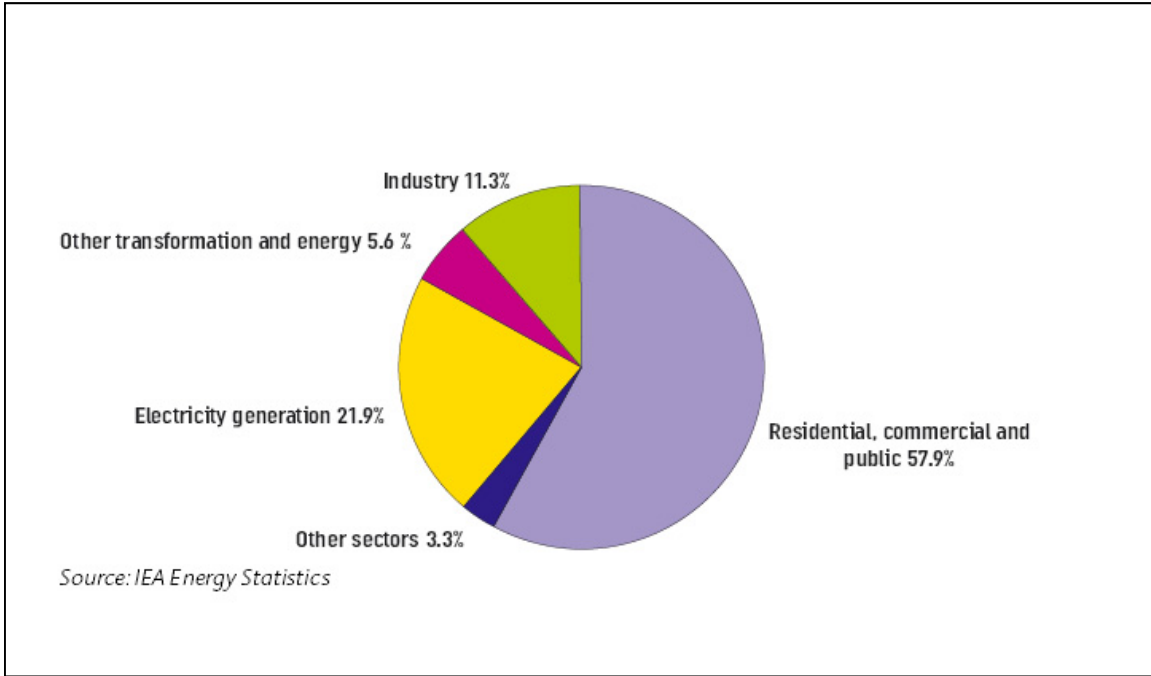


Figure 5: End-use sectors that consume renewable energy (IEA 2006)

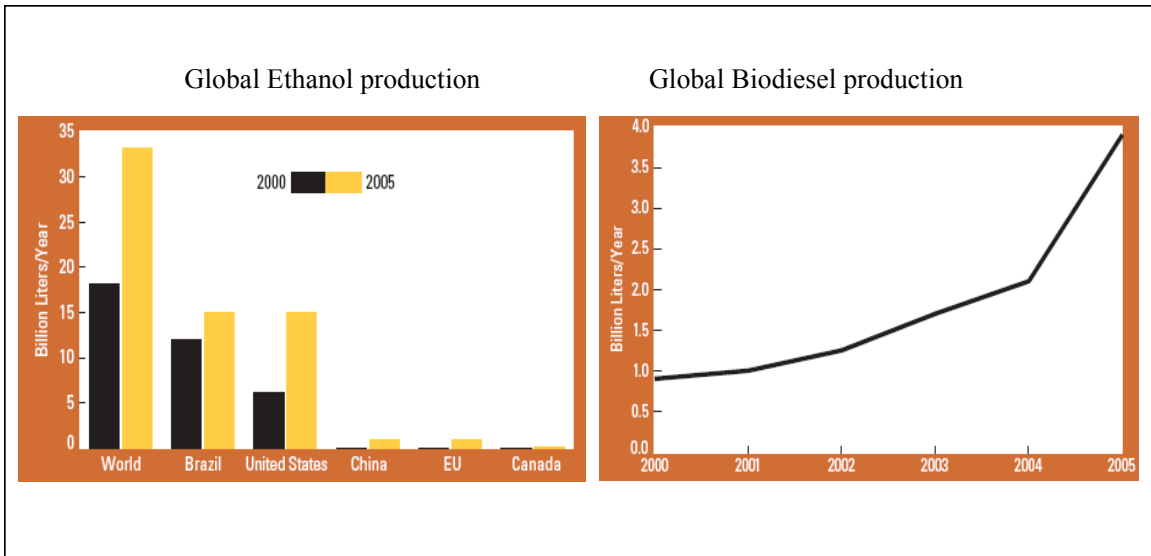


Figure 6: Global production of ethanol and biodiesel (Martinot 2005)

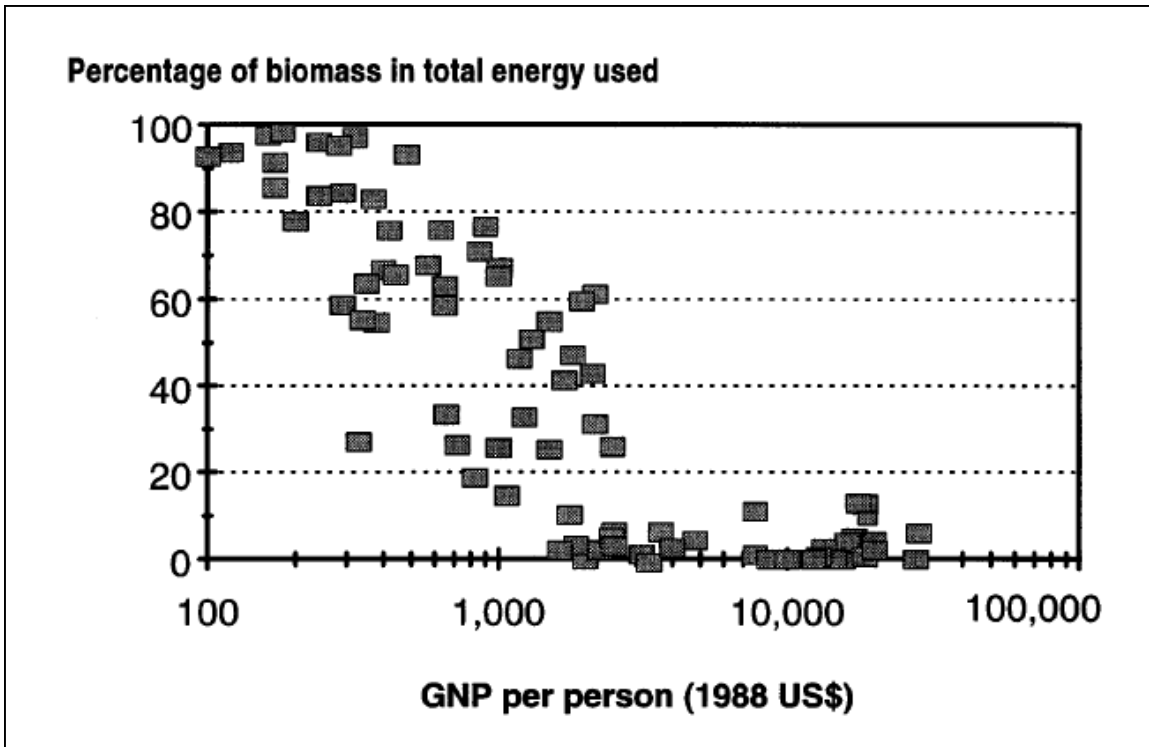


Figure 7: Correlation between GDP and use of biomass energy for various countries (Barnes 1996)

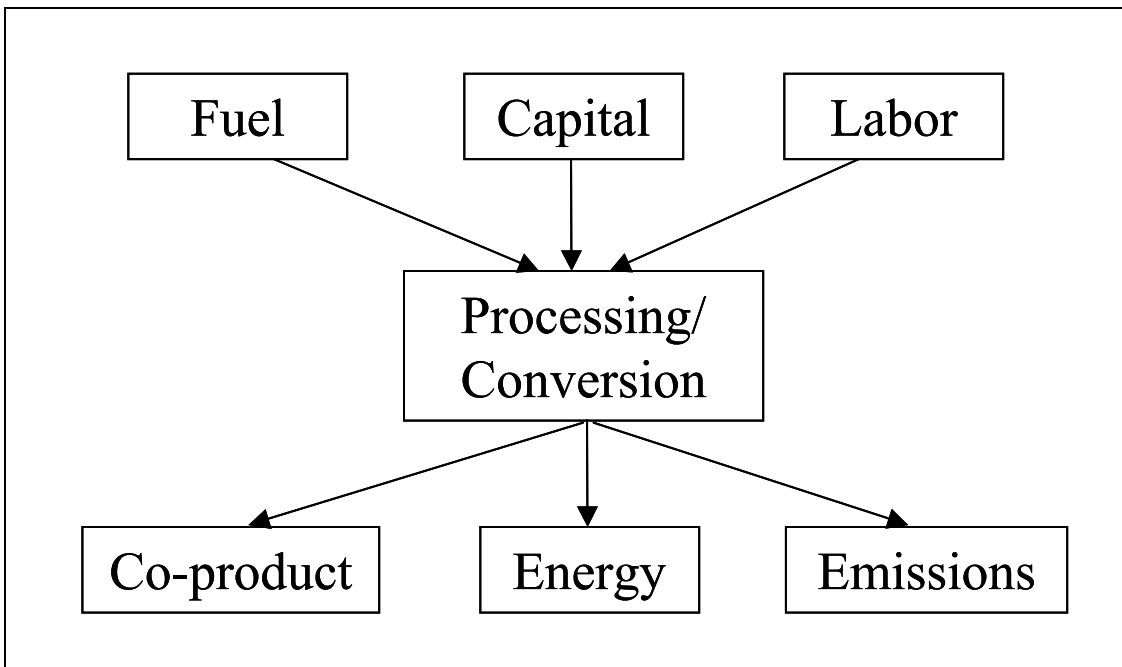


Figure 8: Schematic of a bioenergy production system

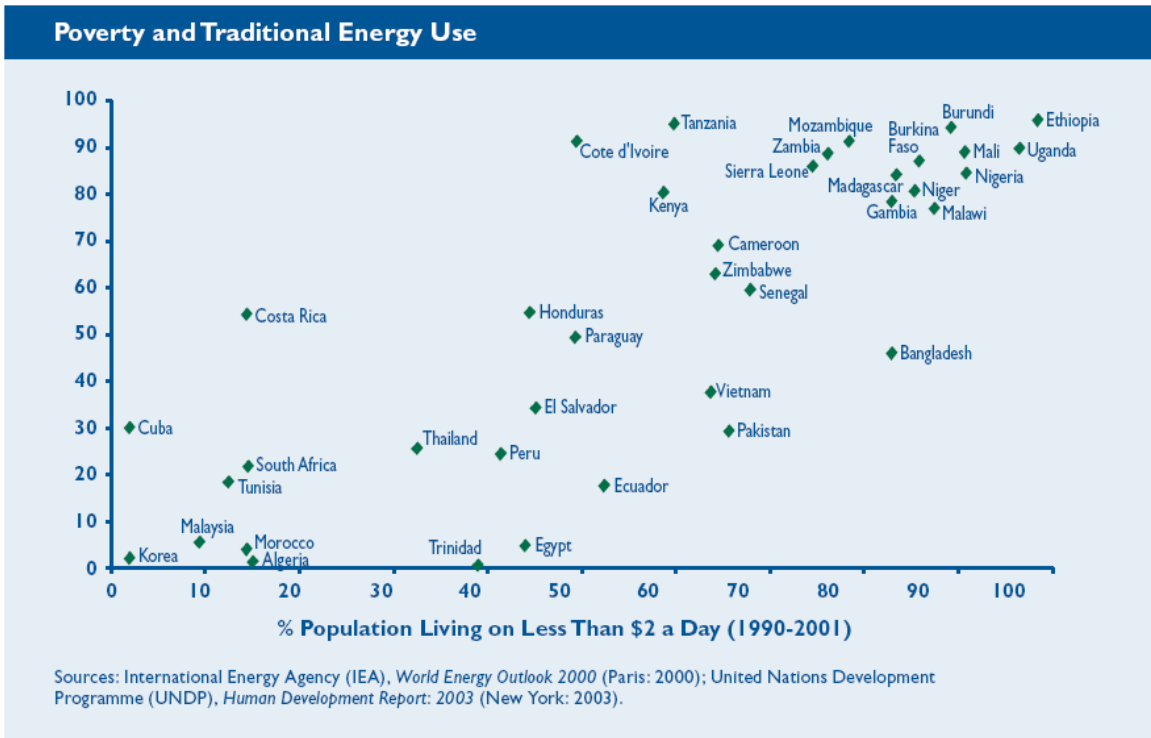


Figure 9: Poverty and biomass energy use (Karekezi 2006)

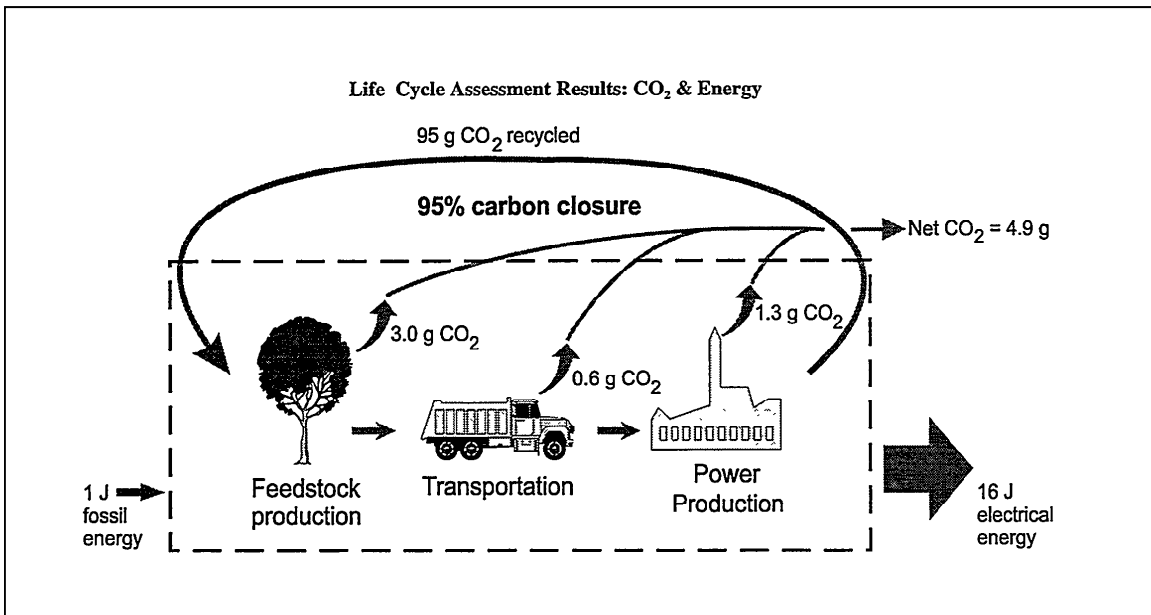


Figure 10: LCA of biomass gasification (Mann 1997)

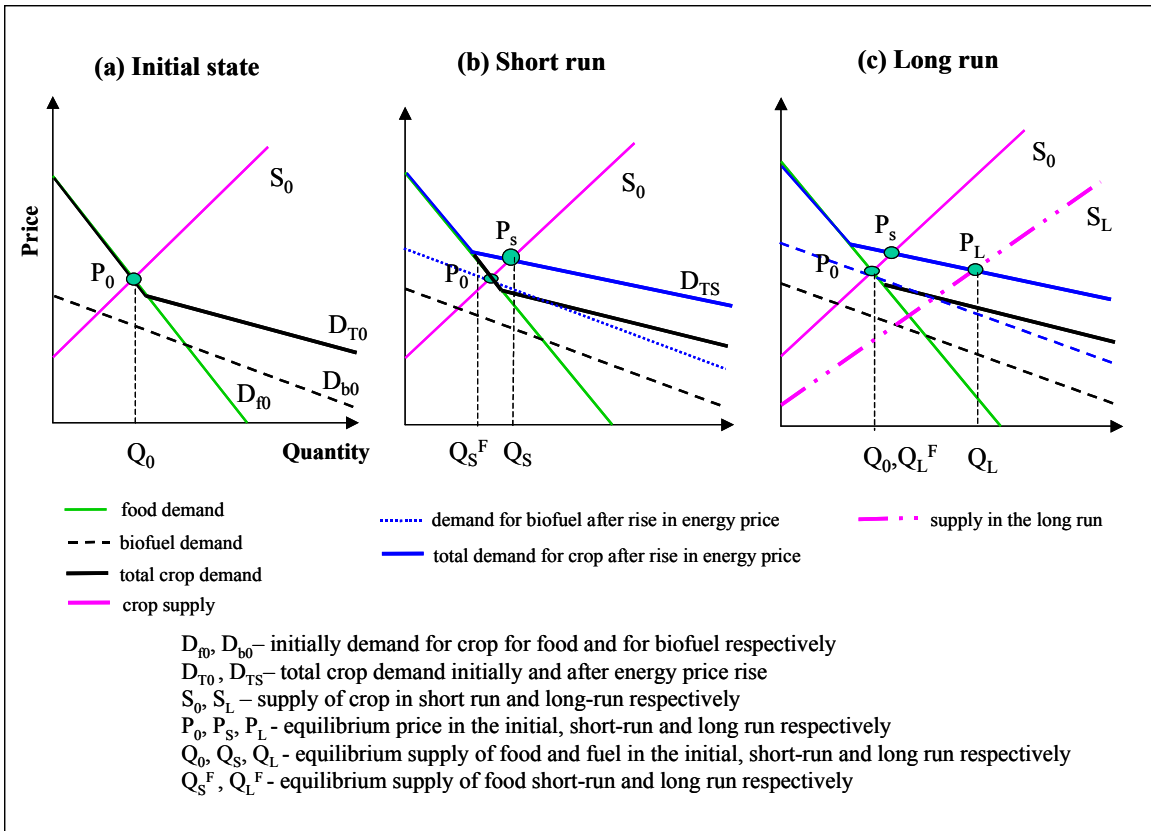


Figure 11: Conceptual model of supply and demand for multi-purpose crop

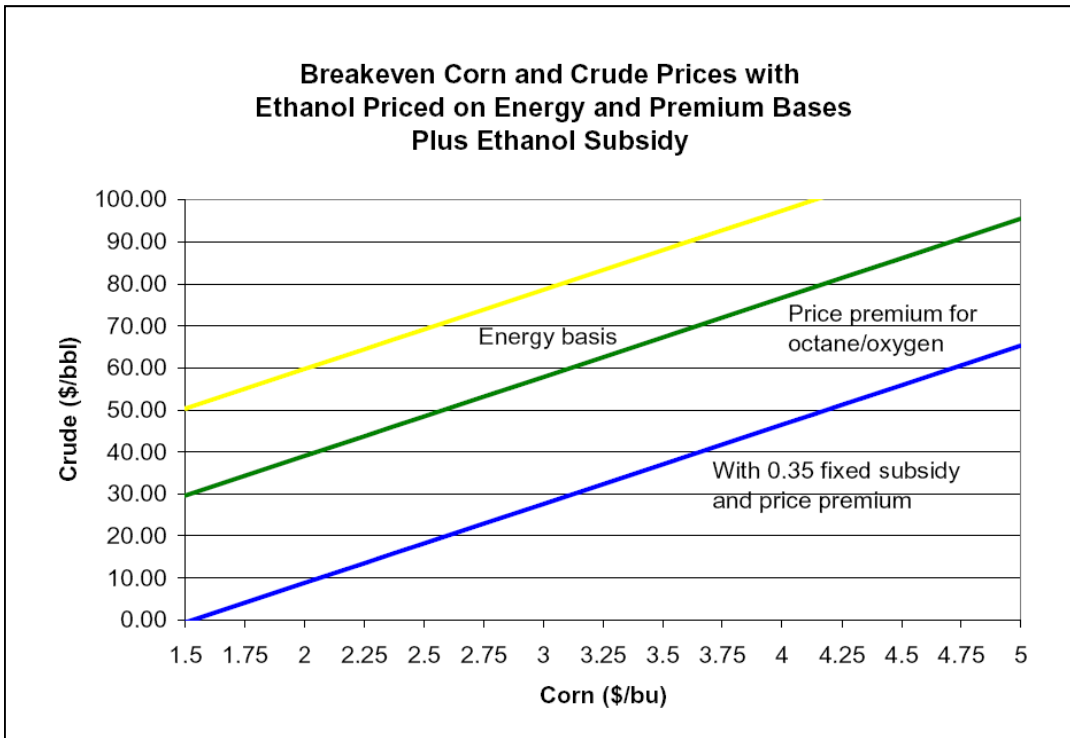


Figure 12: Relationship between crude oil price and break-even price of corn for ethanol (Tyner 2007)

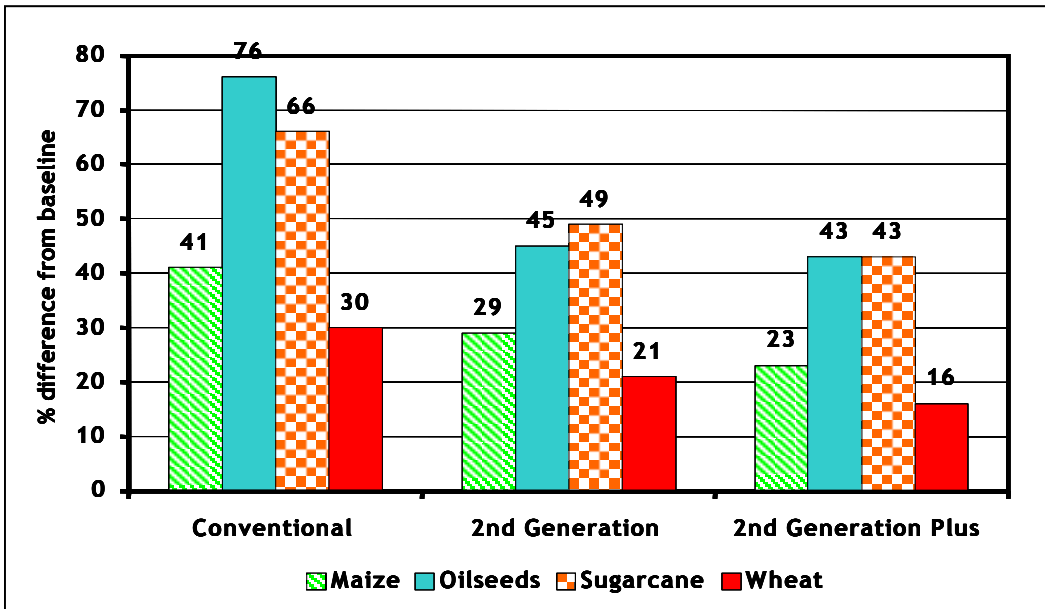


Figure 13: Impact of biofuel production on global crop prices in 2020 (Msangi 2006)

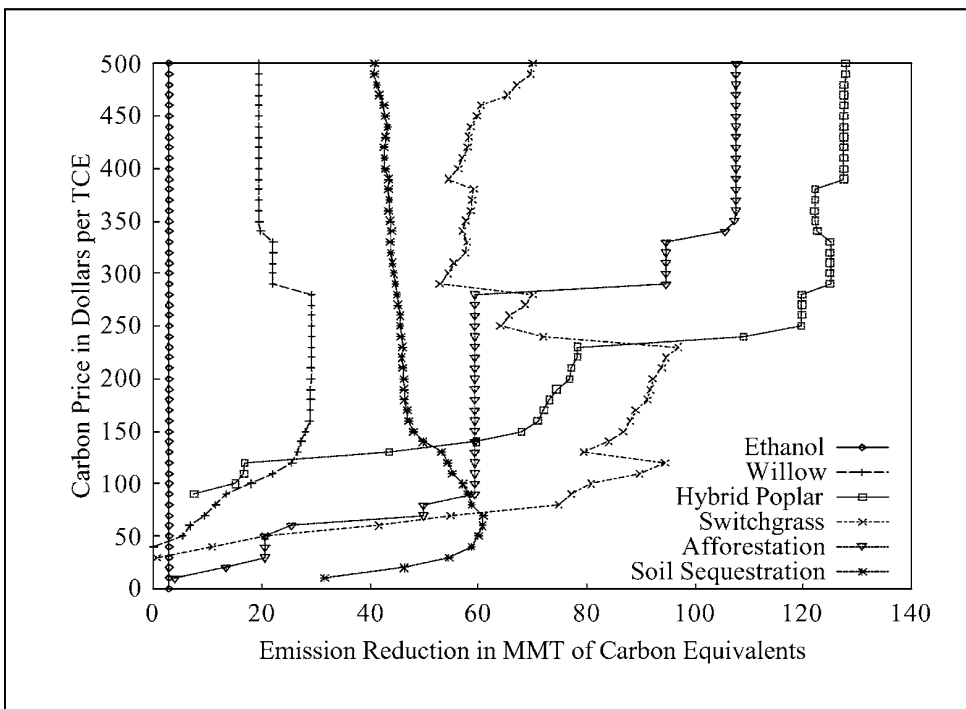


Figure 14: Supply curve for carbon sequestration through biomass activities (Schneider 2003)

End use	Income stage		
	Low	Medium	High
<b><u>Household</u></b>			
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
<b><u>Agriculture</u></b>			
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
<b><u>Industry</u></b>			
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

Table 1: Sources of rural energy for various end-uses at different household incomes (Barnes 1996)

Characteristic of Technology	Traditional	Modern
<b>Fuel</b>	mostly gathered or collected and in some cases purchased	commercially procured
<b>Capital</b>	low capital cost	high capital cost
<b>Labor</b>	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
<b>Conversion process</b>	low efficiency and poor utilization of biomass	higher efficiency and higher utilization of biomass
<b>Energy uses</b>	energy for cooking and heating in poor households in developing countries	commercial heating, electricity and transportation
<b>Emission controls</b>	poor emission controls	controlled emissions
<b>Co-product</b>	no co-products	commercially useful co-products

Table 2: Comparison of characteristics of traditional and modern biofuels

Feedstock type	Type of biofuel	Major end-use	Crops in temperate climes	Crops in tropical climes	Conversion technology	Technology maturity	Commercial Maturity
<b>Sugar and Starch</b>	Ethanol	Transportation	Corn, Sugarbeet, Wheat	Sugarcane, Sorghum, Cassava	Biochemical conversion (Fermentation)	High	High
<b>Oil Seeds</b>	Biodiesel	Transportation	Soy, Rapeseed	Palm, <i>Jatropha*</i> , <i>Castor</i>	Transesterification	High	High
<b>Wood**</b>	Fuelwood, Syn-gas	Cooking, Heating, Electricity	Willow, Poplar	Eucalyptus, Acacia, Prosopis	Direct combustion, Thermochemical conversion	High	Low
<b>Municipal and agricultural waste**</b>	Syn-gas or Biogas	Heating, Electricity	<i>na***</i>	<i>na</i>	Direct combustion, Thermochemical, Anaerobic digestion	High	Low
<b>Perennial grasses (cellulose)</b>	Ethanol	Transportation	<i>Switchgrass</i> , <i>Miscanthus</i>	-	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

Table 3: Biofuel technology matrix

Ethanol feedstock	Global acreage (million hectares)*	Water required mm/yr (low)**	Water required mm/yr (high)**	Crop yield (tonnes per hectare)*	Ethanol conversion efficiency (litre/ton)***	Gasoline equivalent ethanol yield (litre/hectare)	Ethanol yield per unit of water (lit/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	2500	70	70	3300	1.65	10- 12 month
Sugar beet	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

Table 4: Land and water intensity of potential sources for ethanol (Rajagopal 2007)

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	150	na	5000	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 estimates that are typically cited

Table 5: Land and water intensity of major oilseed crops (Rajagopal 2007)

Crop	Global acreage (million hectares)*	Average yield (tons/hectare)*	Global production (million tonnes)	Conversion efficiency (litres/tonne)**	Land intensity (litres/hectare)	Max. ethanol (billion litres)	Gasoline equivalent (billion litres)	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%
<b>Total</b>	<b>599</b>	-	-	-	-	<b>1413</b>	<b>947</b>	<b>86%</b>

\* Data from FAO online statistical database

\*\* Data from various sources

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

Table 6: Potential for ethanol production from major crops



Crop	Global acreage in 2005 (million hectares)*	Average yield (tons/hectare)**	Global production (million tonnes)	Conversion efficiency (litres/tonne)***	Land intensity (litres/hectare)	Max. ethanol (billion litres)	Gasoline equivalent (billion litres)	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%
<b>Total</b>	<b>200</b>					<b>1056</b>	<b>710</b>	<b>64%</b>

\* 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 litres (Kim and Dale 2004)

Table 7: Potential for ethanol from perennial grasses in future based on predictions

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
<b>Total land required to produce the needed oil per village (hec.)</b>	<b>15</b>
Number of village households in India	150,000,000
% of households with no electricity access	60%
Number of unelectrified households	90,000,000
<b>Total land required to electricity rural homes (million hec)</b>	<b>13</b>
Annual consumption of diesel in India (million tonnes)	42
<b>Total land required to meet 20% of diesel demand (million hec)</b>	<b>14</b>

\* Specific fuel consumption refers to the amount of oil (gms) needed to produce one kilo watt hour of electricity

Table 8: Estimate of land needed to electrify rural homes in India using biodiesel (Rajagopal 2007)

Author and year	Product	Country	Feedstock	Conversion process	Indicators used
Tilman et al 2006	Ethanol, Electricity and Synfuel	US	Perennial grasses	Cofiring with coal, cellulosic conversion and Fischer-Tropsch	net energy gain, net carbon sequestration
Farrell et al 2006	Ethanol	US	Corn, switchgrass	Fermentation, enzymatic conversion	net energy gain, net carbon reduction, net petroleum offset
Pimentel and Patzek 2005	Ethanol and Biodiesel	US	Corn, wood, switchgrass,	Fermentation, enzymatic conversion	net energy gain, net carbon reduction
Macedo et al 2004	Ethanol	Brazil	Sugarcane	Fermentation	net energy ratio, net carbon reduction
Nguyen et al 2007	Ethanol	Thailand	Cassava	Fermentation	net energy value
Prakash et al 1998	Ethanol	India	Molasses of sugarcane	Fermentation	net energy ratio, net carbon reduction
Kadam 2000	Ethanol	India	Bagasse of sugarcane	Enzymatic, acid hydrolysis conversion	net energy use, emission of carbon and criteria pollutants
Pimentel and Patzek 2005	Biodiesel	US	Soy and sunflower	Transesterification	net energy gain, net carbon reduction
Sheehan 1998	Biodiesel	US	Soy	Transesterification	net energy ratio, net reduction in carbon and criteria pollutants
Janulis 2004, Mortimer 2003	Biodiesel	Europe / UK	Rapeseed	Transesterification	net reduction in fossil energy use, net carbon reduction
Mann 1997	Electricity	US	Wood	Gasification followed by combustion	net energy gain per unit of fossil input
CIWMB 2005	Electricity	US	MSW	Thermochemical conversion	useful energy yield, emission of carbon, criteria pollutants and carcinogens
Kim and Dale 2005	Crops (Corn)	US	Corn and soybean	na*	non-renewable energy, global warming impact, acidification and eutrophication
Mattson 2000	Oil seeds	Sweden, Brazil and Malaysia	Rapeseed, Soybean and Oil palm	na	long-term soil fertility and biodiversity impacts
Mrini et al 2001	Sugarcane	Morocco	Sugarcane	na	net energy ratio
Lal 2004	na	na	na	na	carbon intensity of agricultural practices

\* na - not applicable

Table 9: List of LCA studies reviewed

Country: Biofuel: Feedstock:	EU Biodiesel Vegetable oil			EU Ethanol Wheat			USA Ethanol Maize			EU Ethanol Sugar beet			Brazil Ethanol Sugar cane		
	Quant.	LC/t	USD/t	Quant.	LC/t	USD/t	Quant.	LC/t	USD/t	Quant.	LC/t	USD/t	Quant.	LC/t	USD/t
Feedstock use, t	1.06			3.49			3.20			12.90			14.87		
Feedstock price	463.16	573.40		103.73	128.41		76.57	76.57		23.87	29.55		32.75	10.95	
Feedstock costs	490.95	607.80		362.11	448.30		244.66	244.66		307.82	381.08		486.98	162.80	
Processing costs excl. energy	69.29	85.78		347.99	430.82		130.18	130.18		288.96	357.74		339.49	113.50	
Energy use: methanol, kg	145.33														
Energy: methanol, price per kg		0.23	0.28												
Energy use: heat, GJ				13.90			16.43			13.90					
Energy: heat, price per GJ					3.46	4.29		4.29	4.29		3.46	4.29			
Energy use: electricity, kWh	315.94			353.85			303.30			353.85					
Energy: electricity, price per kWh		0.031	0.039		0.031	0.039		0.031	0.031		0.031	0.039			
Total energy costs	43.10	53.36		59.18	73.27		79.86	79.86		59.18	73.27				
Gross production costs	603.34	746.95		769.28	952.39		454.71	454.71		655.96	812.09		826.47	276.30	
Energy feed by-product; t cg-eq.				1.63			0.80			0.75					
Domestic price coarse grains					112.96	139.85		76.57	76.57		112.96	139.85			
Protein feed by-product; t om-eq.							0.16								
Domestic price oil meals							178.50	178.50							
Other by-product credit (glycerin)	50.00	61.90					89.82	89.82		84.72	104.88		0.00	0.00	
Total by-product credit	50.00	61.90		183.90	227.67		89.82	89.82		84.72	104.88		0.00	0.00	
Net production costs	553.34	685.05		585.38	724.72		364.89	364.89		571.24	707.21		826.47	276.30	
Net costs, per litre of fuel	0.438	0.542		0.463	0.573		0.289	0.289		0.452	0.560		0.654	0.219	
Net costs, per litre GE	0.395	0.489		0.702	0.869		0.437	0.437		0.685	0.848		0.991	0.331	

Note: Cost calculations for combinations of countries and feedstock commodities other than those shown in this table which are used in the cost comparison are based on the technical coefficients used in this table, whereas domestic commodity prices and regional shares of energy sources in the generation of electricity cause biofuel production costs to differ across countries. Given the implicit assumption of equal technologies and technical coefficients across countries, production cost figures used in the report for country/commodity combinations are indicative only and might differ from specific studies on biofuel production in these countries once these become available.

Source: OECD Secretariat based on data provided in Smeets *et al.* (2005), Aglink database

Table 10: Average cost of production of ethanol in various countries (OECD 2006)

Type of policy	Some examples
Incentive - Tax or Subsidy	Excise tax credit for renewable energy, Carbon tax, Subsidies for flex fuel vehicles, Price supports and deficiency payments, Tariffs or subsidies on imports/exports
Direct control	Renewable fuel standards, Mandatory blending, Emission control standards, Efficiency standards, Acreage control, Quotas on import/export
Enforcement of property rights and trading	Cap and trade
Educational and informational programs	Labeling
Improving governance	Certification programs
Compensation Schemes	Payment for environmental services

Table 11: List of policy tools and some examples

Biofuel	Current capacity	Future targets - quantity and year	Main sources for biofuel	Biofuel policies (explicit)	Main trade policy for biofuels
US	18.4 billion litres of ethanol (2006), 284 million litres biodiesel (2005)	28 billion litres of ethanol by 2012 and 1 billion litres of cellulosic ethanol by 2013	maize and in future cellulosic sources	excise tax credit, mandatory blending, capital grants, vehicle subsidies	import tariff of \$0.1427 per litre ethanol plus advalorem tariff with some exemption for caribbean countries
Brazil	17.5 billion litres (2006)	25% blending of ethanol (has been in effect for long time), 2.4 billion litres of biodiesel by 2013	sugarcane, soybean	mandatory blending, capital subsidies, vehicle subsidies	20% advalorem import tariff on ethanol (waived in case of domestic shortage)
EU	3.6 billion litres of biodiesel (2005), 1.6 billion litres of ethanol (2006)	5.75 percent of transportation fuel on energy basis by 2010	rapeseed, sunflower, wheat, sugar beet and barley	excise tax credit (beginning to be phased out), carbon tax credit, mandatory blending, capital grants and funding for R&D	ad valorem duty of 6.5% on biodiesel and import tariff of \$0.26 per litre on ethanol (latter is waived for some categories countries)
China	1.2 billion litres of ethanol (2006)	na*	maize, cassava, sugarcane	subsidies and tax breaks but only for non-grain feedstock	import tariff of 30% on ethanol
Colombia	400 million litres of ethanol (2006)	10 percent ethanol blending in cities exceed 500,000 people since 2006	sugarcane, oil palm	mandatory blending, tax breaks for sugarcane plantations, capital subsidies	ad valorem import tariff of 15% on ethanol and 10% on biodiesel
Indonesia	340 million litres of biodiesel (2006)	10% ethanol and 10% biodiesel effective April 2006	oil palm	mandatory blending, capital subsidies	lower export tax for processed oils compared to crude palm oil
Malaysia	340 million litres of biodiesel (2006)	5% biodiesel from April 2007	oil palm	mandatory blending, capital subsidies	lower export tax for processed oils compared to crude palm oil
Thailand	330 million litres of ethanol(2006)	na	cassava, sugarcane molasses	price subsidy, capital subsidies,	import tariff of 2.5 baht per litre and ad valorem tariff of 5% on biodiesel
Canada	240 million litres of ethanol (2006)	5% ethanol by 2010 and 2% biodiesel by 2012	maize and wheat	mandatory blending, excise tax credit, capital subsidies	import tariff of \$0.1228 for ethanol and \$0.11 for biodiesel (lower tariffs and exemptions for select countries)
Argentina	204 million litres of ethanol (2006)	5% biofuel by 2010	soybean	excise tax credit, mandatory blending, export tax exemption on biofuel blends	low export tax (5%) for soy biodiesel compared to soy beans (23.5%) and soy oil (20%)
India	200 million litres of ethanol (2006)	5% ethanol in select cities and 10% biodiesel by 2012**	sugarcane molasses, Jatropha (in future)	mandatory blending for ethanol, capital subsidies	advalorem duty of 199% on CIF value of denatured ethanol and 59% duty on undenatured ethanol
Australia	170 million litres of ethanol	350 million litres of biofuel by 2010	wheat and molasses	producer subsidy, capital grants, vehicle standard	import tariff of \$0.31 per litre on both ethanol and biodiesel
Japan	insignificant	360 million litres by 2010 and 10% biofuel by 2030	imported ethanol	excise tax credit	ad valorem import duty of 23.8% on fuel ethanol (to be lowered to 10% by 2010)

\* data not found

\*\* biodiesel policy has not yet passed into law in India and is merely a government preference at this point

Note: agricultural policies that affect production of biofuel crops is not covered here

Table 12: Summary of current production, future targets and policies in various countries

Instrument	Oil use reduction	GHG reduction	Farm income	Ethanol producers	Consumer surplus (Food)	Consumer surplus (Energy)	Govt. Budget
<b>Energy and Fuel Policies</b>							
Biofuel Tax Credit	+	<>	+	+	-	<>	-
Biofuel Mandate	+	<>	+	+	-	-	<>
Carbon/Gasoline Tax	+	+	<>	<>	<>	-	+
Efficiency Standard	+	+	<>	<>	<>	+	<>
Vehicle subsidy	<>	<>	<>	<>	<>	<>	-
<b>Ag and Trade Policies</b>							
Price Support	+	<>	+	<>	+	+	-
Acreage Control	<>	<>	+	-	-	-	-
Import Tariff	+	<>	+	+	-	-	+
Export Subsidy	<>	<>	+	+	-	-	-
Export Quota	+	<>	-	+	+	+	<>
<b>Legend</b>	+	+ve impact	<>	uncertain	-	-ve impact	

Table 13: Possible impact of policy on economic and environmental indicators